Assessing of Circuit Breaker Restrike Risks Using Computer Simulation and Wavelet Analysis

Shui-cheong Kam, BSc, MBA, MEng.

A thesis submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

School of Electrical Engineering and Computer Science
Science and Engineering Faculty
Queensland University of Technology
Queensland, Australia
June 2012
Keywords

Alternative Transient Program, Electromagnetic Transient Program, detection algorithm, high frequency transient phenomena, measurements, model calibration, circuit breaker diagnostics, interrupter risk condition, parameter determination, predictive interpretation technique, re-ignition, restrike switch model, Wavelet Analysis
Abstract

A breaker restrike is an abnormal arcing phenomenon, leading to a possible breaker failure. Eventually, this failure leads to interruption of the transmission and distribution of the electricity supply system until the breaker is replaced. Before 2008, there was little evidence in the literature of monitoring techniques based on restrike measurement and interpretation produced during switching of capacitor banks and shunt reactor banks in power systems. In 2008 a non-intrusive radiometric restrike measurement method and a restrike hardware detection algorithm were developed by M.S. Ramli and B. Kasztenny. However, the limitations of the radiometric measurement method are a band limited frequency response as well as limitations in amplitude determination. Current restrike detection methods and algorithms require the use of wide bandwidth current transformers and high voltage dividers.

A restrike switch model using Alternative Transient Program (ATP) and Wavelet Transforms which support diagnostics are proposed. Restrike phenomena become a new diagnostic process using measurements, ATP and Wavelet Transforms for online interrupter monitoring. This research project investigates the restrike switch model Parameter ‘A’ dielectric voltage gradient related to a normal and slowed case of the contact opening velocity and the escalation voltages, which can be used as a diagnostic tool for a vacuum circuit-breaker (CB) at service voltages between 11 kV and 63 kV. During current interruption of an inductive load at current quenching or chopping, a transient voltage is developed across the contact gap. The dielectric strength of the gap should rise to a point to withstand this transient voltage. If it does not, the gap will flash over, resulting in a restrike. A straight line is fitted through the voltage points at flashover of the contact gap. This is the point at which the gap voltage has reached a value that exceeds the dielectric strength of the gap. This research shows that a change in opening contact velocity of the vacuum CB produces a corresponding change in the slope of the gap escalation voltage envelope.

To investigate the diagnostic process, an ATP restrike switch model was modified with contact opening velocity computation for restrike waveform signature analyses along with experimental investigations. This also enhanced a mathematical CB model with the empirical dielectric model for SF₆ (sulphur hexa-fluoride) CBs at service voltages above 63 kV and a generalised dielectric curve model for 12 kV CBs. A CB
Restrike can be predicted if there is a similar type of restrike waveform signatures for measured and simulated waveforms.

The restripe switch model applications are used for: computer simulations as virtual experiments, including predicting breaker restrikes; estimating the interrupter remaining life of SF₆ puffer CBs; checking system stresses; assessing point-on-wave (POW) operations; and for a restrike detection algorithm development using Wavelet Transforms. A simulated high frequency nozzle current magnitude was applied to an Equation (derived from the literature) which can calculate the life extension of the interrupter of a SF₆ high voltage CB. The restripe waveform signatures for a medium and high voltage CB identify its possible failure mechanism such as delayed opening, degraded dielectric strength and improper contact travel. The simulated and measured restripe waveform signatures are analysed using Matlab software for automatic detection.

Experimental investigation of a 12 kV vacuum CB diagnostic was carried out for the parameter determination and a passive antenna calibration was also successfully developed with applications for field implementation. The degradation features were also evaluated with a predictive interpretation technique from the experiments, and the subsequent simulation indicates that the drop in voltage related to the slow opening velocity mechanism measurement to give a degree of contact degradation. A predictive interpretation technique is a computer modeling for assessing switching device performance, which allows one to vary a single parameter at a time; this is often difficult to do experimentally because of the variable contact opening velocity.

The significance of this thesis outcome is that it is a non-intrusive method developed using measurements, ATP and Wavelet Transforms to predict and interpret a breaker restrike risk. The measurements on high voltage circuit-breakers can identify degradation that can interrupt the distribution and transmission of an electricity supply system. It is hoped that the techniques for the monitoring of restripe phenomena developed by this research will form part of a diagnostic process that will be valuable for detecting breaker stresses relating to the interrupter lifetime.

Suggestions for future research, including a field implementation proposal to validate the restrike switch model for ATP system studies and the hot dielectric strength curve model for SF₆ CBs, are given in Appendix A.
Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of figures</td>
<td>ix</td>
</tr>
<tr>
<td>List of tables</td>
<td>xiii</td>
</tr>
<tr>
<td>List of appendices</td>
<td>xv</td>
</tr>
<tr>
<td>List of abbreviations and symbols</td>
<td>xvii</td>
</tr>
<tr>
<td>Chapter 1: Introduction</td>
<td>25</td>
</tr>
<tr>
<td>1.1 Background and the preliminary literature review</td>
<td>25</td>
</tr>
<tr>
<td>1.2 Breaker restrike/re-ignition studies using computer simulations</td>
<td>28</td>
</tr>
<tr>
<td>1.3 Research goals</td>
<td>34</td>
</tr>
<tr>
<td>1.4 Thesis outline</td>
<td>37</td>
</tr>
<tr>
<td>Chapter 2: Literature Review</td>
<td>39</td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>40</td>
</tr>
<tr>
<td>2.2 Medium and high voltage CB characteristics</td>
<td>40</td>
</tr>
<tr>
<td>2.3 Overview of research on modeling protection with controlled switching</td>
<td>52</td>
</tr>
<tr>
<td>2.4 Determining interrupter life</td>
<td>57</td>
</tr>
<tr>
<td>2.5 Database development in power systems</td>
<td>58</td>
</tr>
<tr>
<td>2.6 Restrike features and breaker model parameters for detection of breaker degradation</td>
<td>58</td>
</tr>
<tr>
<td>2.7 Restrike waveform signature verification with the simulated and measured results</td>
<td>59</td>
</tr>
<tr>
<td>2.8 Online model-based CB monitoring and diagnosis</td>
<td>60</td>
</tr>
<tr>
<td>2.9 Parameter determination and model calibration for computer simulations</td>
<td>62</td>
</tr>
<tr>
<td>2.10 Restrike waveform diagnostic algorithm development for automatic detection</td>
<td>63</td>
</tr>
<tr>
<td>2.11 Gaps for this research</td>
<td>64</td>
</tr>
<tr>
<td>2.12 Creating hypotheses</td>
<td>65</td>
</tr>
<tr>
<td>2.13 Research road map</td>
<td>65</td>
</tr>
<tr>
<td>2.14 Research direction</td>
<td>66</td>
</tr>
<tr>
<td>2.15 Summary and implications</td>
<td>68</td>
</tr>
<tr>
<td>Chapter 3: Proposed Methodology</td>
<td>71</td>
</tr>
<tr>
<td>3.1 Concepts and theories of restrike phenomena</td>
<td>73</td>
</tr>
<tr>
<td>3.1.1 Introduction</td>
<td>73</td>
</tr>
<tr>
<td>3.1.2 Switching transients and abnormal transients</td>
<td>74</td>
</tr>
<tr>
<td>3.1.3 Electrical transient analysis and simulation</td>
<td>74</td>
</tr>
<tr>
<td>3.1.4 Using oscillation frequencies in a reactor switching circuit for checking the accuracy of restrike waveform signatures</td>
<td>75</td>
</tr>
<tr>
<td>3.1.5 Stresses of switching transients to CBs</td>
<td>75</td>
</tr>
<tr>
<td>3.1.6 Conclusions</td>
<td>76</td>
</tr>
</tbody>
</table>
Chapter 4: Restrike Switch Model Applications and Detection Algorithm Development .... 103

4.1 Modeling of restriking and re-ignition phenomena in three-phase capacitor and shunt reactor switching .......................................................... 104
  4.1.1 Introduction ........................................................................... 105
  4.1.2 Capacitor bank switching modeling ....................................... 105
  4.1.3 Methodology and practical applications .................................... 120
4.2 A data-base of ATP simulated waveforms of shunt reactor switching cases with vacuum CBs on motor circuits ........................................... 123
  4.2.1 Introduction ........................................................................... 123
  4.2.2 Motor circuit for overvoltage determination ............................. 124
  4.2.3 Framework of the simulation .................................................... 126
  4.2.4 Simulation and results .............................................................. 130
  4.2.5 Conclusions .......................................................................... 136
4.3 Mayr’s arc equation for SF6 CB degradation and its remaining life prediction from restrike waveform signatures ........................................... 137
  4.3.1 Modeling of the SF6 CB ............................................................. 138
  4.3.2 Summary of SF6 breaker diagnostic and prognostic algorithms ... 141
4.4 A restrike switch model for shunt capacitor bank switching with POW assessments ................................................................................... 144
  4.4.1 Introduction ........................................................................... 145
  4.4.2 Background theory ................................................................. 146
  4.4.3 Simulation models and cases ..................................................... 146
  4.4.4 Simulation results .................................................................... 148
  4.4.5 Conclusion ............................................................................. 157
4.5 A CB restrike detection algorithm using ATP and Wavelet Transforms .... 158
  4.5.1 Introduction ........................................................................... 158
  4.5.2 Existing approach for restrike detection algorithm .................... 159
  4.5.3 Novel approach for restrike detection algorithm ........................ 161
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

5.1 Introduction ........................................................................................................ 180
5.1.1 Model calibration ........................................................................................... 181
5.1.2 Theoretical studies of the vacuum CB restrike behaviour ............................... 183
5.1.3 Laboratory experimental tests ......................................................................... 185
5.2 Modeling of restrikes/re-ignitions behaviour analysis .......................................... 206
5.2.1 Modeling for the power supply source ........................................................... 207
5.2.2 Modeling for a 12 kV vacuum CB recloser—measurements and results 207
5.2.3 Modeling for the existing power transformers—measurements and results 208
5.2.4 Results evaluation .......................................................................................... 209
5.2.5 Model evaluation ............................................................................................ 216
5.3 Discussion ........................................................................................................... 219
5.3.1 A restrike switch model with contact velocity computation ............................ 221
5.3.2 A generalised vacuum dielectric model for 12 kV vacuum CBs .................... 221
5.3.3 A predictive interpretation technique for CB diagnostics .............................. 221
5.3.4 Evaluation of the hypotheses .......................................................................... 222
5.4 Summary and implications .................................................................................. 223

Chapter 6: Conclusions and Future Work Proposal

6.1 Fulfilment of thesis goals ..................................................................................... 225
6.2 Novel contribution of the work ............................................................................ 226
6.3 Future work proposal .......................................................................................... 228
6.3.1 Restrike switch model development proposal .................................................. 228
6.3.2 Parameter variation sensitivity analysis ......................................................... 229
6.3.3 ATP implementation and simulations on large scale power system models 229
6.3.4 Automatic diagnostic algorithm for restrike waveforms using a self-organising map .......................................................... 230
6.3.5 Single-phase laboratory experiments and simulations for a restrike switch model parameter determination and calibration ................................................. 230
6.3.6 A generalised dielectric curve model for vacuum CBs other than the rating 12 kV vacuum CBs ...................................................................................... 232
6.3.7 Arc Equation for vacuum CBs ......................................................................... 232
6.3.8 Hot withstand dielectric model for vacuum CBs ............................................. 232
6.3.9 Other signal processing techniques which can be used for feature extraction and classification of simulated restrike waveforms ................................. 232
6.4 Concluding remarks .......................................................................................... 233
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>References</td>
<td>237</td>
</tr>
<tr>
<td>Publications arising from the thesis</td>
<td>247</td>
</tr>
<tr>
<td>Appendix-A</td>
<td>249</td>
</tr>
<tr>
<td>Appendix-B</td>
<td>253</td>
</tr>
<tr>
<td>Appendix-C</td>
<td>254</td>
</tr>
<tr>
<td>Appendix-D</td>
<td>255</td>
</tr>
<tr>
<td>Appendix-E</td>
<td>264</td>
</tr>
<tr>
<td>Appendix-F</td>
<td>269</td>
</tr>
<tr>
<td>Appendix-G</td>
<td>302</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Transient switching problems (in blue text) and solutions (in green text)</td>
<td>27</td>
</tr>
<tr>
<td>Figure 1.2</td>
<td>Hierarchical structure of a medium and high voltage CB model</td>
<td>28</td>
</tr>
<tr>
<td>Figure 1.3</td>
<td>Main functional parts of a medium and high voltage CB</td>
<td>29</td>
</tr>
<tr>
<td>Figure 1.4</td>
<td>Simple control circuit for breaker open</td>
<td>30</td>
</tr>
<tr>
<td>Figure 1.5</td>
<td>Simple control circuit for breaker close</td>
<td>31</td>
</tr>
<tr>
<td>Figure 1.6</td>
<td>Main functional parts of a medium and high voltage CB</td>
<td>32</td>
</tr>
<tr>
<td>Figure 1.7</td>
<td>Illustration of transient voltage waveform signature</td>
<td>32</td>
</tr>
<tr>
<td>Figure 1.8</td>
<td>Breaking followed by re-ignition</td>
<td>34</td>
</tr>
<tr>
<td>Figure 1.9</td>
<td>Switch current (arc is quenched; however, dielectric re-ignition occurs) for an inductive circuit</td>
<td>35</td>
</tr>
<tr>
<td>Figure 1.10</td>
<td>Restrike voltage waveforms for a capacitor bank circuit</td>
<td>36</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Dielectric strength Slopes A, B, C and D after current interruption</td>
<td>45</td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>Zoomed plot showing the first re-ignition</td>
<td>49</td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Arc resistance calculated by the breaker’s voltage and current</td>
<td>51</td>
</tr>
<tr>
<td>Figure 2.4</td>
<td>Waveform measurement from experiments</td>
<td>55</td>
</tr>
<tr>
<td>Figure 2.5</td>
<td>The simulated waveform is to have an envelope which matches that obtained from measurement</td>
<td>55</td>
</tr>
<tr>
<td>Figure 2.6</td>
<td>Impact of arcing wear on SF₆ interrupter</td>
<td>58</td>
</tr>
<tr>
<td>Figure 2.7</td>
<td>A predictive interpretation technique for CB diagnostics</td>
<td>60</td>
</tr>
<tr>
<td>Figure 2.8</td>
<td>Problem formulation blocks for assessing interrupter risk condition from a restrike switch model using measurements, ATP and Wavelet Transforms</td>
<td>66</td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>The research process</td>
<td>71</td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>Flow chart of the vacuum CB’s restrike modeling with contact opening velocity computation</td>
<td>79</td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>ALCATEL Type 31 cable</td>
<td>81</td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>Escalation voltage (a) vs current (b) across breaker</td>
<td>94</td>
</tr>
<tr>
<td>Figure 4.1</td>
<td>A restrike switch model application and detection algorithm development</td>
<td>104</td>
</tr>
<tr>
<td>Figure 4.2</td>
<td>Capacitor bank single-phase equivalent circuit</td>
<td>105</td>
</tr>
<tr>
<td>Figure 4.3</td>
<td>Single-phase equivalent circuit</td>
<td>106</td>
</tr>
<tr>
<td>Figure 4.4</td>
<td>Capacitor restriking waveforms</td>
<td>107</td>
</tr>
<tr>
<td>Figure 4.5</td>
<td>ATPDRAW diagram for grounded capacitor bank switching example</td>
<td>108</td>
</tr>
<tr>
<td>Figure 4.6</td>
<td>ATPDRAW diagram for ungrounded capacitor bank switching example</td>
<td>109</td>
</tr>
<tr>
<td>Figure 4.7</td>
<td>Three-phase ungrounded capacitor bank configuration</td>
<td>110</td>
</tr>
<tr>
<td>Figure 4.8</td>
<td>Equivalent circuit for three-phase capacitor bank switching and phasor diagram</td>
<td>110</td>
</tr>
<tr>
<td>Figure 4.9</td>
<td>Voltage waveforms across CB CA simulating Pole A restrikes</td>
<td>111</td>
</tr>
<tr>
<td>Figure 4.10</td>
<td>Voltage waveforms across capacitor bank CA simulating Pole A restrikes</td>
<td>112</td>
</tr>
<tr>
<td>Figure 4.11</td>
<td>Current waveforms across capacitor bank CA simulating Pole A restrikes</td>
<td>112</td>
</tr>
<tr>
<td>Figure 4.12</td>
<td>Voltage waveforms across CB, simulating Pole B and C restrikes</td>
<td>113</td>
</tr>
</tbody>
</table>
Figure 4.13. Voltage waveforms across Capacitor Banks B and C, simulating Pole B and C restrikes .................................................................................................................. 113
Figure 4.14. Current waveforms across Capacitor Banks B and C, simulating Pole B and C restrikes .................................................................................................................. 114
Figure 4.15. Single-phase circuit for re-ignition study .............................................. 115
Figure 4.16. Single re-ignition across CB .................................................................. 116
Figure 4.17. Multiple re-ignitions across CB .............................................................. 117
Figure 4.18. Shunt reactor switching ....................................................................... 118
Figure 4.19. Voltage waveform for Phase B voltage interruption of reactor switching .................................................................................................................. 119
Figure 4.20. Virtual current chopping feature for Phase B current interruption of reactor switching ........................................................................................................ 119
Figure 4.21. Power special density plots show the strength of the single restrike (energy) as a function of frequency ................................................................. 121
Figure 4.22. Power special density plots show the strength of the two restrikes (energy) as a function of frequency ................................................................. 121
Figure 4.23. Three-phase equivalent circuit of cable connected motor system AS/IEC 62271-110 circuit ................................................................................................. 124
Figure 4.24. Signals between MODELS and ATP ...................................................... 125
Figure 4.25. Slope of recovery dielectric strength and TRV between arcing contacts .................................................................................................................. 127
Figure 4.26. Database development for diagnostic and prognostic algorithm framework .............................................................................................................. 127
Figure 4.27. ATPDRAW for the motor circuit ............................................................ 128
Figure 4.28. Components in the ATP file .................................................................. 129
Figure 4.29. Three-phase voltage waveform across the vacuum breaker contacts .. 133
Figure 4.30. Three-phase high frequency current waveform across the vacuum breaker .................................................................................................................. 133
Figure 4.31. Three-phase over-voltage waveform across the motor ....................... 133
Figure 4.32. Different voltage waveforms measured for CH1-active/passive antenna, CH2-supply voltage and CH3-reactor voltage ...................................................... 135
Figure 4.33. Restriking current in line with the restriking voltage ............................ 135
Figure 4.34. The number of restrikes with faster sweep speed instruments to identify the restrikes ........................................................................................................ 135
Figure 4.35. Restriking time duration with faster sweep speed instruments to identify the restrikes ........................................................................................................ 136
Figure 4.36. Power spectral density with faster sweep speed instruments to determine the deterioration .................................................................................................. 136
Figure 4.37. Schematic diagram of the proposed extended Mayr’s equation-based arc model, including ATP-EMTP TACS SW(Switch) control and dielectric recovery control unit for post-arc monitoring .......................................................... 139
Figure 4.38. Universal arc representation of modified Mayr’s model ....................... 140
Figure 4.39. The flowchart of the voltage comparator ............................................... 141
Figure 4.40. Simulated ATP switch (red in colour) and a field switch (blue in colour) waveforms .............................................................................................................. 142
Figure 4.41. Three-phase simulated circuit for site .................................................. 143
Figure 4.42. Three-phase simulated re-ignition voltage ........................................... 143
Figure 4.43. Three-phase simulated re-ignition current to predict I’t losses .......... 143
Figure 4.44. Case study 1600 kVA, 750/400 kV transmission transformer ungrounded connection ................................................................. 147
Figure 4.45. Voltage across breaker (110/40/50 kV) for cold withstand dielectric strength curve non-grounded connection .............................................................. 149
Figure 4.47. TRV rise time (0.4/0.1/0.05 kV/μs) for cold withstand dielectric strength curve non-grounded connection .............................................................. 149
Figure 4.46. Current across breaker (2000/1500/1100 A) for cold withstand dielectric strength curve non-grounded connection .............................................................. 149
Figure 4.48. Voltage across breaker (35/15/45 kV) for cold withstand dielectric strength curve grounded connection .............................................................. 150
Figure 4.49. Current across breaker (800/600/500 A) for cold withstand dielectric strength curve grounded connection .............................................................. 150
Figure 4.50. TRV rise time (0.13/0.08/0.1 kV/μs) for cold withstand dielectric strength curve non-grounded connection .............................................................. 150
Figure 4.51. Voltage across breaker (45/0/28 kV) for cold withstand dielectric strength curve non-grounded connection .............................................................. 151
Figure 4.52. Current across breaker (80/120/200 A) for cold withstand dielectric strength curve non-grounded connection .............................................................. 151
Figure 4.53. TRV rise time (0.9/0.4/0.7 kV/μs) for cold withstand dielectric strength curve non-grounded connection; no POW .............................................................. 151
Figure 4.54. Voltage across breaker (18/16/18 kV) for hot withstand dielectric strength curve non-grounded connection .............................................................. 152
Figure 4.55. Current across breaker (220/100/110 A) for hot withstand dielectric strength curve non-grounded connection .............................................................. 152
Figure 4.56. TRV rise time (0.13/0.08/0.3 kV/μs) for hot withstand dielectric strength curve non-grounded connection .............................................................. 152
Figure 4.57. Current across breaker (800/1000/1200 A) for cold withstand dielectric strength curve grounded connection .............................................................. 154
Figure 4.58. Current across breaker (800/900/1200 A) for hot withstand dielectric strength curve grounded connection .............................................................. 154
Figure 4.59. Current across breaker (80/100/240 A) for cold withstand dielectric strength curve non-grounded connection .............................................................. 154
Figure 4.60. Current across breaker (80/100/230 A) for hot withstand dielectric strength curve non-grounded connection .............................................................. 155
Figure 4.61. State machine for restrike detection .............................................................. 160
Figure 4.62. Using Wavelet Transforms for diagnostic algorithms development with experimental data .............................................................. 161
Figure 4.63. Wavelet decomposition of single-phase supply .............................................................. 162
Figure 4.64. Example of voltage waveform across C2 from Figure 4.3 .............................................................. 165
Figure 4.65. Poor result using db1 at Detail 1 .............................................................. 165
Figure 4.66. Good result using db5 at Detail 1 .............................................................. 166
Figure 4.67. Probabilities of diagnostic and false alarm at Detail 1, db5 .............................................................. 173
Figure 4.68. Comparison of using energy Level D2, D3 and D2 or D3 .............................................................. 174
Figure 4.69. Probability of detection vs energy level at D2 or D3 .............................................................. 175
Figure 4.70. Typical wavelet decomposition of a measured restrike waveform .............................................................. 177
Figure 4.71. Probability of detection vs energy level at D4 or D5 .............................................................. 177

Figure 5.1. Parameter determination and model calibration of a restrike switch model .............................................................. 182
Figure 5.2. A methodology for a systematic parameter determination and calibration of the restrike switch model .............................................................. 182
Figure 5.3. Simulation circuit analysis .............................................................. 183
Figure 5.33. Voltage waveforms for normal contact opening velocity: measurement vs simulation ........................................................................................................ 217
Figure 5.34. Current waveforms for normal contact opening velocity: measurement vs simulation ........................................................................................................ 217
Figure 5.35. Voltage waveforms for slow contact opening velocity: measurement vs simulation ........................................................................................................ 218
Figure 5.36. Current waveforms for slow contact opening velocity: measurement vs simulation ........................................................................................................ 218

Figure F.1. A typical curve of dielectric recovery characteristic of the SF₆ interrupter with conversion with per unit for overvoltage .......................................................... 272
Figure F.2. Overvoltage curves in regression lines of each CB type ........................................... 274
Figure F.3. Chopping number in various CB regression lines ..................................................... 275
Figure F.4. Curve of overvoltages and dielectric recovery .......................................................... 276
Figure F.5. Dielectric recovery data for Model A GCB .............................................................. 277
Figure F.6. Dielectric recovery data for Model B GCB .............................................................. 277
Figure F.7. Dielectric recovery data for Model C GCB .............................................................. 278
Figure F.8. Combined dielectric recovery data for Model A, B and C GCB ......................... 278
Figure F.9. Dielectric recovery for reference geometry .............................................................. 280
Figure F.10. Dielectric recovery for enlarged geometry .............................................................. 281
Figure F.11. Field tests in Germany ........................................................................................... 282
Figure F.12. Switching overvoltages recorded during the field tests in Spain, but the data calculated from the results of the field tests in Germany ........................................ 283
Figure F.13. Laboratory dielectric recovery data from Japan ....................................................... 286
Figure F.14. Combined data from fields and laboratory dielectric recovery results 288
Figure F.15. A hot dielectric recovery model derived from the laboratory dielectric recovery data from Japan and the measured data from Korean experimental results .............................................................. 289
Figure F.16. A general dielectric strength model for 12 kV vacuum CBs taking vacuum breakdown mechanism into account ................................................................. 294
Figure F.17. A novel statistical dielectric strength curve taking consideration of transitional process, chopping current and rate of current rise after current interruption .............................................................. 295
Figure F.18. Dielectric strength characteristic derived from Ref.[143] and Ref.[147] .............................................................. 296
Figure F.19. Experimental circuit arrangement in a laboratory ................................................... 297
Figure F.20. ATPDRAW Model to duplicate for the experimental measurements for simulated waveforms production .............................................................. 299
Figure F.21. Number of restrikes for different dielectric curves .............................................. 300

Figure G.1. A laboratory test setup with inductive load ........................................................... 302
Figure G.2. Re-ignition at recovery voltage peak for a circuit with low supply-side capacitance ...................................................................................................................... 303
Figure G.3. Oscillograms of voltage (upper) and current (lower) after re-ignition . 305
# List of Tables

Table 3.1. ALCATEL cable data ................................................................. 82  
Table 3.2. Typical stray capacitances of HV and LV to ground and between HV and LV side (nF) ................................................................. 85  
Table 3.3. System status definition for CB degradation conditions .............. 95  
Table 3.4. Features for individual signals .............................................. 96  

Table 4.1. The comparison of using the formulae and computer simulation for grounded capacitor bank ................................................................. 108  
Table 4.2. Circuit data ........................................................................... 115  
Table 4.3. Revised circuit data ................................................................. 116  
Table 4.4. Comparison of calculated and simulated phase-to-ground overvoltages and frequency ........................................................................... 118  
Table 4.5. Parameters of 6.6 kV motor circuits ......................................... 125  
Table 4.6. Circuit parameters as per AS 62271.110 .................................. 128  
Table 4.7. Peak voltage buildup for detecting restrikes ............................. 131  
Table 4.8. Power spectral density indicating the wear ............................... 132  
Table 4.9. Diagnostic and prognostic algorithms for SF₆ breaker .............. 142  
Table 4.10. Grounded capacitor bank switching performance .................. 153  
Table 4.11. Non-grounded capacitor bank switching performance ............ 153  
Table 4.12. Inrush current for grounded capacitor bank switching performance ................................................................. 155  
Table 4.13. Inrush current for non-grounded capacitor bank switching performance ................................................................. 155  
Table 4.14. Simplified linear extrapolation .............................................. 156  
Table 4.15. First phase of screening wavelets testing results ...................... 167  
Table 4.16. Second phase of screening wavelet testing result .................... 170  
Table 4.17. Probability of first test result, P₁ ........................................... 171  
Table 4.18. Probability of second test result, P₂ ..................................... 172  
Table 4.19. Final result of wavelet selection, P₃ ....................................... 172  

Table 5.1. Equipment data for measurement test .................................... 186  
Table 5.2. Comparison of breakdown voltage per mm up to 4 mm at the time of contact opening ................................................................. 200  
Table 5.3. Comparison of contact opening velocity .................................. 200  
Table 5.4. Comparison between Greenwood’s and the experimental results ... 212  

Table E.1. ABB single-phase SWER transformer nameplate data ............ 267  
Table E.2. Power transformer nameplate data ......................................... 267  

Table F.1. Comparison amongst the failure data ..................................... 270  
Table F.2. Field data in Spain ................................................................. 273  
Table F.3. Results of the tests ................................................................. 274  
Table F.4. Comparison amongst Model A, B and C calculated results .......... 279  
Table F.5. Comparison between the reference geometry and enlarged geometry of the nozzles ................................................................. 281  
Table F.6. Comparison between the field data in Spain and Germany ......... 284  
Table F.7. Laboratory test data in Japan .................................................. 285
Table F.8. Comparison amongst the data in Spain and Germany and Japan ........287
Table F.9. $di/dt$ characteristics parameters .................................................293
Table F.10. Data of cable ...............................................................................298
Table F.11. Results for different dielectric strength curves ..............................300
# List of Appendices

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix-A</td>
<td>Field Implementation Proposal</td>
<td>249</td>
</tr>
<tr>
<td>Appendix-B</td>
<td>Scheme of restrikes to determine breaker risk level</td>
<td>253</td>
</tr>
<tr>
<td>Appendix-C</td>
<td>Summary of the breaker ABCD parameter experimental results</td>
<td>254</td>
</tr>
<tr>
<td>Appendix-D</td>
<td>PI Model of the vacuum circuit breaker</td>
<td>255</td>
</tr>
<tr>
<td>Appendix-E</td>
<td>A high frequency power transformer model</td>
<td>264</td>
</tr>
<tr>
<td>Appendix-F</td>
<td>Models for the hot withstand dielectric strength characteristics curves for SF₆ CBs and 12 kV vacuum CBs</td>
<td>269</td>
</tr>
<tr>
<td>Appendix-G</td>
<td>A predictive interpretation technique for CB diagnostics</td>
<td>302</td>
</tr>
</tbody>
</table>
### List of principal abbreviations and symbols

**Abbreviations**

AC – alternating current

ATP- Alternative Transient Program

CB – circuit-breaker

$C_L$ - the stray capacitance of the reactor and bus-bar

$C_S$ - the stray capacitance of source side circuit

CRO – cathode ray oscilloscope

DFT - Discrete Fourier Transform

EMTP – Electromagnetic Transient Program

FFT - Fast Fourier Transform

GCB – gas circuit-breaker

HV – high voltage (above 63 kV)

$I_i$ - load-side current

$I_	ext{chng}$ - equivalent chopping current

$L_B$ - inductance of the busbar between CB and

$L_d$ - inductance of the reactor

$L_s$ - inductance of source side circuit (source-side voltage)

MV – medium voltage (between 11 kV and 63 kV)

POW – point-on-wave

pu - per unit quantity

RDDS – rate of decay of dielectric strength

RRDS – rate of rise of dielectric strength

RRRV – rate of rise of recovery voltage

$\text{SF}_6$ - Sulphur Hexafluoride

SOM – Self-organising Map

TRV – transient recovery voltage

$U_{on}$ - voltage trapped on load side capacitance
U_{os} - source-side voltage
U_{l} - load-side voltage
U_{tr} or u_{tr} - TRV
U_{dn} - dielectric voltage of the CB
U_{r} - voltage across CB at re-ignition
U_{m} - chopping overvoltage (suppression peak)

Z_{c} - characteristic impedance of the reactor
Z_{S} - characteristic impedance of the source

Symbols
\omega_{l} - angular frequency of the load side circuit
\omega_{h} - angular frequency of the re-ignition circuit
\omega_{s} - angular frequency of the supply source
\alpha - phase angle of load side voltage
\delta - the damping constant
\alpha = the load supply angle
Statement of original authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature:…………………………
Name: Shui-cheong Kam
Date:…21 June 2012…………………………
Acknowledgements

First of all, I am indeed grateful to Associate Professor David Birtwhistle (retired) who, during his service at QUT, provided me with a doctoral position (under his supervision) to develop a non-intrusive method to diagnose a breaker restrike risk for high voltage CBs to prevent the interruption of the distribution and transmission of an electricity supply system. Without his advice and support, this research would not have been possible.

Sincere thanks and gratitude are also extended to my principal supervisor, Professor Gerard Ledwich, and my associate supervisor, Dr. Shawn Nielsen for their precious time and valuable support in designing and building a POW control circuit box, and for their inspiration and research direction. Special thanks are also extended for the support and advice provided by the technical workshop staff, Mr. Wolfgang Maier and Mr. Brendon Stichbur, in setting up 11 kV equipment for parameter determination and model calibration.

I would also like to thank my friends in the United States, Singapore, Brisbane, Sydney, Hong Kong and Spain, including Dr. Pengju Kang, Dr. Tak-wai Chan, Mr. Kim Kwok, Mr. Paul Chan, Mr. John Wong, Dr. Amy Chan, Dr. AnDr.ew Wong, Mr. Alex Tang, Mr. Sai-kee Lai, Dr. Shun-wah Lee, Dr. Tony O'Connor and Ms Inmaculada Tomeo-Reyes. I thank all who have contributed to make this experience an unforgettable one.

I am also indebted to Dr. Barbara Jack who helped me to improve my learning skills and to Dr. Susan Gould who has taken care of my physical health during my studies at QUT. Special thanks are given to my colleague, Dr. Iman Ziari, for polishing my Final Seminar presentation. Last but not least, I infinitely thank my family – my wife Shik-kwan(Clare), my son Tak-ming (Paul) and my daughter Tak-yung (Jane) – for their kindness, love, support and patience during the period of this research.
Chapter 1: Introduction

This chapter outlines the background, goals and structure of this study. A preliminary literature review is provided in Section 1.1. A summary of the current literature and studies on breaker restrike detection problems – more specifically, on medium voltage and high voltage CB restrike/re-ignition detection problems using computer simulation – are then presented in Section 1.2. The goals of this research are presented in Section 1.3. Finally, Section 1.4 is an outline of the remaining chapters of the thesis.

1.1 Background and the preliminary literature review

Medium and high voltage CBs are the most critical switching elements in a power system because the performance of the circuit switching elements determines the desired level of power quality and availability in any power system. CBs are required not only to interrupt faults, but also to switch under system conditions ranging from “no-load” through to full rated asymmetrical fault currents. The electrical stresses placed on a CB vary considerably with the specific nature of the circuit being switched. Interrupting large fault currents at medium and high voltages involves high thermal and dielectric withstand stresses being placed on a CB. Inductive or capacitive currents for low current can also place high (dielectric) stresses on a CB.

The original idea for this research project came from a 2002 consultancy report by Dr. David Birtwhistle [1] which recommended development of a non-intrusive method to diagnose a breaker restrike for high voltage CBs to prevent interruption to the distribution and transmission of an electricity supply system. Restrike is an abnormal arcing phenomenon for a CB, giving an indication of possible interruption failure. The need for remaining lifetime prediction for an interrupter is based on the fact that many utilities struggle to manage their assets and, with the move toward condition-based rather than
time-based maintenance, the issue of CB residual life is actively being pursued [2, 3]. Also, remaining life assessment is a common objective for asset management nowadays.

Restrike overvoltage is the cause of failure of SF$_6$ CBs and is one of a number of transient switching problems. This has been verified by extensive investigation involving system studies, laboratory and site tests. Computer simulations [4],[5] can be used to recommend a model to identify the breaker restrike causes in this research project:

*A model is a physical and/or mathematical description of something or some process, that helps us to better understand the object on what is going on in the process. A good model explains what we observe physically. It should be consistent with all our observations or as a minimum; it should not be in conflict with any of them. In the best of circumstances it should be predictive, that is to say it should accurately foretell what is to expect if this or that parameter is changed.*

*A great advantage of computer modeling is the ability it provides, to test the sensitivity of a process or series of events to any of the parameters involved by varying the parameter while keeping the others constant.* [6]

Boyd reports that unexpected breaker restrikes can occur due to: the CB being tested to an inadequate or old standard; an inaccurate system study or failure of voltage limiting equipment, e.g., a surge arrestor; incorrect operation of controlled switching; interrupter wear and tear due to daily operation and high frequency re-ignition current [7]. There was no evidence of currently available monitoring techniques in use to measure restrikes produced during CB switching of capacitor banks and shunt reactors [8]. This was Ramli’s motivation to develop a radiometric measurement hardware method as a non-intrusive restrike detection technique[8].

Transients have been calculated for a number of well-known types of equipment mal-function, by using a powerful transient simulation program [9] developed by the power systems research community over more than thirty years. Figure 1.1 illustrates a set of transient switching problems and solutions. Restrikes or re-ignitions occur when the voltage across the switch contacts rises very quickly if the rate of the system transient recovery voltage (TRV) exceeds the dielectric strength in the medium between the contacts. This phenomenon suggests that impending failure of CBs due to degradation within the CB can be identified by detailed analysis of restrike waveform signatures.
Therefore, computer modeling and simulations and signal processing methods for detection of degradation may provide condition precursors of CB failure. Also, this research project is solidly in the area of Asset Management, with the aim of developing new approaches to identifying the condition of interrupters by monitoring high-magnitude transient phenomena with computer simulations.

Figure 1.1. Transient switching problems (in blue text) and solutions (in green text) [10]

From a customer viewpoint, the safety and CB operation of power systems can be improved if detection can be achieved for intermittent faults between phase and ground. These faults may not cause CB operation failure, but may cause transient voltages from causes such as trees briefly touching power-lines when blown by the wind. The other operational aspects which need to be addressed is the short duration voltage sags caused by temporary arcing, such as welding. Polluted insulators, when wet, may also cause transient discharges; voltage depression following a fuse or recloser operation can also pose operational problems [11, 12]. Ferroresonance is an unstable high voltage that can occur on three-phase electrical systems under specific conditions, potentially causing the failure of equipment. The ferroresonance problem is difficult to detect because the random overvoltage that occurs only exists for a short transient of a few cycles; these cycles may be repeated depending on the circuit parameters and initial condition of the non-linear inductance of the transformer core.

In summary, as a contribution to this research project, the preliminary literature review identified computer modeling, simulations and signal processing as an
alternative method for predicting the breaker restrike risk. Restrike waveform signatures for breaker condition monitoring have also been identified as a new research direction for power quality.

1.2 Breaker restrike/re-ignition studies using computer simulations

A medium and high voltage CB is an electrical switching device designed to make, carry, and interrupt all currents occurring in a power system [13]. It must change unfailingly from conducting to isolating status when called on to operate, or vice versa, normally within a few cycles of the power frequency voltage.

Modeling a medium and high voltage CB requires 3 hierarchical systems for CBs: interrupter, operation mechanism and breaker control (See Figure 1.2) [12]. An interrupter is an on-off component part and there are two parts to the operating mechanism: hydraulic and mechanical. A medium and high voltage CB consists of two main parts [14] with a linkage between them (Figure 1.3): primary equipment (the medium and high voltage part of the switchgear dedicated to medium and high voltage insulation, current flow and interruption); and auxiliary equipment (the low voltage part of the switchgear dedicated to operation, control and monitoring of the main components).

![Figure 1.2. Hierarchical structure of a medium and high voltage CB model](image-url)
The interrupter is the active part in the network, which contains the parts at medium or high voltage potential. It has two sets of contacts: one for carrying the continuous current and one for arcing during opening and closing. Arc extinction for current breaking is facilitated by arc quenching, which makes use of the insulating medium already present within the interrupter housing. The state of the art for medium and high voltage CBs is SF$_6$ (sulphur hexa-fluoride), and vacuum for the insulating and arc quenching medium [16] & [17]. During current interruption, this gas is blown at the electric arc between the parting contacts in order to facilitate its extinction by cooling. The necessary pressure is generated either by mechanical compression (puffer principle [16], [18] & [17]) or by the heat of the arc itself (self-blast principle [16] & [17]). Small inductive currents are interrupted more smoothly, also reducing the dielectric stresses on the power system. The driving force for opening and closing the contacts is supplied by the operating mechanism via a mechanical linkage.

To close the remotely-operated CB, the breaker control switch needs to be turned to the closed position. This provides a complete path through the closing relay (CR) and energizes the closing relay. The closing relay shuts an auxiliary contact, which energizes the closing coil (CC), which, in turn, shuts the breaker, as shown in Figure 1.4. The breaker latches in the closed position. Once the breaker is shut, the "b" contact associated with the closing relay opens, de-energizing the closing relay and, thereby, the closing coil. When the breaker closes, the "a" contact also closes, which enables the trip
circuit for manual or automatic trips of the breaker. The breaker control switch may now be released and will automatically return to the neutral position. To open the breaker, the breaker control switch needs to be turned to the trip position. This action energizes the trip coil (TC), which acts directly on the breaker to release the latching mechanism that holds the breaker closed.

![Diagram of circuit breaker operation](image)

**Figure 1.4. Simple control circuit for breaker open**

When the latching mechanism is released, the breaker will open, opening the "a" contact for the tripping coil and de-energizing the tripping coil. Also, when the breaker opens, the "b" contact will close, thereby setting up the CB to be remotely closed using the closing relay, when desired. The breaker control switch may now be released. Figure 1.5 shows the simple control CB close. The three most commonly-used automatic trip features for a CB are based on overcurrent, underfrequency, and undervoltage. If any one of these conditions exists while the CB is closed, it will close its associated contact and energize the tripping coil; this, in turn, will trip the CB.
A review of the literature found that computer simulations of transients caused by switching operations in power systems can assist in preventing equipment failure in the electromagnetic environment in which the devices operate [19]. Many publications examine the process of multiple re-ignitions in vacuum CBs [19] & [4]. However, in this thesis, only a few publications are highlighted as only Veuhoff [20] and Popov [4] have detailed information about their CB model for re-ignitions. Significantly, their model is valid for less than 600 Amperes, this being their definition of a small inductive current switching condition. The following problems can arise in the case of switching small inductive and capacitive currents [4].

Following interruption, the CB is stressed by the difference between the source-side and load voltages, as shown in Figure 1.6 and Figure 1.7. The transient recovery
The expression for the TRV consists of three frequency components. One term occurs at the source power frequency $\omega$, another with load side natural frequency $\omega_1$ and the other is at the source side natural frequency $\omega_s$.

The component with the source side natural frequency, expressed as $(I_{ch}Z_c)e^{-\delta t}\sin(\omega t)$, is normally very small compared with the load side component because of the characteristic impedance of the reactor $Z_c >> Z_s$ (the characteristic impedance of the
source)[21], and vanishes quickly due to source side damping. Therefore, this component can be ignored without introducing a significant error and the TRV can be expressed by:
\[
\sin(\delta) = \text{the damping constant} \quad \text{and} \quad \alpha = \text{the load supply angle}
\]

where \( \delta \) = the damping constant and \( \alpha \) = the load supply angle

The fundamental principle of CB design is that the dielectric strength between opening contacts must always be greater than the TRV. If this is not the case and the TRV is greater than the dielectric strength across the contacts, then the arc across the CB gap will re-ignite. Dielectric breakdown is termed ‘re-ignition’ if it occurs within 0.25 cycle (5 ms) after an initial arc extinction at a 50 Hz current zero. If the current flow at the contact resumes at any time after the 0.25 cycle (5 ms), the phenomenon is called a ‘restrike’[21]. Restriking occurs because the trapped charge results in an elevated voltage across the switch for capacitor bank switching or for a no load transmission line. Usually TRV is also involved in the interruption, and the peak voltage occurs after the initial current interruption occurs, namely, after 10 ms. If the restriking voltage is lower, it can of course, occur earlier, sometimes after 5 ms. Multiple restrikes are due to the amount of trapped charge stored in the capacitor banks. This can be prevented by means of a rapid build-up of dielectric strength in the CB, or by circuit damping for capacitor bank switching [21].

A capacitor bank or simple transmission line can be represented by a lump capacitance, \( C \), connected to a busbar via a high voltage CB. Disconnection of capacitor banks and dropping of unloaded overhead lines and cables, which also have a highly capacitive behaviour, can lead to some dangerous overvoltages. The most hazardous situations for the equipment are presented when the CB does not break at once and a re-ignition or restrike takes place.

Generally, re-ignitions does not occur as a single switching; it is usual to observe a series of re-ignitions and restrikes. A brief explanation of the phenomenon is given below.

When the CB opens, the load side inductance and capacitance start to resonate at the frequency
This resonant frequency \( f \) can be used to check the accuracy of the computer simulations.

If the CB starts its separation process near the current zero crossing, the gap does not have enough time to build a sufficient distance for a sufficiently strong withstand voltage, and the result is that it re-ignites (See Figure 1.8).

![Diagram of CB separation process](image)

With the exception of [23], little work has been done on the use of transient waveshapes to **diagnose the condition of CBs to predict a breaker restrike risk and estimate its remaining interrupter lifetime. This is the knowledge gap to be filled by this thesis.** The possible restrike detection solutions are measurements guided by computer simulations, and signal processing methods such as Wavelet Transforms for power quality problems (as stated in Section 1.1).

### 1.3 Research goals

The goals of this research are: 1) to use the A, B, C and D characteristic restrike parameters as a diagnostic tool for vacuum CBs (A change in these parameters indicates a change in the breaker conditions); 2) to measure the characteristic restrike parameters via a non-intrusive antenna. Obviously, the voltage and current against time relationship can be calculated for an electric circuit transient problem with mathematical Equations. From this relationship, data is interpreted into the breaker degradation information and the results are then validated with practical experiments. This will be undertaken with computer modeling and simulations, and with experiments which show the
methodology for computing medium CBs and network parameters with the overvoltage and current level.

In this research, a medium and high voltage CB is accurately modeled to take into account the occurrence of late re-ignition for vacuum CB and the hot recovery dielectric strength characteristics for SF$_6$ CB. The statistical analysis investigates how frequency is the occurrence of overvoltages for shunt reactor and capacitor bank switching. There are three components of switch current waveform signature: current chopping, arc extinction (thermal phase) and dielectric re-ignition (dielectric phase), as shown in Figure 1.9 [24]. There are three components of restrike voltage waveform signatures: instant of current interruption, and recovery voltage and restrike, as shown in Figure 1.10. This figure also shows the restrike overvoltage, which is the summation of source voltage and the recovery voltage. In general, thermal breakdown occurs immediately after interrupting a short-circuit current since the insulating gas in the post-plasma space is hot, and polluted with vaporised metal, and the initial rate of rise of the dielectric strength recovery characteristics is slow.

![Figure 1.9. Switch current (arc is quenched; however, dielectric re-ignition occurs) for an inductive circuit](24)
In practice, the probability of recognition of medium and high voltage CBs varies with the possible overvoltage level for different power loads and different cable lengths. Knowledge of how this re-ignition can occur can assist the users of medium and high voltage CBs in deciding whether there is a need for surge protection and controlled switching. Also, restrike waveform signatures provide information about the condition of medium and high voltage CB. For example, variation in the rise of voltage when switching similar currents gives an indication of mechanism wear; excessive arc voltage indicates interrupter problems; the $i^2t$ arc energy summation [25] is an indicator of contact wear; reduction in the envelope may indicate mechanism problems or degradation of the insulating fluid; and excessive pre-arcing may indicate contact or insulation problem [26]. This research will also develop a predictive interpretation technique for CB diagnostics. It uses computer modeling to predict a breaker performance in order to improve asset management by estimating the medium and high voltage CB risk conditions from transient disturbance waveforms.
1.4 Thesis outline

The research covered by this particular project involves aspects of several electrical engineering subject areas including power transients, power system modeling, signal processing, asset management, and medium and high voltage switchgear technology. The thesis is written in six chapters and includes: a restrike switch model and detection algorithm development using Wavelet Transforms; parameter determination and model calibration with a 12 kV vacuum CB laboratory experimental process; analysis of results and their comparison with the existing literature; and proposed future work.

This chapter provides an introduction to the background, the preliminary literature review, a statement of the medium and high voltage CB restrike/re-ignition detection problem and the research goals.

Chapter 2 is a literature review of topics pertinent to developing a conceptual framework. Themes considered include CB characteristics and modeling protection with controlled switching. Database development in power systems, and waveform features for detection of breaker degradation are also covered. Other areas covered are: simulated and measured waveform signature results, model-based CB monitoring and diagnosis, parameter determination and model calibration for computer simulations. A restrike switch model and restrike detection algorithms are reviewed. Gaps needing to be addressed in this research are then identified, and hypotheses are framed. Finally, the research questions are proposed.

Chapter 3 describes the proposed methodology for assessing interrupter risk condition from a restrike switch model using measurements, ATP and Wavelets Transforms. A restripe switch with contact opening velocity computation is modified and detection algorithm is developed for medium and high voltage CBs. The breaker restripe diagnostic problem is formulated to answer the research questions and to fill the research gaps identified in the literature review of the previous chapter. The problem is further illustrated with features selection according to operational parameter variation and features extraction, database development and online monitoring. The predictive interpretation technique is restripe breaker features from parameter determination studies developing from simulated waveforms using vacuum CBs.
Chapter 4 outlines restrike switch model applications and detection algorithm development. It provides examples of the practicality of the proposed methodology with computer simulations as virtual experimental applications. The restrike switch model applications development are: SF\textsubscript{6} puffer CBs and vacuum CBs case studies, database development, the interrupter remaining life prediction and POW assessments. Also, a restrike detection algorithm is developed for simulated and measured waveforms with Wavelet Transforms for computer online monitoring operations.

Chapter 5 presents the analysis of results for parameter determination and model calibration. This includes parameter determination and model calibration with a 12 kV vacuum CB laboratory experimental process for the restrike switch model, including the process details, layout, instrumentation and simulation tools. The contact travel degradation features and the breaker parameters are determined from the experiments. Analysis of results includes discussions, interpretation and analysis of the experimental process.

Conclusions of this research are summarized in Chapter 6, and its original contributions are identified. Future research proposals, including a field implementation proposal to validate the restrike switch model and the hot dielectric strength curve model for SF\textsubscript{6} CBs, are also given in this chapter.
Chapter 2: Literature Review

This chapter begins with an introductory research background (Section 2.1) and reviews literature on the following topics:

- medium and high voltage CB characteristics (Section 2.2), including chopping current, dielectric behaviour, high frequency (HF) current interruption capability and arc resistance
- modeling protection with controlled switching (Section 2.3), including PSCAD/EMTDC and ATP/EMTP and restrike switch models, and determining interrupter life (Section 2.4)
- database development in power systems for online monitoring applications (Section 2.5); restrike features and breaker model parameters for detection of breaker degradation (Section 2.6); restrike waveform signatures verified with the simulated and measured results (Section 2.7); online model-based CB monitoring and diagnosis (Section 2.8); parameter determination and model calibration for computer simulations (Section 2.9); and restrike diagnostic algorithm development (Section 2.10).

Gaps for this research are then identified (Section 2.11) and hypotheses created (Section 2.12). Finally, a research road map (Section 2.13) and research direction (Section 2.14) are proposed to modify a restrike switch model with contact opening velocity computation and to develop a predictive interpretation technique for CB diagnostics. A summary and implications conclude this chapter.
2.1 Introduction

After CBs have been installed in service, an interruption to their current leads to an electrical degradation of the interrupting unit, especially of the nozzle and electrode [25]. A nozzle is a mechanical device designed to control the direction or characteristics of a SF₆ flow as it exits (or enters) an enclosed cylinder assembly via an orifice. Catastrophic failures of SF₆ CBs have been reported during shunt reactor and capacitor bank de-energisation, as evidenced by the destruction of the interrupter nozzle by cumulative restrikes. As the objective of this thesis is to develop non-intrusive restrike monitoring techniques, the purpose of this review is to identify a proposed method for, and the gaps that need to be addressed by, this research.

2.2 Medium and high voltage CB characteristics

The early studies on CB overvoltage failure were conducted through a theoretical analysis by Deaton [27] and EMTP modeling by Veuhoff [20]. The studies confirmed that most vacuum CB failure were due to restrike overvoltage. The CB characteristics are detailed below.

A: Chopping current

This phenomenon occurs in the case of switching small inductive and capacitive load currents. High overvoltage can be generated due to reactive circuit elements when the current is interrupted before the power frequency (f) current goes to zero. The arc during the opening of contacts becomes unstable and the current declines toward zero with a very high di/dt. In the last point of contact of the arc, a very high current density exists, and heats up the contact material.

Metal vapour emerges and current continues to flow through the metal vapour arc. If the current falls below the assigned specific value, the metal vapour arc collapses. This phenomenon is known as current chopping [28] & [28]. The point at which the current begins to decline is the chopping level and the value of the current at this point is called the chopping current \( i_{ch} \). The arc instability and the resulting current chopping are mainly caused by the choice of contact material, as shown in Ref.[30].
Other parameters that influence current chopping are the amplitude of the 50/60 Hz load current (I) and the characteristic impedance of the load (Z_N) that is switched [9] and [11]. Equation (2.1) can be used to represent experimental results for load currents in the range from 45 A to 170 A,

\[ i_{ch} = a - b \log(Z_N) \]  

(2.1)

where a, b and c are constants that depend on the contact material.

While Damstra and Smeets [7] and [12] used Equation (2.2) to predict the chopping current of vacuum CB,

\[ i_{ch} = (2\pi f l \alpha \beta)^{q} \]  

(2.2)

where \( \alpha = 6.2 \times 10^{-8} \) (s); \( \beta = 14.3 \); \( q = -0.07512 \)

The chopping current calculated by Equation (2.1) varied between 3 A to 8 A and it is found that Equation (2.2) is not valid for \( I < i_{ch} \). The predicted \( i_{ch} \) can have a standard deviation of 15% [7], [9] and [15]. This current is also estimated by Equation (2.2) and for chrome copper alloy, it was estimated to be less than 5 A for a load current in the range of 800 A [28]. Ref [13] ignores \( i_{ch} \) due to the very low probability of the chopping current occurrence for the range of applied voltages. The higher the chopping current level, the higher the TRV. The dielectric recovery of the vacuum gap depends mainly on the contact opening velocity. When the contacts open at some instant of the power frequency current, the arc will exist until the current zero is reached. The time interval between the instant of opening of the CB and the natural current zero is called an arcing time. For a short arcing time, after the arc is extinguished, the contact gap will be small and only a small TRV is needed for a restrike to occur, depending on the dielectric characteristic of the actual gap. The first restrike depends on the chopping current and the resulting TRV across the contacts. The reported duration to reach \( i_{ch} \) depends on the thermal situation of the gap and the response is modeled as a decaying current, modulated with high frequency due to TRV transients. Existing models of current chopping have been developed in [22]; these all depend on particular input to develop the required outputs.

**Input:**
(i) Load current at the time of opening the contacts
(ii) Characteristic load impedance
(iii) Arc voltage

**Output:** (i) Rate of load current decay

(ii) Time of complete opening of the two closed contacts

Drawback of the models in [22]: The detailed mechanism relating to cathode spots which vary with load current and ion velocity is not incorporated to predict the rate and time duration to reach current chopping status.

For a single SF$_6$ puffer interrupter CB, the chopping current level is given by the equation

$$i_{ch} = \lambda F^{0.5}$$  \hspace{1cm} (2.3)

where $i_{ch}$ is the current level at the instant of chopping (A), $C_t$ is the total capacitance in parallel with the breaker (F) and $\lambda$ is the chopping number for a single interrupter ($\lambda F^{0.5}$).

The statistical formulas for determining chopping numbers dependent and independent of arcing time are stated in IEEE Standard C37.015-1993. The chopping current parameter for vacuum CBs relating to different materials was studied in the early 1960s [4]; however, there has not been much work done for the past thirty years due to the advance of technology. SF$_6$ CBs parameters were first reported in 1985 [29] and then in IEEE Standard C37.015-1993.

**B: Dielectric behavior**

Dielectric behavior for the normal cold temperature will be different from the dielectric strength of vacuum CB after the current is interrupted. After the vacuum CB has interrupted the current, the gas will be hot, as the dielectric withstand capability of the gap across the contacts tries to withstand the voltage stress. The modeling of the voltage withstand capability of moving contacts is of great importance in the study of restrikes. If the TRV is greater than the withstand voltage at any given time, the arc reignites to cause restrike across the contacts [9]. The withstand voltage is modeled as linearly dependent for the first millimeter after contact opening, with the voltage stress taken as a uniform field [19]. Later in the opening process for a long gap, the field strength is modeled as the square root of the gap distance. The withstand capability thus becomes a function of the speed of contact opening. The movement is slow in the initial period of moving and then the gap distance becomes linear with time as it is not accelerating. This implies that the withstand capability is also a function of the speed of contact opening [4].
this gives an opportunity to experimentally validate the linear motion of the opening contact. A linear coherence between contact distance and time is normally assumed [28]. However, the dielectric can show different behavior with aging and time of operation.

When restrike occurs due to TRV exceeding the dielectric breakdown (BD), a high frequency re-ignition pulse current flows through a vacuum CB. In general, researchers identify a slope straight line equation for the voltage with a different slope gradient up to the first millimeter. The dielectric withstand BD is modeled according to the withstand voltage with time from the instant of contact separation being modeled as a straight line equation with a different slope gradient for determinations [20],[30],[31],[32] and [33]. These researchers used different voltage gradients either with gap distances or times, such as 20 kV/mm [30] and 30 kV/mm [20], and 20 or 40 kV/ms. After 1997, most authors adopted Ref. [31] for the re-ignition simulation, except for Ref. [34] who adopted the four typical dielectric strength characteristic from Ref.[32] and Ref.[33], who adopted a manufacturer’s equation and data, for the simplicity of the calculations.

Glinkowski reports that there were three physical breakdown mechanisms: (1) field-induced electron emission, (2) micro-particles and (3) micro-discharge control the vacuum breakdown voltage [28]. In fact, the initiation and development of a vacuum breakdown event is a wholly stochastic process under the framework of probability [4].

The vacuum breakdown curve (breakdown voltage $V_{BD}$ vs. electrodes separations) for single-break vacuum CBs can be divided into two different sections. Within small separations ($s<2$mm), a linear relation between $V_{BD}$ and $s$ is valid. When the separation exceeds 3 mm, primarily micro-particles cause the voltage breakdown [35]. Equation [36] is:

$$V_{BD} = k \cdot s^\alpha$$

where $\alpha$ varies between 0.4 and 0.7.

Alternatively, it can be expressed as:

$$V_{BD} = \alpha \cdot d^n$$  \hspace{1cm} (2.4)

where $d$ is the distance and $n$ is the relationship index.

Ref.[32] was the seminal paper that introduced a statistical vacuum CB model.
with a straight line slope for dielectric voltage breakdown versus a gap from 0 to 5 mm. This study also pointed out that a non-linear curve characteristic is applied from 0 to 1 ms for dielectric voltage breakdown versus the time for a 6.3 kV vacuum CB model using ATP simulations [28].

Veuhoff proposes the statistical vacuum dielectric strength related to the recovery voltage for computer simulation [20]. The Slopes A, B, C, and D, shown in Figure 2.1, represent the different dielectric strength characteristics for different prestressing until the completed arc quenching. Veuhoff [20] states that the dielectric recovered its cold dielectric strength depending on the time of occurrence of \( i_{ch} \). The dielectric strength depended on the rate of the rise of the recovery voltage, which occurred across the opening contacts. Depending on the ignition-delay, higher values were reached by a higher rate of the rising of the recovery voltage. Taking the two characteristic Slopes A and B in Figure 2.1, in the duration of \( t_A \) with \( du/dt > 100 \) kV/µs, the dielectric strength Curve A is used as a limit-curve. For longer times (\( t_B \)), a transition to the dielectric strength Slope B takes place where \( du/dt < 100 \) kV/µs.

Possible dielectric strength curves, as shown in Figure 2.1 after current interruption, represent the strength characteristics for different prestressing until the completed air is quenching. It has been proved by Glinkowski that the vacuum CB recovers its cold dielectric strength by the time of the low frequency chopping current [28]. Each frequency is governed by the components in each loop in the circuit. Many test have been performed in different laboratories for the past twenty years [28]. The dielectric strength depends on the rate of the rise of the recovery voltage which occurs in the opening contact-system. Although Ref. [24] also exploits a multi-parameter mathematical CB model with this criteria, there is no experiment to verify these results.
None of the papers used practical information from measurements related to the vacuum breakdown mechanism behavior in a gap opening up to 5 mm. Ref. [20] takes a more realistic approach for computer simulation using a straight line slope relation between dielectric strength characteristics with gap distance variation on contact opening.

Researchers have used different methods to implement a statistical vacuum CB dielectric strength model. For example:

1. The value of vacuum CB dielectric strength across opening contacts is assumed to be the mean value of a Gaussian distribution with a standard deviation of 15% for the proposed statistical model [34].
2. The probability of breakdown voltage is represented by a Normal distribution of the withstand voltage with a standard deviation 10% as a statistical vacuum CB dielectric strength model [4].
3. The statistical properties of dielectric strength ($V$) are expressed by a Weibull distribution with a parameter $m$ in (10) describing the possible scatter [30].

\[
P(V) = 1 - \exp \left[ -1.125 \left( \frac{V}{V_0} - 0.2 \right)^m \right]
\]  
(2.5)
The average dielectric strength rise with distance is taken as 20 to 50 kV/ms and \( m \) as 4.

4. Dielectric strength rise (K-factor) is expressed as a statistical value with a constant average. This assumption is traditional, and seems to be proven in many experiments. The statistical property of a dielectric strength breakdown is expressed by a Weibull distribution [28].

A linear dependency of dielectric strength with contact distance is assumed by Glinkowski [31], but there is no information in the literature about when to use the equations. This gives an opportunity to derive a generalized vacuum dielectric curve model. The predicted four dielectric strength characteristics from the moment of contact separation (\( t_{open} \)) to any desired time \( t \) in \( \mu \)s are as follows:

\[
\begin{align*}
V &= 2 \left( t - t_{open} \right) \text{ (kV or V)} \quad \text{– depends on the specified time (ms or s) unit.} \\
V &= 20 \left( t - t_{open} \right) \\
V &= 30 \left( t - t_{open} \right) + 1000 \\
V &= 50 \left( t - t_{open} \right)
\end{align*}
\]

The main parameters which control the occurrence of restrikes are the dielectric withstand capability of the gap and the value of the connected circuit components. Existing studies only examine the restrikes which occurred in the first millimeter using a straight line equation; none consider the three periods for restrikes: (a) from 2.5 ms…10 ms after current zero “early restrikes”, (b) from 10 ms….50 ms “intermediate restrikes” and (c) from 50 ms…9 s after current zero “late restrikes”[37]. A generalised vacuum dielectric curve model is identified in this study to cover restrikes for the contact travelling distance over 1 millimeter, as well as determining when to use the curve at different voltages.

Current ATP models incorporating restrikes into simulations use a fixed contact opening velocity of 1 m/s. In the literature to date, no-one has considered the slope of dielectric strength as an important factor for modeling the contact opening velocity for vacuum CBs in order to identify the breaker degradation condition. This is one of the gaps to be filled by this research.

**Modeling hot SF6 dielectric strength recovery**

The dielectric strength recovery characteristics are inherent in this CB, and the process of recovering dielectric strength is referred to as ‘cold recovery voltage’.
There has been no report on determining an accurate dynamic dielectric recovery characteristic suitable for the CB under consideration in previous research. The dielectric recovery characteristics vary from CB to CB, and even if a dynamic dielectric characteristic could be determined, it is a research problem to incorporate such a characteristic into a mathematical model analysis. Boggs et al. [38] argue that the arc interruption and recovery of the dielectric withstand of the contact arc immediately after current zero are determined by the thermal behaviour of the arc extinguishing medium. After the residual arc has disappeared, further recovery of the voltage withstand is determined by the dielectric characteristics of the gas between the open contacts. The dielectric withstand of the decaying arc column always increases sufficiently rapidly to withstand the rapid voltage oscillation. For the SF₆ CB operation, the shorter the time constant, the lower the electric conductivity at current zero, which results in a higher interruption capability and lower probability of re-ignition.

Schotzau et al. [39] argue that the dielectric phase is of crucial importance for a CB with a rated voltage per break above 200 kV, due to the temperature decay and the density of the SF₆ gas, which determine the dielectric recovery after current zero. Improved knowledge of dielectric recovery are a prerequisite to developing new CBs of higher interrupting capability. More theoretical and experimental investigations into ignition processes are required in order to determine how, for example, the magnitude of the turbulent effects leads to the fast decay of the arc temperature after current interruption at zero and why a nearly linear increase of the breakdown voltage against time occurs.

Crawford and Edels [40] determined that the dielectric recovery regime can be broadly labelled into three regions: thermal, transition and Paschen. They suggest that the recovery voltage will have a low value in the first 200 μs after current zero, until the temperature in the arc channel falls below the dissociation temperature of the gas. It is also reported by Crawford and Edels that many researchers concerned with predicting the current zero behaviour of SF₆ CBs in flow have found poor correlation between their determinations and measurements [41]. Researchers have resorted to using values of thermal conductivity in their determinations that were arbitrarily made several times greater than values identified in the literature. The
increased values of thermal conductivity are now considered to be necessary to account for the effect of turbulence.

Since 1990 all researchers have used a cold dielectric curve for SF₆ CB computation [21]. Considerable data in Ref. [41] and Ref. [42] should assist in the development of a statistical ATP model for SF₆ puffer CBs. In accordance with the statistical theory of breakdown, this study proposes to compute with a lower breakdown probability and fewer numbers of restrike/re-ignition for a SF₆ puffer CB. This may improve the accuracy of ATP simulation results. A statistical ATP model for the SF₆ dielectric strength recovery curve is developed for asset management as an innovation for improving the accuracy in computer modeling and simulations.

C: High frequency (HF) current interruption capability

The vacuum CB quenching capability is defined as a critical current slope at which the slope of the current is lower than the slope, for which the arc extinguishes at the instant of a high frequency current zero. The vacuum CB ability to interrupt these high frequency currents, however, may lead to multiple gap breakdowns (re-ignitions) which may be the cause of very severe overvoltages under certain network conditions. These vacuum CB characteristics have been experimentally investigated by several researchers who found that the slopes of the high frequency quenching are not constant, but depend on the re-ignition voltage [4]. This also gives an indication of zero quenching condition and the degradation monitoring high-magnitude transient phenomenon using restrike waveform signatures for electrical stresses relating to the breaker lifetime.

Ref. [43] reports that the HF quenching capability is defined by the slope of the HF reignited current at HF current zero. An example is shown in Figure 2.2. Zoomed plot shows the first re-ignition to calculate HF quenching capability Parameter ‘D’ by first two data marker = (-1.562-(-17,187))/(2783.2-2784.2)=15.62 A/µs
Earlier, many authors assumed the slope to be constant, but later it has become clear that the slope also depends on the reignited voltage and that it shows also a time dependent behaviour. The most popularly accepted approach is that decreased di/dt is an acceptable path for interrupting current [30]. The interruptable di/dt changes by a factor of 2 to 3, depending on circuit parameters. The current may be interrupted during one of the high frequency excursions through zero. This is known as virtual current chopping [28]. Hence, like dielectric characteristics, the statistical properties of HF current interruption are used for prediction of the probability of current interruption by [32]. In that n is the parameter responsible for (di/dt) scattering. The average interruptable di/dt is taken as 100 to 200 A/µs with n = 4.

\[
P\left(\frac{di}{dt}\right) = 1 - \exp\left[-1.125 \left(\frac{di}{dt} - 0.2\right)^n\right]
\]  

(2.6)

where \(\bar{\cdot}\) = mean

When multiple re-ignitions occur, a high frequency current (i_{HF}) appears with them [20]. It is anticipated this will occur in the current rise range 50 A/µs < di/dt < 150 A/µs. For the rate of the current rise in the range 150 A/µs < di/dt < 600 A/µs, the dielectric strength Curve C shown in Figure 2.1 is used. The range 600 A/µs <
di/dt < 1000 A/µs corresponds to Curve D. A rate of the current rise above 1000 A/µs cannot be interrupted by the vacuum CB.

Multiple re-ignitions are more likely after a very short arcing-time. The occurrence of the chopping current and restrike will have a statistical scatter distribution due to different vacuum CB qualities. This is simulated with a random number generator in the developed EMTP program [7].

When restrike occurs, a high frequency arc current flows through the opening contacts of vacuum CB. The high frequency current is superimposed on the power frequency current and may be interrupted at one of the zero crossings generated by the reactive load. The arc extinguishes at the instant of a high frequency current zero, when the slope of the current is lower than the so called critical current slope [31]. Most researchers [20], [4] and [30] used the arc quenching capability as measured by Glinkowski [31]. However, Ref. [32] and [34] used the four sets of data from Czarnecki L & M. Lindmayer from the manufacturer data [45] and [45]. The statistical variation 10% Normal distribution was taken [4]. However, the voltage escalation cannot occur in SF₆ CB due to high frequency currents around 600 kHz [46], and the possibility of high frequency current interruption occurrence is very small in actual gas-insulated switchgear substation [46]. This implies that high frequency zero current quenching is not required for SF₆ CB computer modeling.

D: Arc resistance

The physical phenomena in the vacuum CB during a switching operation are very complex and, therefore, the models of vacuum CBs are also very complex. When performing a switching operation, a conducting plasma channel is created between the breaker contacts; this channel is called the ‘vacuum arc’. When the arc is extinguished, a transient recovery voltage appears across the terminals and this voltage can give rise to another breakdown in the vacuum and create a new conducting plasma channel between the breaker contacts. The arc formed by the plasma can become unstable and create high frequency currents, which the breaker must be able to interrupt. The advanced and unstable nature of the conducting plasma channels means that there is no universal precise vacuum arc model [34]. However, controlling arc resistance during interruption can be calculated with MODELS (ATP simulation tools) from the network data: load-arc current, voltage on the source and load side of the breaker [32] and [4], as shown in Figure 2.3. A variable arc
resistance ATP type-91, as Model B – when compared with ATP type-13 switch, which was used to study overvoltage due to re-ignition – produced similar waveforms, but with a time delay [4].

![ARC MODEL Diagram](image)

Figure 2.3. Arc resistance calculated by the breaker’s voltage and current

Most authors [21], [47] and [48] analyse the Mayer arc model for the prediction of SF₆ puffer CB degradation. This was achieved by the comparison between the measured waveforms and the simulated waveforms. Then the simulated waveforms were processed to extract the parameters with reference to the original manufacturer data for arc conductivity, time constant, power loss and power. However, the Mayr’s arc Model cannot be applied to vacuum arc due to small vacuum arc voltage. Thus, the opportunity to develop a vacuum arc equation for the prediction of vacuum CB degradation is identified.

In summary, CB contact conditions are significantly affected by the chopping current magnitude. This can be an adjustable variable to determine the service condition with 3 to 8 Amp for vacuum CB and an equation for SF₆ CB. Previous researchers have employed a straight line equation for vacuum CB re-ignition/restrike computation and cold dielectric curve for SF₆ CB. However, a more accurate equation can be derived from a vacuum breakdown equation over 1 millimetre.

A hot dielectric curve is proposed for more realistic SF₆ CB computation. This allows for the detection of the insulation degradation of SF₆ CB by Mayr’s arc Equation. It also provides an opportunity to develop a vacuum arc equation for vacuum CB degradation from experiments.
2.3 Overview of research on modeling protection with controlled switching

The term ‘controlled switching’, which including synchronized switching and point-on-wave (POW) switching, is applied as the principle of coordinating the instant of opening or closing of a circuit with a specific target point on an associated voltage or current form [49]. Since the early 1990s, a large number of EMTP system studies have been run to decide whether or not it is necessary to apply the surge arrestors and controlled switching for protection; however, these studies only focused on the effect of prestrike [50]. The term ‘conventional controlled switching’ is defined as an ‘inserted resistor or zero-voltage across the breaker’. There are a number of controlled load switching applications that have been developed and implemented. In fact, POW controlled switching is a solution for restrike maintenance problems because the interrupter can close at zero degree with zero current magnitude.

In the EMTP system studies, the few existing mathematical CB models are mostly characterized by experimental parameters which have validated their results with measured waveforms and hand determinations and/or with relevant standards. These restrike breaker computer modeling and simulations are:

1. A simple parallel switch, for which the voltage drop is zero when closed, and the current is zero when open [51] (This type of switch allows one open/close operation per simulation. There have been very few reports about this model, with the exception of Ref. [51], and further research work can be developed with this model.)
2. Dielectric reset model with or without Arc model – Mayr’s Equation for SF$_6$ CB [21] and Andres and Varey for vacuum CB [28]
3. Arc model – Mayr’s Equation for SF$_6$ CB [21] and Andres and Varey for vacuum CB
4. A time switch controlled with pre-defined chopping current [52]
5. A combination of any of the above, such as Leung [48] and Chang [47], for arc contact modeling.

Related variables such as dielectric envelope, dielectric strength equation, chopping current, and high frequency quenching value may be obtained either as measured parameters or as a range of typical values from the literature. Both Ma’s [22] and Popov’s [4] studies, along with Popov’s work in 2007 [53], validate that
there is little difference between the waveform signature of a dielectric model with or without vacuum arc. Therefore, this research agrees with Ma’s [22] thesis that the dielectric withstand characteristics of the CBs are the most important factors controlling re-ignition.

Many published papers about restrike CB modeling using either PSCAD/EMTDC or ATP/EMTP for restrikes in medium and high voltage CBs have summarized the characteristics which have been used for the simulation in this study. They also provide guidance for matching simulated and measured waveforms, as discussed below.

A: PSCAD/EMTDC

PSCAD/EMTDC is a popular tool for constructing networks by dragging and dropping appropriate model blocks on the drawing canvas and connecting them afterwards by drag and stretch wires.

**Capacitor switching vacuum CB**

In 1995, Fu [52] recognised restrike and current interruption conditions as switching controls to model the restrike phenomenon; however, this paper did not have any information about the switching algorithms. In 2007, Wang [54] examined inrush and outrush current, breaker TRV and arrestor energy levels, without any details about restrike modeling, despite the fact that the results were checked with hand determinations. One year later, a dielectric reset model, which can be applied to both capacitor switching and reactor switching for PSCAD, was demonstrated by Kandakatla [55], using a CB model capable of self re-ignition and restrikes for capacitor switching from Rao [56].

**Reactor switching vacuum CB**

In 2006, vacuum CBs were analysed by Rao [56] with a random arcing time, current chopping, characteristic of dielectric recovery dielectric strength, with a Gaussian distribution of 15% and high frequency current interruption capability. This paper does not provide any experimental or field waveforms for results comparison. Three year later, Maksic [57] demonstrated a vacuum CB with current chopping, a linear dielectric withstand of contact gap and high frequency current interruption capability, which has a measured waveform for the vacuum CB on opening. The results can be compared with ATP for the same circuit configuration.
In 1999, Cipcigan [58] utilized PSCAD to establish a valuable data base for an expert system applied in POW switching for H420(SF₆ CB), with and without a surge arrester. The simulated results phase-to-ground overvoltage with 1.65 p.u. were compared with field tests with 1.18 p.u. to 1.54 p.u. However, there are no modeling details or real data for comparison. There is only one study – Ref. [59] – which considers capacitor switching for SF₆ CB using PSCAD. This paper examines both shunt reactor and shunt capacitor system studies with the results in different transient recovery voltages, rate of recovery voltages and interrupted currents. Although there is no information about the CB model or system data, this paper gives some idea about system requirements for the replication of the computer simulations.

**B: ATP-EMTP**

EMTP is a popular electromagnetic transient program providing network simulations. A PC version of the EMTP known as ATP (Alternative Transient Program) is being used in many universities and by authorized organizations in many countries around the world.

**Capacitor switching vacuum CB**

In 2005, Das [59] demonstrated the waveform signatures with and without restrikes as a good reference to check simulated waveforms for capacitor bank switching. Two year later, Gebhardt [60] illustrated restrike simulated waveforms for three-phase circuit capacitor load associated with multiple breaker restrikes and voltage escalation; however, there were no details about the CB modeling. These two papers provide a reference waveform signature for simulated data with and without restrikes, and suggest the idea of multiple restrikes and voltage escalation for ungrounded capacitor bank network at 11 kV.

**Reactor switching vacuum CB**

In 1995, Kosmac [32] presented his paper with a statistical vacuum CB model with chopping current, dielectric voltage breakdown and high frequency arc quenching capability. Helmer’s EMTP model [19] was a complete CB model for overvoltage prediction. There are many published papers [43] for vacuum CB reactor switching. Only Veouff [20] applied the dielectric strength related to the rate of the rise of the recovery voltage [20], and Popov [53] provided simulated waveforms and measured waveforms for comparison [53]. These two papers are valuable for further restrike switch model development, as shown in Figure 2.4 and Figure 2.5.
Comparisons can be made using both authors’ methods to see which one has features closer to real data. However, no experimental parameters of the vacuum CB, or features to verify the re-ignition/restrike phenomenon, were found. This is one of the gaps found in this literature review.

Figure 2.4. Waveform measurement from experiments

[53]

Figure 2.5. The simulated waveform is to have an envelope which matches that obtained from measurement

[53]

**Capacitor switching SF6 CB**

To date, no computer simulations for restrike waveforms of the capacitor switching SF6 CB have been reported. In 1992, Boyd [7] recognised the deficiencies in the capacitor bank switching with EMTP in Australian Standards in relation to conditions such as test voltage specification, allowance source side voltage variation
and arcing control time. Therefore, there is a lack of information about restriking phenomena and re-ignition in three-phase circuit. Power systems will have three-phase capacitive and inductive switching. It is quite common for three-phase capacitor banks to have an ungrounded neutral, and ungrounded-neutral banks are often used at higher system voltages. Grounded capacitor banks are controlled by closing the three phases at three successive phase-to-ground voltage zeros (60° separation). Ungrounded banks are controlled by closing the first two phases at a phase-to-phase voltage zero and then delaying the third phase 90° (phase-to-ground voltage zero). Computer modeling and simulations will be useful to check current and previous capacitor switching standards.

**Reactor switching SF6 CB**

In 1988, Phaniray’s [61] paper illustrated CB models with EMTP arc characteristics: Mayr, Urbanek and Kopplin. The models did not have any details about SF$_6$ CB reactor switching due to current chopping and multiple restrikes which, in turn, cause dangerous overvoltages.

In 1992, McCabe [62] investigated the use of EMTP simulation of voltage escalation with chopping current only for re-ignition, with and without varistors. The arcing time was shown relating to the chopping current, which was also validated by field tests in 1994 [63].

In 1996, Ma [21] examined reactor switching with SF$_6$ CB, including dielectric reset, chopping current and arcing resistance. In this paper, the simulated and the measured waveforms were different. In the next year, however, Prikler [64] illustrated a time controlled switch with pre-defined current chopping level (I$_{ch}$ ~ 3 - 10 Amps.) for restrike simulated waveforms which matched with the measured waveforms.

In 2001, Okabe et al. [65] showed the 500 kV shunt reactor interruption experimental results for the characteristics of high-frequency arc extinction at re-ignition above 290 kHz; however, there was no information about the high frequency current interruption of SF$_6$ CB. In 2005, Leung [48] presented arc contact modeling with TRV rise time results comparable to the IEEE standard C37.013-1997.

In 2006, Chang [47] demonstrated a practical SF$_6$ CB arc model incorporating Mayr’s non-linear differential equation and EMTP TACS control switch control for
the shunt reactor switching transient duty. The results were checked against measured values, calculated value and simulation values but without any real waveform data for comparison. Moreover, both Leung [48] and Chang [47] do not consider the value of critical current and voltage for re-ignitions/restrikes.

In summary, there are more restrike breaker papers published for ATP-EMTP than PSCAD/EMTDC, and the ATP-EMTP results are mostly compared with measured waveforms and relevant standards. Different CB models can produce simulated waveform signatures similar to measured waveform signatures. Therefore, ATP-EMTP is recommended for the restrike breaker features as a diagnostic tool for predicting restrikes in medium and high voltage CBs. In general, there are many options to model real waveform data for simulated waveforms by trial and error with different restrike CB models. Modeling of a real waveform data for a restrike breaker requires a lot of time and effort in observing the original features because it needs equipment and site data for the computer modeling and simulations.

2.4 Determining interrupter life

There has been very little research on determining interrupter life. For example, determining if the contacts are the limiting interrupter life components [66, 67] for vacuum CB and the nozzle current is useful in estimating the interrupter remaining life for SF₆ CB [25]. As the vacuum contact erosion proceeds, an indicator is within the range of the stripe when the vacuum interrupter is operable [6]; however, the high frequency transient current has not often been noted as the precursor of interrupter failure. It is hypothesised in this thesis that the interrupter life can be predicted for the contact and the nozzle of the interrupter for SF₆ CB and the contact of vacuum CB due to high frequency transient current when restrike occurs. It is also hypothesised that different signatures of high frequency transient current will give different indications of the causes of restrikes. Alternatively, contact wear is automatically calculated for each interrupter by the control cubicle on the basis of current and mechanical operation and the remaining contact life (as given by technical data of the vacuum CB manufacturers).
2.5 Database development in power systems

There has been extensive research on database development using ATP and Matlab for fault location in power distribution systems for power quality monitoring [68]. A similar database development should be able to be established for restrike waveform signatures with degradation features for online condition monitoring.

2.6 Restrike features and breaker model parameters for detection of breaker degradation

No investigation has been reported on restrike features and breaker model parameters of CB degradation, either locally or internationally. However, there are a few papers from Japan about nozzle and contact deterioration due to the high frequency inrush current for capacitor bank switching. Some relevant projects are reviewed and presented below.

1. Capacitor bank switching restrike waveforms
The features are rise time TRV, frequency response, current amplitude, harmonic analysis [69], and contact and nozzle deterioration [70] (as shown in Figure 2.6), as well as a breakdown of fixed defects in SF$_6$ CB under different voltage wave shapes [23].

![Image of capacitors with labels: "NEW" interrupted (no arcing wear), "WORN" interrupted (arching wear at maintenance limit).](image)

Figure 2.6. Impact of arcing wear on SF6 interrupter [71]

2. Shunt reactor switching restrike waveforms
The features are dielectric envelope [53] and chopping current [64].
Chapter 2: Literature Review

Fan [72] argues that the deterioration of insulation material and wear of arcing contact are related to operation times of CBs, switching current and the duration of arcing time as well as to the monitoring of the $I^2t$ accumulation value as the maintenance policy. It is also hypothesised [53] that the interrupter failure occurred during the final opening, when a restrike punctured right through the nozzle between the moving main contact and the fixed arcing contact of the interrupter. The nozzle current was extinguished but ionized gases were forced though the puncture by the action of the puffer. This allowed the power frequency current to restart between the main contacts outside the nozzle, out of the effective area of arc interruption.

Lui et al. [73] argue that in CB failures under reactor switching applications, single-interrupter SF$_6$ CBs may be affected by a phenomenon termed [74] “parasitic arcing” which is due to the capacitance and inductance associated with arcing on re-ignition. This is also related to Ref. [70] which showed that that the electrical durability of current collectors against high-frequency re-ignition currents was associated with shunt-reactor current switching. Therefore, the author proposes to use ATP for high frequency nozzle current computation so that the $I^2t$ accumulation value can determine the remaining life of the SF$_6$ CBs.

2.7 Restrike waveform signature verification with the simulated and measured results

Ref. [25] reports good agreement between experiment and simulation and ensures the use of calculated results and information from simulation, which allows us to visualize and evaluate the aging process inside the interrupter unit. However, apart from the studies of Helmer [45] and Lopez-Roldan [43], there is little published research on restrike simulated waveforms verified with measured waveforms. Also, no experimental parameters of the vacuum CB were found in Lopez-Roldan’s study [42] which only used a straight line dielectric strength equation as a feature to verify the re-ignition/restrike phenomenon. Ramli [8] adopted the same circuit as Lopez-Roldan, but without any computer simulation results. Both Ramli [8] and Lopez-Roldan demonstrated the trend for the magnitude of restrike voltage and the frequency of restriking to facilitate early identification of degradation of the CB condition. They illustrated the effect of the Fast Fourier Transformer (FFT) on the
HF pulse and showed that each HF pulse contained a frequency component of 10 MHz and 2.6 MHz.

Based on these findings, experimental parameters of the vacuum CB and more characteristic features will be used to verify the similarity of simulated and measured waveforms. A restrike switch model for reactor switching with ATP simulation is proposed in this thesis; subsequently, the simulated waveform is compared with measured waveform for the model calibration and evaluation. A predictive interpretation technique using computer modeling and simulations is developed, as shown in Figure 2.7. The literature review has revealed very little research of this type.

![Image](image.png)

Figure 2.7. A predictive interpretation technique for CB diagnostics [53]

2.8 Online model-based CB monitoring and diagnosis

The term "online" refers to the respective actions performed with the CB while in service. The terminology adopted by CIGRE WG 13.09 for the field of diagnostic techniques is used, with the exception of the term "diagnosis" and related terms, which are used as in the field of artificial intelligence (AI). Model-based diagnosis (MBD) is an approach for integrating physical knowledge into a reasoning engine. It
Chapter 2: Literature Review

uses a model that imitates the performance of a real CB under observation and predicts the system’s behaviour by simulating its outputs, given a set of input conditions [75].

This model was first developed by Stanek [15] in 2000. A generalised CB model was proposed with three main functional parts: CB control, operating mechanism and the interrupter. The approach used for diagnosis is a combination of case based and model based strategies. This was done by utilizing the designed model to simulate the fault modes of the CB and generating several cases that could be used in determining the diagnosis. He argued that numerous articles in literature (cited above) were strong evidence for the intelligent online condition monitoring of medium and high voltage CBs, and that such monitoring was expected to yield not only technical but also economic benefits. He further stated that the existing systems were unable to fully satisfy this demand because they did not exploit the full potential of the data gathered. In fact, he was the first author who proposed the first model-based diagnostic systems for online condition monitoring of CBs. The following parameters are identified in a medium and high voltage CB:

• Contact position (travel) and/or velocity
• Continuity of trip and close circuits, or trigger coil operating current
• Insulating and arc quenching medium, e.g., SF₆ gas density and purity
• Contact wear based on accumulated switching duty
• Timing of switching operations
• Current of mechanism charging motor
• Charging time of the mechanism
• Self-testing of the entire monitoring system, including sensors.

The above methods had only been considered for off-line testing so far, not for continuous online monitoring. Other approaches to online condition assessment of medium and high voltage CBs include: evaluation of data from control and protection systems, partial discharge monitoring, monitoring of moving particles/parts, and evaluation of vibrations due to contact problems in metal-clad GIS. The limiting factor in applying online condition monitoring and diagnosis is very often economic considerations which limit monitoring functions to those which are strictly necessary in the eyes of the utility.
In 2007, Zeineldin et al. [15] extended the model developed in [15] so as to include a trip coil model that simulates the dip that occurs in the trip coil current, an arc model, and a model for CB vibration. The simulated waveforms produced were similar to the signatures of measured waveforms presented in previous literature. Fine-tuning of the developed model using experimental measurements is proposed to overcome the non-match of the real measured CB waveforms due to the normalised CB parameters. Authors have developed their models in the Matlab/Simulink environment and have not considered interfacing their work with the electric circuits. Therefore, model-based development is a present trend for online condition monitoring and diagnosis of CBs. Restrike waveform signatures database development with possible causes of restrikes and a predictive interpretation technique are explored in this research.

2.9 Parameter determination and model calibration for computer simulations

From the literature review, it is seen that most of the past studies on CB modeling and simulations are focused on the circuit interaction and breaker behaviour[22, 76], and on the improvement of equipment models such as transformers [77] and breakers [32]. However, there is no published research on parameter determination and model calibration, or on the simulation process of the circuit component or breaker behavior; nor is there a defined methodology for analysis of these parameters (including chopping current, dielectric strength envelope and high frequency quenching capacity). Thus, this current study of medium and high voltage CBs restrike prediction, using restrike waveform signatures as a diagnostic tool, is a novel and significant contribution.

The importance of applying a computer modeling technique lies in its ability to predict the power equipment failure with parameter determination and model calibration process as part of the experimental process. Vacuum dielectric strength gradient Parameter ‘A’, voltage Parameter ‘B’ at t=0, the gradient Parameter ‘C’ di/dt high frequency quenching zero current capacity and Parameter ‘D’ di/dt high frequency quenching zero current capacity at t=0 are determined from experiments for computer simulations.
2.10 Restrike waveform diagnostic algorithm development for automatic detection

In order to assure consumers that their electricity supply is free of disturbance and to monitor equipment sensitivity, there has been extensive previous work on the detection of power system transient disturbances and fault location using wavelets and neural network. Most of this work focuses on customer education about the ramifications of power quality and new developments in instrumentation and systems analysis, which are generally acknowledged as promising factors towards solutions for power quality problems [78]. Most power quality research work has been concerned with detecting and classifying transient disturbances in order to ascertain the “Power Quality” before appropriate mitigation action can be taken. This work is based on the analysis of transient disturbances provided by very simple models and there has certainly been no attempt (with the exception of Van Rensburg [79]) to investigate arcing fault.

There is very limited research work on detecting transient phenomenon caused by equipment deterioration. There are opportunities to extend the work done by examining the detection and classification of equipment deterioration caused by transient phenomenon using advanced modeling techniques, knowledge of the system and wavelet analysis. It is proposed to simulate those events in power systems that are associated with CB deterioration or failure that cause transients in the network. Events that will be investigated may include disconnecting capacitor banks and three-phase reactors.

With the exception of the studies by Kasztenny [83], there are very few published papers or theses on restrike simulated waveforms detection algorithms. Previous research has been aimed at detecting the magnitude and duration of transients on restriking current only. Therefore, there exists the possibility of developing voltage waveform analysis for monitoring CB deterioration.

Advanced modeling, simulation and Wavelets analysis are identified as tools for power quality applications [80]. Therefore, the following research tasks are proposed:

a) Development of techniques for automatic detection of restriking/re-ignition events occurring on power distribution and transmission systems
b) Feature extraction using Wavelet Transforms as a tool to diagnose restrike waveform signatures for online monitoring.

2.11 Gaps for this research

The questions that framed this study (encompassing the determination of the restriking process) led to the use of the problem formulation approach to the research design and proposed methodology: assessing interrupter risk condition from a restrike switch model using measurements, ATP and wavelets.

How do we determine the breaker parameters and model calibration as well as the evaluation process from measured waveforms against the simulated waveforms from vacuum dielectric strength Parameters ‘A’ and ‘B’ and the slope di/dt Parameters ‘C’ and ‘D’ high frequency quenching zero current capacity? The answer is: from experiments for computer simulations.

The following gaps are identified in the literature review:

1. Current trends in online circuit breaker condition monitoring have not used restrike voltage waveform signatures as a diagnostic tool [81, 82].

2. Restrike switch modeling in circuit breakers with a dielectric reset switch (use the A, B, C and D for the ATP program input in vacuum[34], changes in these can infer some condition diagnosis). (Therefore, the main hypothesis of this thesis is that Parameter ‘A’ is related to normal and slow contact opening velocity for a vacuum CB restrike risk condition.)

3. Limitations in the radiometric measurement method [8] and the hardware method [83].

4. Computer simulation of transients due to switching operations in power systems is to avoid equipment failure and misoperation during real operations in the electromagnetic environment in which the devices must operate; restrike waveform signatures for the maintenance risk prediction of interrupter condition have not been researched for power quality, and a restrike switch model and waveform signature features have not been identified.
5. Inaccurate POW controlled switching operation resulted in high voltage transients and caused nuisance tripping for prestrike.
6. Hot dielectric withstand strength curve for SF6 CBs was not created.
7. A vacuum arc dielectric straight line equation for re-ignition prediction is not accurate and needs improvement.
8. The need for experimental parameters of the vacuum CB and more characteristic features to verify the similarity of simulated and measured waveform signatures are identified in Ref. [43].

2.12 Creating hypotheses

The main hypothesis is as follows:

**Hypothesis 1:** Restrike voltage escalation sometimes causes a flashover in insulation failure due to the high frequency transient change of inductive current interruption by vacuum strength. ATP is used to estimate the dielectric strength failure rate and interrupter risk condition as a function of the breaker model ABCD parameter. The parameter ‘A’ is also a function of the contact opening velocity for CB diagnostics.

Other hypotheses are derived from this main hypothesis:

**Hypothesis 1a:** A CB restrike can be predicted if there is a similar type of waveform signature for measured and simulated waveforms.

**Hypothesis 1b:** A CB model parameter/feature is a diagnostic tool to interpret the breaker risk condition from the transient waveform signatures and escalation voltages as a function of the breaker model characteristics for breaker performance.

**Hypothesis 1c:** A computer simulation can provide a breaker risk predictive interpretation technique.

2.13 Research road map

The research road map (Figure 2.8) is formulated according to the literature review, the proposed methodology and 12 kV vacuum CB single-phase experiment to evaluate the restrike switch model with contact opening velocity
computation. There are three stages of this research project: the literature review; second stage is ATP simulations and its calibration and parameters determination with 12 kV vacuum CB single-phase experiment; and a predictive interpretation technique for CB diagnostics and restrike diagnostic algorithm development (with Wavelet Transforms and non-intrusive measurement, using a wide bandwidth antenna for field diagnostics of individual CB).

Figure 2.8. Problem formulation blocks for assessing interrupter risk condition from a restrike switch model using measurements, ATP and Wavelet Transforms

2.14 Research direction

There are several areas in which refinements can be made to the restrike switch model with contact opening velocity computation and its model applications development, including a diagnostic algorithm for medium and high voltage CBs using restrike waveform signatures. Some of these areas are identified as follows:

1. Restriking current is focused on the impending failure features, such as SF₆ CB contacts and nozzles for computer modeling and simulations.

2. If the statistical properties of the withstand voltage in the vacuum CB mode are assumed to be in linear straight line equation, the velocity of contact separation is considered to be constant. This velocity might vary with time. When the contact starts moving, it might be relatively low and then become higher. Also, the withstand
voltage might be considered to be nonlinearly dependent on the gap distance. Development of the vacuum CB switch model is the generalised vacuum dielectric curve model to cover the restrikes more than 1 millimetre, and breaker Parameter ‘A’ is a function of contact opening velocity.

3. To determine whether ATP is the appropriate software tool for this research, the following issues were considered:
   - A restrike switch model calibration and evaluation.
   - Breaker deterioration can be observed from the RRRV and the constant for rate of change of high-frequency current quenching capacity.
   - The prediction variables for capacitor switching are: series inrush current limiting reactors, resistance switching or use of Pre-Insertion Resistors (PIR), POW switching (supply angle) and application of surge arrestors. All these methods are considered as conventional controlled switching methods. The current trend is model-based controlled switching with ATP computer modeling and simulations for breaker performance prediction.
   - The prediction by variables for reactor switching are TRV rise time, recovery slope and the breakdown reduction factor.

   Gaps in the literature highlighted the need for further research on restrike detection tools for capacitor bank switching (See Ref. [83]) and lead to the formulation of the following scope and innovative goals of this research.

   **A: Capacitor current switching**
   1. Investigation with a three-phase transformer supply with an earthed neutral and without neutral.
   2. Ungrounded capacitor bank neutral with no restrikes; a parallel switch for capacitor switching to simulate restriking of the CB in this condition; restriking with voltage escalation; and then various pole-opening sequences.
   3. Extension to three-phase context switching of capacitor banks, both grounded and ungrounded.
   4. Model-based controlled switching with ATP simulated waveform signatures for performance prediction for both cold and hot dielectric strength curves.

   **B: Reactor switching**
1. A generalised dielectric model for 12 kV vacuum CB is validated and the di/dt clearing away degraded switch features are compared with real waveform data from the experimental process.

2. Database development for motor circuit.

2.15 Summary and implications

This literature review has identified the gaps and the proposed methodology for this research project: the use of measurements, ATP-EMTP simulations and Wavelet Transforms as part of the diagnostic process during CB switching of shunt reactor and shunt capacitor banks in power systems.

The proposed methodology is to achieve the early detection of high-frequency restriking phenomena by trending the magnitude of restrike current/voltage and predicting the frequency of restriking to facilitate early identification of CB degradation condition, using a predictive interpretation technique. The possible improvements on the current characteristics of restrike switch model are: the novel SF₆ CB hot dielectric strength recovery curve model and the generalised vacuum dielectric curve model dielectric Parameter ‘A’ as a function of contact opening velocity. The proposed methodology is a restrike switch model and detection algorithm development using Wavelet Transforms for medium and high voltage CBs. The restrike switch model is a reinvention of Lopze-Roldan’s [88] idea of waveform measurement from experiments and then comparing this with ATPDRAW simulation results to verify the re-ignition and restriking phenomena.

In order to support the practicality of a restrike switch model with contact opening velocity computation, the restrike switch model applications development are investigated with virtual experiments, and a predictive interpretation technique is used for monitoring high-magnitude transient phenomena using restrike waveform signatures for stresses relating to the breaker lifetime. Parameter determination and model calibration process from a 12 kV vacuum CB experiments is developed for future field implementation of SF₆ CBs to prevent the interruption of the distribution and transmission of an electricity supply system.

CB diagnostics is proposed with a predictive interpretation technique guided by measurements and restrike diagnostic and diagnostic algorithms using Wavelet
Chapter 2: Literature Review

Transforms as a proposed method for the breaker restrike problem. A wide bandwidth antenna is recommended for field validation of hot SF₆ CBs dielectric curve model and the restrike switch model as well as the actual breaker restrike occurrence in field implementation work.
Chapter 3: Proposed Methodology

This chapter outlines the proposed methodology for assessing interrupter risk condition from a restrike switch model using measurements, ATP and Wavelets Transforms. Hence, the breaker restrike detection problem is formulated to answer the research questions and to fill the gaps, as stated in the literature review of the last chapter. A predictive interpretation technique is illustrated with operational parameter variation, features extraction, and database development for online monitoring. The proposed methodology is presented in eight sections in this chapter, following the steps shown in Figure 3.1.

![Diagram of research process]

Figure 3.1. The research process
Chapter 3: Proposed Methodology

i. Concepts and theories of restrike phenomenon

As a restrike switch model with contact opening velocity computation is defined as ‘a mathematical CB re-ignition model interfacing with an electric circuit to produce restrike waveform signatures’, it is necessary to have a general understanding of restrike phenomenon. For this purpose, the most important concepts and theories of restrike phenomenon have been gathered in this section. The objective is to provide some essential knowledge to facilitate the review of the literature relating to breaker performance modeling and simulations using restrike waveform signatures.

ii. Experimental 12 kV vacuum CB for parameter determination and model calibration:

(For details, refer to Chapter 5.)

iii. Models for dielectric strength curves: the hot withstand dielectric strength characteristics curves for SF₆ CBs and 12 kV vacuum CB

Models for the withstand dielectric strength curves include a hot recovery dielectric characteristic equation for SF₆ CBs and a generalised dielectric equation for 12 kV vacuum CBs, which are developed to improve the accuracy of the computer simulations for restrike waveform signatures.

iv. A predictive interpretation technique for converting prediction into a diagnostic test

This section includes breaker failure and basic maintenance knowledge, degradation and failure patterns, a predictive interpretation technique, principle of a predictive interpretation technique, a diagnostic test and selection of features for breaker restrike monitoring. The purpose of this section is to show the conversion from a predictive interpretation technique into a diagnostic test for automatic processing with Matlab programming.

v. Features selection due to operational conditions and parameter variation for simulated restrike waveform signatures libraries

The method using a straight line dielectric equation to characterise the re-striking behaviour of a vacuum CB is inadequate because the curve starts diverging from a straight-line [43] when using more characteristic features to verify the similarity of simulated and measured waveforms due to parameter variation and
Chapter 3: Proposed Methodology

operational condition variation. It is proposed that these features be used in the
diagnosis of the causes of restrikes in this thesis.

vi. Features extraction from restrike waveform signatures for online monitoring

An operator experienced with fault recorder records can often recognize faults
due to restrikes from their distinctive "signatures" or “features” on a fault record.
From features extracted from the restrike waveform signatures, diagnostic tools can
be developed that will identify breaker restrike detection problems or potential
causes of the restrike problems for the network power monitoring system. Such
diagnostic tools will be able to automatically identify restrike phenomena. The
concept of "simulated restrike waveform signature feature libraries" involves
having different types of restrike waveform signatures for different parameters and
conditions with the appropriate mother wavelets, and selecting the threshold values
for each feature (for example, slow contact opening velocity). The reason why we
need to establish these libraries is because it is impossible to have identical
signatures for simulated waveforms and measured waveforms. An example of
features extraction from restrike breaker for online monitoring is voltages on either
side of the breakers and the number of re-ignition and restrikes.

vii. Wavelet Transforms for online monitoring

(Details of Wavelet Transforms for online monitoring are given in the next
chapter.)

viii. Antenna calibration for field implementation:

(For details, refer to Chapter 5.)

3.1 Concepts and theories of restrike phenomena

3.1.1 Introduction

This section explains related concepts and theories of restrike phenomena in
circuits as a requisite knowledge for the restrike switch model applications
development. It explains different kinds of switching transients, defines ‘normal
transients’ and ‘abnormal switching transients’, and illustrates oscillating modes in
an electric circuit. The restrike waveform signature is checked to determine the
accuracy of the simulation case studies against the frequency response equations.
Chapter 3: Proposed Methodology

Effects of voltage and current transients to the medium and high voltage CBs are presented at the end of this section.

3.1.2 Switching transients and abnormal transients

The analysis of the restrike phenomena, starts by expressing the differential equations that describe the behaviour of the electrical system. The solutions of these differential equations give some useful information as far as circuit behaviour is concerned. Tools such as Laplace Transform are very useful in dealing with differential equations, which then is handled in the frequency domain. Today, computer simulations can solve the differential equations and integration for electric circuits interfacing with medium and high voltage CBs with linear forms.

A transient is said to be ‘normal’ [11] if the transient starts when the circuit is in a quiescent state, this is, it does not have stored energy. On the contrary, if the system has already some energy stored, then the effects of the transient can be stronger and the transient is known as ‘abnormal’ [11].

Two basic theories account for the ability of a medium and high voltage CB arc gap to withstand the recovery voltage [84]:

- Energy Balance Theory for thermal failure. This assumes that before arc extinction can be achieved, the energy extracted by cooling the arc must exceed the energy supplied from the circuit.
- Dielectric Recovery Theory for dielectric failure. This refers to the rate at which the dielectric recovers after arc extinction, compared to voltage rise across the arc gap.

In the particular simulation case studies related to the Dielectric Recovery Theory in this thesis, abnormal switching transients are frequent where it is common to observe multiple re-ignitions. This is because transients follow one after the other within a very narrow time period. In the next subsections, some of these abnormal switching phenomena are explained.

3.1.3 Electrical transient analysis and simulation

Electrical transients analysis and simulation are generally called the ‘travelling wave technique’, or the ‘time-domain method’ [85]. The parameters required for transient analysis are series impedance and shunt admittance for a transient on a
distribution-parameter line. The accuracy of the restrike waveform signatures is dependent on awareness of current restrike problems. These are related to the recovery voltage difference at the gap that exceeds the withstand dielectric strength medium. The problems are:

- ‘Reliability of a simulation tool’, defined as the consistency of the simulation results: This restrike problem is very much dependent on the user’s knowledge of the software simulation tool.
- Assumptions about, and limitations of, a software simulation tool: This restrike problem can be overcome by a deep understanding of the physical phenomena to be simulated.
- Input data: Error output is given if input data beyond the assumptions about, and the limitations of, the tool are used; for example, if the fact that the proposed CB model is only valid up to 600 A [4] is ignored.

3.1.4 Using oscillation frequencies in a reactor switching circuit for checking the accuracy of restrike waveform signatures

The disconnection of small inductive element from a high voltage system can impose a severe stress on a medium and high voltage CB. A reactor circuit, other than a capacitor circuit, is another type of electric circuit which represents a load connected to a voltage supply by means of a CB and a cable. The source has been modeled with an AC voltage source ($S_{\text{source}}$), a source inductance [including busbar inductance ($L_{n}$)], stray capacitance of the busbars ($C_{n}$) and connecting equipment. The frequency plots are very useful tools to analyze and understand the oscillatory behavior of a circuit and to check the accuracy of computer simulations, as shown in Ref. [97].

3.1.5 Stresses of switching transients to CBs

Stresses of switching transients to CBs are:

- Voltage transients stress the recovering arc column of a medium and high voltage CB and cause re-ignitions. These also stress power system insulation and can cause flashover for reactor switching due to crest magnitude and the rapid rise time of the rate recovery rise voltage (RRRV) and the TRV.
Current transients mechanically thermally stress medium and high voltage CBs and power system equipment, such as a contact and nozzle for capacitor switching.

The working life of medium and high voltage CBs is a function of the interrupting current magnitude and the permissible number of switching operations. With the results of the interrupting current from computer modeling and simulations, we can predict and calculate the extension of the remaining life of a medium and high voltage CB.

3.1.6 Conclusions

The general concepts and theories required to perform simulation case studies for the restrike switch model are:

- The generating restrike waveform signatures to predict restrikes in medium and high voltage CBs are the data for the transient switching voltage across the breaker and the withstand dielectric strength at the medium between the gap of the CB opening contacts. This is called ‘dielectric recovery theory’.
- A transient is associated with the change in the steady-state conditions of a power system. Transients are caused by the interconnection and/or disconnection of two systems and are called ‘switching transients’.
- Switching transients have been divided into two categories: simple switching transients and abnormal switching transients. The main difference between them is that an abnormal switching transient does not start from a quiescent energy state.
- A capacitor switching circuit is exposed to the trapped charges and the current waveform is 90° ahead of the voltage switch in 90°, causing the most hazardous situations to be presented when the breaker does not break at once and a re-ignition or restrike takes place due to the escalation voltages.
- The switching of an inductive load is exposed to the re-ignition and restrike problem since it represents the worst case scenario for the transient voltage. When the current reaches the chopping level, the voltage in that phase is very close to its maximum because of the 90° or 270° phase shift. If the breaker contacts are opened at that moment, the transient voltage is superimposed on the power frequency voltage when it is at its maximum. This produces transient overvoltages of the highest magnitude.
Chapter 3: Proposed Methodology

Oscillation frequencies for the capacitor and reactor switching circuit can be used for checking the accuracy of restrike waveform signatures.

- The main stresses causing switching transients to CBs are voltage and current transients, the rise-time of TRV and RRRV.
- High-magnitude transient restrike phenomena are studied in this thesis using restrike waveform signatures for stresses relating to the breaker lifetime.

3.2 Very high frequency modeling of restrike waveform signatures

Four different oscillatory behaviours are classified below (See Ref [43]):

1. Voltage Oscillation (1-1.5 kHz): when the switch is totally opened, and after a series of multiple re-ignitions, the load oscillates at its natural frequency.
2. Restrikes (20-100 kHz): the multiple re-ignitions are responsible for exciting this frequency range.
3. Breakdown (~ 1.5 MHz): this high frequency corresponds to the breakdown oscillation that occurs when the voltage across the switch exceeds the dielectric withstand of the gap and an arc is initiated.
4. Cable reflection (tens of MHz): the reflection frequency depends on the velocity of propagation of the electromagnetic waves on a particular cable and the length of the cable.

A typical transient waveform signature is shown in Ref. [86]. The restrike components – including CBs, cables, overhead transmission lines and transformers – are modeled in accordance with very fast transient modeling guidelines [87].

Two main problems are observed for modeling the very fast transient behaviour of a system component [88]:

- Very fast transients do not happen at a single, fixed frequency, but at a wide range of frequencies. Every piece of equipment is frequency dependent. Therefore, the parameters take different values according to the frequency from which they are being exited at that instant.
- It is impossible to build a unique model that is a valid representation of all kinds of very fast transient phenomena.

The simulations have been performed using ATP. Indeed, one of the main reasons for using ATP and not any other simulation package is that the majority of the published restrike cases are done with ATP [4]. ATP has many interesting features for modeling power systems; however, it is certainly incomplete in this particular case where very fast transient phenomena are studied. Depending on the
complexity requirements of the solutions where standard ATP models are insufficient, the modeling of the following equipment can be used if required:
- CB models for modeling and simulating restrike behaviour
- Cables at very high frequency behaviour
- Overhead transmission lines modeling at very high frequency behaviour
- High frequency transformer modeling.

Details of these models are given in the following section.

3.2.1 CB models applications development for simulated restriking waveform

A medium and high voltage CB can be modeled as either parallel switch (approximation) or dielectric reset switch (more detailed) for restrike switch modeling, depending on what effects are to be observed. For a parallel switch, the voltage controlled switch is set at 1.5 per unit (p.u.) to simulate a restrike so that flashover occurs. For the dielectric reset switch to analyse very fast transient overvoltages, the restrike switch model must include at least three properties for a CB, as shown in Figure 3.2, which shows the ATP-EMTP model of a vacuum CB to be used for restrike modeling with contact opening velocity computation.

The input values for determining the state of the switch are the current through the breaker [denoted as \( i(t) \)] and the voltage across the switch (\( \delta u \)), which is in fact the difference between the source voltage and the load voltage. The \( t_{open} \) is a parameter that denotes the instant when the contacts begin to open. \( U_b(t) \) and \( di/dt \) are the characteristics of the breaker determined by Equation (3.18), and the variable ‘slope’ denotes the actual slope of the CB computed at every instant of the simulation.

Current ATP models incorporating restrikes into simulations are not adequate for our purposes as they use a fixed velocity of 1 m/s. For diagnostics purposes, we need a variable contact velocity by changing parameter A (V/s) into (V/mm)(mm/s).
Figure 3.2. Flow chart of the vacuum CB’s restrike modeling with contact opening velocity computation [4]

The three properties of CB restrike modeling are as shown in Figure 3.2:

- Chopping current for both the switching of inductive loads of vacuum CBs or SF₆ CBs only
- Dielectric recovery withstand characteristic between breaker contacts for both vacuum CBs or SF₆ CBs
- High frequency current quenching capability for vacuum CB only (The method used in this thesis to determine the quenching capability of a vacuum CB is given by Glinkowski [28]. Some authors model the high frequency current quenching capability according to the slope of the high frequency current [4]. The model used in this work offers the possibility of quenching the current at the first zero crossing or after a specified number of zero crossings. It does not account for the slope of the current. For the frequency current quenching capability for SF₆ CBs, we find that no
effect has been taken for computer simulations since SF\textsubscript{6} CBs have no high frequency zero current quenching capacity.)

The **current chopping level** can be defined as, and it is usually set to, a 3A to 8 A value for a vacuum CB [4]. However, the current chopping mode does not exactly work as it should because, while it should only work before the first power frequency zero crossing, it works every time, even at high frequencies. This creates faster TRVs at high frequencies and, therefore, a higher density of multiple re-ignitions.

The **cold withstand curve** is not given by vacuum CB manufacturers but it can be estimated from experimental results. If measurements are available, then the envelope curve of the voltage across the breaker contacts can be estimated. The cold withstand is a function of the contact distance and the velocity of contact separation. The researchers that have experimentally investigated the withstand capability have found that the data varies following a statistical distribution. Some researchers represent it following an exponential curve, while others believe that a linear characterization is enough [51]. This model gives the possibility of specifying an envelope curve with two points other than the origin (the coordinates have to be deduced from the experimental data). Another very interesting phenomenon derived from multiple re-ignitions is that the gap does not have time to recover from re-ignition to re-ignition and its withstand decreases. The reason is that when an arc is extinguished, conducting particles precedent from the CB contacts are still floating in the gap and reduce the withstand capability of the gap. The decreased withstand is known as **hot withstand capability for SF\textsubscript{6} CB** and is modeled in Appendix F.

### 3.2.2 Cables

Cables are often modeled in ATP by making use of \( \Pi \)-sections as a means of the Cable Constants with capacitive and inductive mutual coupling between the phases. The ATP has supporting routines to compute cable parameters based on the various dimensions of the cable and its materials. The model can account for arbitrary shaped cables, snaking of cables, etc. The user can select any of the several models for cables such as lumped or distributed parameters; frequency independent or frequency dependent models [89]. The choice of cable model is dependent on a number of factors such as the length of the cable, the nature of the simulation (fault,
surges, etc.) and the fidelity of the results. The following are the various options for cable models [4]:

1) **Bergeron**: Distributed, but frequency dependent parameter model
2) **PI**: Nominal PI-equivalent model with lumped parameters which is suitable for short lines
3) **Noda**: Frequency dependent model (This algorithm models the frequency dependent transmission lines and cables in the phase domain.)
4) **Semlyen**: Frequency dependent simple fitted model (Semlyen model was one of the first frequency dependent line models. It may give inaccurate or unstable solutions at high frequency oscillations.)
5) **JMarti**: Frequency dependent model with constant transformation matrix that is suitable for simulating travelling wave phenomenon in long cables.

The ALCATEL OALC-4 Type 31 cable is an example that can be used in the simulation. The data of the cable, which is provided by the manufacturer ALCATEL [90], is shown in Figure 3.3 and Table 3.1. The cable has a steel tube at its core, containing 6 to 12 optical fibers. The steel tube is surrounded by two layers of high strength steel wires enclosed within a thin copper sheath. The insulation of the outer layer is made of polyethylene material.

![Figure 3.3. ALCATEL Type 31 cable](image-url)
Table 3.1. ALCATEL cable data [90]

<table>
<thead>
<tr>
<th></th>
<th>Theoretical values</th>
<th>ATP values</th>
<th>ALCATEL values</th>
</tr>
</thead>
<tbody>
<tr>
<td>R (Ω/km)</td>
<td>1.03</td>
<td>1.03</td>
<td>1</td>
</tr>
<tr>
<td>L (mH/km)</td>
<td>0.3424</td>
<td>0.3422</td>
<td>0.128</td>
</tr>
<tr>
<td>C (μF/km)</td>
<td>0.179</td>
<td>0.179</td>
<td>0.2</td>
</tr>
</tbody>
</table>

In this thesis, for restrike breaker computations, the model with Π-sections is applied. To obtain more accurate results for frequency dependency of the cable, more Π-sections increase the number of parallel R-L branches in one Π-section [4] and then verify the determinations with the measurements.

3.2.3 Overhead transmission lines

Three scenarios might be considered in the initial parametric studies: a) both circuits are un-transposed, b) only one circuit is transposed and c) both circuits are transposed. From the available line models within ATP, JMARTI was selected to represent the transmission line as it can accurately handle the distributed nature of the line impedance and admittance as well their variations with frequency [91].

3.2.4 Transformers

Modeling of transformers is a complex issue, especially at high frequencies [4]. To model the transient behaviour of a transformer, both its non-linear behaviour and its frequency-dependent effects must be considered.

Ref. [92] summarizes the two main transformer high frequency modeling techniques:

1) **Detailed internal winding models** - This type of model consists of large networks of capacitances and coupled inductances obtained from the discretization of distributed self and mutual winding inductances and capacitances. The determination of these parameters involves the solution of complex field problems and requires information on the physical layout and construction details of the transformer. This information is not available and is generally considered as the property of transformer manufacturers. These models have the advantage of allowing access to internal points along the winding, making it possible to assess internal winding
stresses. In general, internal winding models can predict transformer resonances but cannot reproduce the associated damping. This limitation makes this class of models suitable for the determination of initial voltage distribution along a winding due to impulse excitation, but unsuitable for the determination of transients involving the interaction between system and transformer. Moreover, the size of the matrices involved makes this kind of representation impractical for EMTP system studies (for example, ATP-EMTP studies).

2) **Terminal Models** - Models belonging to this type are based on simulation of the frequency and/or time domain characteristics at the terminals of the transformer by means of complex equivalent circuits or other closed-form representations. These “terminal” models have had varying degrees of success in accurately reproducing the frequency behaviour of single-phase transformers. The main drawback of the methods proposed to date appears to be that they are not sufficiently general to be applicable to three-phase transformers. It seems obvious that the most adequate transformer model is a terminal model, since the interest lies in analysing the interaction of the transformer with the system. For the moment, there is not so much concern about knowing the response of a particular winding to an external stimulus.

A good analysis of modeling needs is found in [4]:

Operation of vacuum CBs causes switching surges that generate electromagnetic transients in a wide range of frequencies. Therefore, the transformer model must be able to represent the behaviour of the system not only at power frequency, but also at high frequencies. Extensive research has been carried out by CIGRE WG 13.02 on switching of small inductive currents; however, the transformer models used were often simplified by considering the transformer hysteresis or saturation and the total transformer capacitance. The main disadvantage of these kinds of models is that the total transformer capacitance does not adequately characterize every frequency component. However, the transformer model used in this work considers only the stray capacitances of the transformer and is able to represent frequencies of up to 100 kHz. The stray capacitances comprise the phase to ground capacitances and the lumped winding capacitances.

**For the case of vacuum CB re-ignition**, a high frequency modeling of the transformer is needed. At high frequencies, fast flux variations take place and the saturation and hysteresis of the transformer core do not play a significant role and
can therefore be neglected. Due to the flux penetration at a relatively higher frequency range, the performance of an iron core winding tends to be linear. However, below 100 kHz, where switching transients are likely to be present, the linear assumption is not obvious. The terminal impedance characteristic gives sufficient information about the wide frequency range performance but it varies depending on the load. If the transformer is not loaded, the magnetizing inductance takes more weight than the leakage inductance for frequencies below 100 kHz and, as a consequence, the magnitude of the impedance rises and the resonance frequencies shift (The value of the magnetizing inductance is much higher than the leakage inductance). On the contrary, if the transformer is short circuited, the main flux in the core is partially cancelled by the secondary ampere turns and the effect of the iron core is negligible (The leakage inductance is dominant). Depending on the frequency, the behaviour of the transformer is different. This implies that we can accurately calculate switching overvoltages if a different model is used for each different transient condition.

In this work, a high frequency power transformer model has been chosen from the literature. The model is basically a typical high frequency power transformer model to which the winding lumped stray capacitances and the phase to ground capacitances have been attached. The proposed restrike switch model is reasonably accurate for frequencies between 1 MHz and 100 MHz, but for higher frequencies another more complex model must be used. The transformer RLC parameters were obtained from the literature [93] and then the values were compared with measurements and Matlab Simulink simulations for evaluation.

For the core-form transformers, typical values of stray capacitances are given in Table 3.2 for restrike switch model simulation in next chapter. For the dry-type transformers, the value of the stray capacitances are in the order of hundreds of pico Farads, or approximately ten times smaller compared to the core-form transformer [86].
Table 3.2. Typical stray capacitances of HV and LV to ground and between HV and LV side (nF) [86]

<table>
<thead>
<tr>
<th>Transformer rating (MVA)</th>
<th>HV-ground cap.</th>
<th>LV-ground cap.</th>
<th>HV-LV capacitance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2-14</td>
<td>3.1-16</td>
<td>1.2-17</td>
</tr>
<tr>
<td>2</td>
<td>1.2-16</td>
<td>3-16</td>
<td>1-18</td>
</tr>
<tr>
<td>5</td>
<td>1.2-14</td>
<td>5.5-17</td>
<td>1.1-20</td>
</tr>
<tr>
<td>10</td>
<td>4-7</td>
<td>8-18</td>
<td>4-11</td>
</tr>
<tr>
<td>25</td>
<td>2.8-4.2</td>
<td>5.2-20</td>
<td>2.5-18</td>
</tr>
<tr>
<td>50</td>
<td>4-6.8</td>
<td>3-24</td>
<td>3.4-11</td>
</tr>
<tr>
<td>75</td>
<td>3.5-7</td>
<td>2.8-13</td>
<td>5.5-13</td>
</tr>
</tbody>
</table>

3.3 A predictive interpretation technique for CB diagnostics

After obtaining restrike waveform signatures from computer modeling and simulations, it is necessary to convert the data into breaker condition information with a predictive interpretation technique. The method is also to bridge the interpretation function between a restrike switch model and a restrike diagnostic test, using Wavelet Transforms. The method includes: breaker failure and basic maintenance knowledge, degradation and failure pattern, a predictive interpretation technique development, principle of a predictive interpretation technique and diagnostic test, and choice of features for breaker restrike monitoring.

3.3.1 Breaker failure and basic maintenance knowledge

In the case of CBs, their initial capacity – for example, rated load, interrupting rating, rated voltage, impulse withstand voltage – is carefully selected to cover maximum system requirements and allows for some margin of deterioration. When a CB is put into service, stresses from the system it is connected with, as well as the aging of the CB itself, cause it to deteriorate. Maintenance activity is performed to ensure that its capacity stays above the maximum system requirement, but it cannot raise the capacity above the initial installed capacity. This means that it must be maintained within the margin of deterioration. Generally, the variable stress or loading applied to a CB depends on the system requirements; for example, load
current variation according to time of day or seasons, or higher interrupting rating requirement due to the connection of new power plant.

Whenever the system requirement is higher than the actual performance of the CB, it is unable to fulfill its required function. This is called ‘functional failure’. This view of failure is based on the assumption that most items operate reliably until the end of useful life and then wear out, and the belief that the breaker has life form a basic rule of preventive maintenance. This suggests that breaker overhauls or component replacements should be done at fixed intervals, not later than the end of its useful life – even if it has not failed. However, the CB nowadays is generally far more complex and leads to various failure patterns.

3.3.2 Degradation and failure patterns

In practice, the CB is always subjected to a wide variety of stresses after being put into service. These stresses cause the CB to deteriorate by lowering its capability, or more accurately, its resistance to stress. In order to select the proper maintenance techniques, it is necessary to know the relationship between age and failure, which can be separated into two categories as explained below.

3.3.2.1 Age-related failure patterns

The prediction of CB life could be performed with great accuracy if the deterioration were directly proportional to the applied stress and if the stress were applied regularly throughout the life of the CB. Unfortunately, in practice, two identical CBs put into service at the same time under the same working conditions will fail at different ages. This is not only because of a small variation in their initial resistance to failure, but also because they are subjected to different stresses at different times throughout their lives. Even though any CB has its individual end of lifetime, the failure of a large proportion of CBs will gather around the mean life or the so-called ‘average life’ of the CB with typical characteristics of a normal or Gaussian distribution as long as they deteriorate in this manner. If the average life can be determined, the preventive maintenance can be effectively applied. The failure pattern according to age-related failure should show the rapid increase in failure rate and probability of failure when the CBs get older, especially after their useful life.
3.3.2.2 Non age-related failure patterns

The increase in CB complexity, such as more associated components, and the variation of applied stresses in service are the primary reasons for non-age-related failure. Generally, the stresses in service occur irregularly and the condition or performance does not deteriorate proportionally to the stresses. Therefore, it is impractical to apply preventive maintenance and condition-based maintenance is now preferred for the CB with non age-related failure patterns.

3.3.3 A predictive interpretation technique development

In general, the CB with non age-related failure pattern has no average life and the relationship between failure and operating age cannot be determined. However, when failures are about to occur or are in the process of occurring, some kind of detectable information should be capable of identifying the deterioration in condition, if the appropriate diagnostic tools are applied.

The purposes of predictive interpretation technique is: to determine the condition of a specific CB and its associated components, to improve its utilization by prolonging its potential lifetime and economics of operation, to reduce failure rate, to increase reliability and availability, to optimize maintenance activity and cost reduction, to facilitate the provision of spare parts, and to develop an understanding of the condition of a large number of CBs in similar circumstances by examining a representative sample of the population. The requirements of the technique are that it be: simple in application and interpretation, economical in initial cost and installation, reliable in operation, able to interpret a wide range of CB failure modes, and able to be used by non-professional staff. The predictive interpretation technique of medium and high voltage CBs can be divided into manual, temporary and continuous (including on-line) condition monitoring. The complexity of the predictive interpretation technique depends on the type and rating of the CB, its importance in the system and user preferences.

3.3.4 Principle of a predictive interpretation technique and diagnostic test

A predictive interpretation technique and diagnostic system normally forms as an information chain. A predictive interpretation technique starts with the data acquisition, signal processing, feature extraction and decision-making. Then, the
output from a predictive interpretation technique – whether it is from periodic or continuous monitoring or from in-service or out-of-service diagnostic tests – will be sent to a user-interface unit, where the results are presented to the user.

In general, the function of each component in a predictive interpretation technique and diagnostic system can be described as follows:

- Data acquisition processes the output from binary to suit digital signal processing by analog to digital (A/D) conversion and immediately stores data.
- Signal processing and feature extraction are the processes to determine the characteristics values of the signal – such as crest-value, value at the same time point – and to derive and find the relation between these values. The parameters and extracted features should be sufficiently sensitive to behaviour changes of failure part.
- Decision-making is the analytical process. The detected changes in signatures obtained in operation of the breaker after failure are compared with signatures obtained during normal operating conditions and stored in a database for analysis. Any exceed-acceptable limit value will be evaluated to determine the condition of the CB.
- The user-interface presents the result information, which is easily interpreted by a human operator.
- Stress in operation, such as the number of switching operations and short-circuit current interruption, is primarily used to determine the deterioration of CB according to stress and aging. Then, the deterioration is further evaluated to model the changes of condition with time. If the condition exceeds the acceptable limit, a replacement is proposed.

3.3.5 Choice of features for breaker condition assessment

Restrike detection systems required reliability and high sensitivity add more complexity and make them vulnerable to disturbances from external sources. Thus, a restrike assessment system should select the most basic and important functions, minimize the number of parameters and be kept simple and straightforward.

The electrical parameters that should be monitored (as shown in Appendix G) are listed as follow:
Chapter 3: Proposed Methodology

- Voltage crest value
- Current magnitude
- Number of restrikes
- Voltage signature
- Current signature
- Oscillation frequency
- Breakdown reduction factor
- Rate of change of high frequency current quenching
- Slope of rate of rise of recovery voltage

The interrupter wear resulting from current interruptions consists mainly of the nozzle ablation and the contact erosion. The nozzle ablation is caused by the energy from the radiated power from the arc, as well as by thermal conduction when arc plasma makes contact with the nozzle wall.

The contact erosion is caused primarily by the vaporization of the cathode and the anode electrodes. The determination cannot be made directly; however, indirect methods using measurements of current and arcing time can be performed with a conventional instrument, such as a current transformer. The arcing time can be extracted from the contact separation or contact travel measurement. The product of the current and the arcing time should provide a related parameter of contact erosion and nozzle ablation to ampere-seconds of arcing.

3.4 Features due to operational parameter variation for diagnostic purposes

The purpose of generating restrike waveform signatures with features is to recognise the parameters at each variable because small differences in the values of the circuit parameters can result in large differences in the severity of duty due to the transient phenomena which occur when a circuit is switched by a vacuum CB [4]. A sensitivity study is performed if one or several parameters can be accurately determined. Results derived from such a sensitivity study will show that these parameters with features are of concern for diagnostic purposes, and justify using more characteristic features to verify the similarity of simulated waveform signatures and measured waveform signatures.
Chapter 3: Proposed Methodology

There are no published research results on parameters in the re-ignition or restriking process, nor is there a defined methodology for analysis of these parameters affecting restriking switch features. The method in this study is the actual re-ignition phenomenon influenced by the CB parameters and the network from the combined experiments and computer simulations on energising a capacitive load [94]. The first step consists of the determination of suitable characteristics versus time from the voltage or current waveforms, including two interrupter degradation factors (as shown in Appendix G): the recovery slope and the breakdown reduction factor. In the second step, the characteristics versus time form from the appropriate mother wavelets and the threshold values for each feature.

During the ATPDRAW simulations, crest magnitude, rise time, recovery slope and breakdown reduction factor are observed when the variations are found. It is of the highest interest to identify the relationship between the voltage stress and the current degradation, as the escalated restrikes are generated in the power network under these conditions. Comparisons will be made for the simulated waveform features with the experimental results to test the robustness of the predictive interpretation technique in Chapter 5. A novel method of analysing simulated restrike waveforms for the online breaker condition monitoring is developed. This section is organised as follows: background theory about re-ignition and an explanation of the predictive interpretation technique.

3.4.1 Background theory

Waveform features for breaker restrike with gradual dielectric strength deterioration or slow contact opening velocity is identified as a problem statement to validate the restrike switch model. It is suggested to take the harmful or ineffective aspect of the system and exaggerate it to the most extreme form of the failure. This catastrophic condition now becomes the measure of desired performance. To identify the restrike waveform features for vacuum dielectric strength degradation, the nine-step process is as follows:

1. Formulation of the original problem.
   There is a system – a power source containing a CB, bus bars, and load.
   An undesired effect – re-ignition or restrike occurs between the breaker under abnormal transient condition.
Chapter 3: Proposed Methodology

It is necessary to identify the features of this phenomenon. Why and how did the restrike/re-ignition occur?

2. Formulation of the inverted problem.
   It is necessary to produce re-ignition/restrike between the terminals of the breaker under different operating conditions.

3. Amplification of the inverted problem.
   It is necessary to produce a variety of restrike waveform signatures under different condition with different parameters.

4. Search for apparent solutions to the inverted problem.
   For a restrike or re-ignition to occur between the breaker terminals, this condition is required: recovery voltage exceeding the withstand dielectric strength. Either the recovery voltage slope or the high frequency current quenching are possible waveform features to distinguish each parameter for vacuum dielectric strength.

5. Identification and utilisation of resources.
   - Analysis of readily-available resources: parasitic capacitance, chopping current value, inductance value between vacuum CB and the transformer load source impedance.
   - Field resource: dielectric strength characteristic curve.
   - Space resource: contact opening velocity
   - Time resources: contact opening time, breaker angle.

6. Search for the needed effect.
   In this step we consider how the resources available in the system might bring about the apparent solution, indicated in Step 4. Each resource represents a parameter affecting the magnitude of voltage or current or the resonant frequency. Two interrupter degradation factors – the recovery slope and the breakdown reduction factor – are possible candidates to indicate the interrupter performance.

7. Formulation of hypotheses and tasks for verification.
   It is obvious that the breaker dielectric failure is due to the high frequency current quenching magnitude or the decrease of the dielectric strength. To be sure that this scenario is valid, we must verify the following:
   Each resource parameter will affect the breaker parameter A, B, C and D value.
   The degradation of the breaker can be diagnosed with the constant value.

8. Development needed to prevent failures.
To prevent re-ignition/restrike occurring in the future it is necessary to develop a restrike/re-ignition diagnosis algorithm with restrike waveform signatures.

3.4.1.1. Re-ignitions

A re-ignition of the vacuum arc is a temporary electrical breakdown of the vacuum in the vacuum CB. The dielectric withstand of the vacuum CB is the subject in the analysis of the degradation. When the breaker contacts start to separate, the withstand voltage of the gap starts increasing. During the first millimetre of separation, the withstand voltage increases linearly and at that point after it increases proportionally to the square of the distance between the contacts [86]. In the model that is used in this project, a linear relation between the withstand voltage and the time after separation is assumed [56]. This relation is seen in Equation (3.17):

\[ U = A(t - t_0) + B; \quad (3.17) \]

where \( t_0 \) = The moment of contact separation.

\( U \) = the withstand voltage

\( A \) = Rate of rise of dielectric strength.

\( B \) = Breaker TRV just before current zero.

The values of \( A \) and \( B \) vary for the different vacuum CBs. The constant \( A \) describes, as mentioned, the rate of rise of dielectric strength (RRDS) when the breaker is opening. When the breaker is closing, the constant \( A \) describes the rate of decay of dielectric strength (RDDS). The value of the constant \( A \) is suggested to be between 2 V/µs and 50 V/µs when \( B \) is set to zero in Ref. [6]; this is quite normal when determining the dielectric withstand of the breaker. The value of the dielectric strength determined in Equation (3.17) is also following a Gaussian distribution with a standard deviation of 15% of the dielectric mean value [56]. If the value of the TRV exceeds the dielectric withstand of the gap between the contacts, the arc will be re-established and the breaker will conduct current again. This causes a high frequency (HF) current to be superimposed on the power frequency current. This HF current will be extinguished at current zero and the race between the TRV and the dielectric withstand will begin again.

3.4.1.2 High frequency current quenching capability

The HF currents that occur after a re-ignition of the arc are mainly determined by the stray parameters of the vacuum CB, such as dielectric strength. The HF current will be superimposed on the power frequency current and, if the HF
current has a larger magnitude than the power frequency current, it can cause the current to pass zeros. Most vacuum CBs have the ability to quench the HF current at a zero crossing, and thereby extinguish the vacuum arc [56]. The vacuum CB cannot extinguish these HF currents if the $\frac{di}{dt}$ value of the current is too high. Since the magnitude of the currents is damped quite quickly, the $\frac{di}{dt}$ of the current is also decreasing. When $\frac{di}{dt}$ is small enough, the vacuum CB quenches the HF current at one of its zero crossings. A method of determining the quenching capability of a vacuum CB is to model it as a linear function with respect to time:

$$\frac{di}{dt} = C(t - t_0) + D;$$

(3.18)

where

$\frac{di}{dt}$ = the critical slope of the frequency current as a function of time

t$_0$ = The moment of contact separation.

C and D = Breaker constants.

Equation (3.18) gives the mean value of the quenching capability and, once again, it follows a Gaussian distribution where the standard deviation is 15% of the mean value. The suggested values of the constant C is between -0.034A/µs$^2$ and 1A/µs$^2$. Some authors describes the HF quenching capability $\frac{di}{dt}$ to be constant, C = 0, and suggested values of D to be between 100 A/µs$^2$ and 600 A/µs$^2$[95]. Recent research shows that the quenching capability is not constant, but depends on the re-ignition voltage [4]. Details refer to Figure 2.1.

3.4.1.3 Proposed approaches for restrike features characterization

When the vacuum CB breaks the HF current that has occurred due to a re-ignition of the arc, the TRV of the breaker starts rising again. When the TRV reaches the dielectric withstand of the breaker gap, the arc will ignite again and cause another HF current to be superimposed on the power frequency current. This phenomenon is called ‘multiple re-ignitions’. Figure 3.4 shows the current of the breaker during multiple re-ignitions of the vacuum arc. Simulated results are presented in Appendix F.
The following parameters are proposed to be investigated for the occurrence of multiple re-ignitions with computer simulations for the transient waveforms with a breaker degradation feature:

1. Parasitic capacitance
2. Contact opening velocity
3. Chopping current value
4. Dielectric strength variation
5. Breaker angle
6. Inductance value between vacuum CB and the transformer load source impedance.

The time between contact separation and first arc extinguishing is called the ‘arching time’; in other words, the arcing time is the time between contact separation and the time of current chopping. If the arcing time is short, such as POW operation, then the dielectric strength of the gap will not have time to reach a high value before the arc is extinguished, and the probability of re-ignitions is higher. In vacuum CB with high RRDS, the possibly of restrikes will be smaller since the breaker regains its dielectric withstand faster than breakers with low RRDS.

3.5 Features extraction from a simulated restrike waveform for online monitoring

After collection of the data from CBs, an operator usually examines the new record and Dr. aws a conclusion based on the overall information, including previous records. An automated analysis system works differently. In order to use the online information as the original data, it must be able to describe the information quantitatively. The role of the preprocessing system described in this thesis is to
extract the pertinent information (features) in the form of signal parameters. This process is also called ‘feature extraction’.

The important features for the CB condition fall into two categories: system status features and features that describe the shape of the individual signal. A ‘system status’ refers to a state transition or an unusual change in the switch profile. The time when the system status happens and sequences of events are of interest for analysing the CB condition. A maximum of eight system statuses have been identified in Table 3.3 and Table 3.4 to describe the features of different signals.

<table>
<thead>
<tr>
<th>System status #</th>
<th>Event Description</th>
<th>Signal Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Parasitic capacitance</td>
<td>S1</td>
</tr>
<tr>
<td>2</td>
<td>Contact opening velocity</td>
<td>S2</td>
</tr>
<tr>
<td>3</td>
<td>Dielectric strength variation</td>
<td>S3</td>
</tr>
<tr>
<td>4</td>
<td>Breaker angle</td>
<td>S4</td>
</tr>
<tr>
<td>5</td>
<td>Inductance value between vacuum CB and the source impedance</td>
<td>S5</td>
</tr>
<tr>
<td>6</td>
<td>Inductance value between vacuum CB and load impedance</td>
<td>S6</td>
</tr>
<tr>
<td>7</td>
<td>Chopping current</td>
<td>S7</td>
</tr>
</tbody>
</table>

Table 3.3. System status definition for CB degradation conditions
### Table 3.4. Features for individual signals

<table>
<thead>
<tr>
<th>System name #</th>
<th>Feature Description</th>
<th>Signal Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage on either side of the breaker</td>
<td>Amplitude</td>
<td>G1</td>
</tr>
<tr>
<td>Current</td>
<td>Amplitude</td>
<td>G2</td>
</tr>
<tr>
<td>Nos. of restrikes</td>
<td>Number</td>
<td>G3</td>
</tr>
<tr>
<td>Voltage Signature</td>
<td>Mother Wavelet</td>
<td>G4</td>
</tr>
<tr>
<td>Current Signature</td>
<td>Slope (di/dt)</td>
<td>G5</td>
</tr>
<tr>
<td>Feature oscillation frequency (MHz)</td>
<td>Number</td>
<td>G6</td>
</tr>
<tr>
<td>Recovery curve (S)</td>
<td>Number</td>
<td>G7</td>
</tr>
<tr>
<td>Breakdown reduction factor(α)</td>
<td>Number</td>
<td>G8</td>
</tr>
</tbody>
</table>

### 3.5.1 Basic concept

Simulated restrike breaker diagnosis is based on a restrike switch model of the CB under observation. This model can accurately simulate the system's behavior under restrike conditions. Its operation depends on internal parameters (e.g., dielectric strength curve) as well as external inputs (power network data). When the model is presented with a combination of parameter and input values, it will yield the same data as would be measured by the oscilloscope under the same conditions.

From the simulation results, meaningful quantities for assessing the condition of the system are extracted; they are called ‘features’ (See Table 3.3* and Table 3.4 in previous section). These features should be sensitive to certain changes in the system. The set of all these features at a given time is called ‘system status’. In addition, it is helpful to compensate for dependencies of the extracted features. The basic method for simulated restrike breaker diagnosis is two-fold: First, the ATP model is used to simulate all possible cases, and these cases are stored in a database; then, this database is used to find the most likely diagnosis when a deviation from normal operation has been detected. This is explained in detail in the next section.
3.5.2 The method

The process of reaching a diagnosis via the simulated restrike waveform signature approach is first explained in algorithms. Then, each step is individually elaborated. Part 1 of simulated restrike waveform signature diagnosis is executed offline on a workstation computer as below:

1. Make a list of all possible (anticipated) combinations of the model input values.
2. For every feasible combination of input values from the list:
   - Run a simulation on the ATP model
   - Extract the system status from the resulting data

Store the system status, including input values that led to it, in a database for later reference. Part 2 uses the database from Part 1 and is performed on the target monitoring computer as follows:

1. From the database, extract the voltage and current system status. Voltage and current system status deviates from expected status? Yes.
2. Look up the best matching simulated system status in the database from Part 1.
3. Present the result as the voltage and current diagnosis.
4. (Optional) If possible, run additional simulations to refine the result.

Each step is further explained in the following sections.

**Part 1: Pre-processing**

This part of simulated restrike breaker diagnosis is executed off-line, on a computer which holds the ATP model of the system to be monitored. The computation results form a database, which is transferred to the target system (the computer that actually monitors operation of the device); there, it is used to perform the actual diagnosis.

**List of Model Inputs and Parameters**

As a first step, simulated restrike breaker diagnosis requires a list of input and parameter values for the model. A model input describes an external influence on the system, for example, a supply angle. Conversely, a model parameter describes a condition inside the system, such as a busduct inductance. In many cases, these parameters are not directly accessible for measurement and only manifest themselves
through their influence on the system behavior. This holds true for the examples given above.

Every list entry contains either the entire set of input values or those parameters which deviate from their restrike value only. It is important to also include the no-restrike case. For example, consider a CB model with a total of three inputs or parameters. One of these parameters (#3) represents the number of restrikes. With medium and high voltage CBs, the assumption of single or, at the most, double restrikes (i.e., only one or no more than two components fail simultaneously) is usually justified.

Using the list created above, the following steps are executed for every list entry.

**ATP Simulation**

The ATP model is presented with the input and parameter values from one list entry and a simulation run is started. The model generates the same outputs (data) that would be read from the voltage and current waveforms under the same external and internal operating conditions. One simulation is conducted for each item on the list, under all possible normal operating conditions.

**Model Status (Feature Extraction)**

From the simulation results (model outputs), the model status is created. It consists of a set of N numbers, the "features" of the data series from Wavelet Transforms. Every model output, just like a sensor on the real system, creates a series of "readings", a time series, of the observed quantity. A feature is a single number that reflects one interesting aspect of this signal. An example of features extracted from a voltage waveform signature on a medium and high voltage CB include initial and final signature. It makes sense to select features of the kind that will change noticeably with variations in the model inputs and parameters.

**Generating the diagnostic database**

The model status from the previous step, together with the model inputs and parameters, forms a new case in the diagnostic database for use in diagnosis. Again, either the entire set of features or only those parameters which deviate from their normal values are included. The information thus saved is essentially of two kinds:
Chapter 3: Proposed Methodology

1. Information that is equivalent to, or can be derived from, monitored quantities in the system, regardless of whether it relates to an internal or an external parameter. These features are called "visible" features.

2. Information that cannot be derived from the monitored quantities, referred to as "hidden" features. The data records (one for each case) should therefore be structured so that the visible and the hidden features are grouped, while still allowing easy reference to each group of visible and the hidden features. This is explained in greater detail below. Also, the analog (continuous) and digital (binary) features should be kept together to facilitate later determination. Note that this database should be in a format which can be conveniently transferred to, and processed by, the diagnosis computer.

At first glance, this database bears some resemblance to the concept of "restrike breaker signature libraries" with the appropriate mother wavelets and the threshold values for each feature, such as slow contact opening velocity. However, the fundamental difference is that simulated restrike breaker diagnosis does not attempt to simulate and record all possible restrikes – which is impossible for analog systems, anyway. Rather, the idea is to include a number of selected cases that may occur in reality; then, the best match needs to be found for the diagnosis.

Part 2: Diagnosis processing

This part of simulated restrike breaker diagnosis is executed automatically by the diagnostic computer. It uses the diagnostic database created in Part 1 to find the most likely cause of a detected anomaly.

Extract System Status

From the collected data, the same N features are extracted, forming the system status. Obviously, only the visible features can be obtained; the aim is to also derive the corresponding invisible features. For continuous monitoring, the data need to be partitioned chronologically such that every section is equivalent to a simulation run. These sections may overlap. As an example: For condition assessment of a parasite capacitance, the voltage and current are monitored. As long as the breaker is off, there is no need to analyze its voltage and current. The only quantity that needs to be measured during that time is the interval between two terminals. On the other hand, as soon as the breaker is switched on, the voltage and current are recorded to yield
such features as peak current, and steady state current. In addition, it is important to distinguish whether the breaker was energized in consequence of a switching event.

**Detect Deviations**

The system status is tested for deviations from the normal or expected values; these deviations are called ‘symptoms’. In many cases, a simple threshold check will be sufficient. For features which are dependent on other quantities, such as the variation of operating times, the dependencies must be compensated beforehand, or the threshold must be shifted accordingly.

It is possible to omit this step and feed the entire system status, as extracted from the database, directly into the next step. This has advantages for processing velocity but is detrimental to full documentation of the diagnostic process and the ability to explain the reasoning that led to the final decision to the user.

**Find Case in Database**

The system status, or collection of N features, is looked up in the database. However, it is unlikely that all analog values will exactly match any case from the simulations. Therefore, it makes sense to choose the case that resembles the voltage and current system status "most closely" as the diagnosis. The closest case is determined on the basis of the individual case, such as same signature feature for the slope (di/dt) A/s².

The output of this step is the best matching case, or a list of cases, selected from the database. It contains not only the visible features, but additional features derived from the database readings. Thus, it yields valuable information about quantities that are not normally accessible to inspection.

**Report Diagnosis**

The diagnosis (or list of probable diagnoses) found in the previous step can be reported offline. The result needs to be processed in order to plainly show the nature and location of the diagnosed problem. Since the simulated restrike case was known at the time of creating the problems list, it should be easy to include a text field describing the problem with each record in the database. This text can be presented to the user, together with a list of the most significantly deviating parameters. That way, the operator is informed of the situation and can initiate the necessary steps to take action.
Additional Simulations (optional)

If the features of the simulated case selected as diagnosis do not match the system status exactly, as is likely to be the case, it is possible to run additional simulations to pinpoint the problem more precisely. Since the general location and type of the restrike are already known, one or two simulation runs should be sufficient for an exact assessment of the situation. For example, consider a source inductance parameter with a threshold values of 0.1 from wavelet transform; the database contains simulated cases with threshold values of 0.1 from wavelet transform. If during matching these two cases were found as the most likely diagnoses, additional simulation runs could be performed with threshold values of 0.1 from wavelet transform; the results, compared with the system status, should produce an even better match for processing the final diagnosis.

Obviously, this step is only possible if the model and ATP software are accessible to the user. This might be the case at a larger plant containing several breakers (such as a high voltage substation), where a single installation on one supervisory computer is sufficient, because the probability of a restrike occurring in more than one breaker simultaneously is very low. Typical steps used in the classification of power system events, such as feature extraction and optimization, can be similarly applied for breaker degradation events to develop an online rule-based expert systems for asset management.

3.6 Wavelet Transforms

A mathematical CB model or a restrike switch model is applied for restrike prediction using the ATP to examine worst case condition in a power network. However, we cannot simply use ATP simulation for restrike detection algorithms. Wavelet Transforms are the most commonly used in signal processing and power quality problems. Therefore, a restrike detection algorithm using Wavelet Transforms is presented in the next chapter.
3.7 Summary

This chapter has presented a proposed methodology of assessing interrupter risk condition from a restrike switch model using measurements, ATP and Wavelets Transforms with the following:

- A restrike switch model (defined as a mathematical re-ignition CB model interfacing with an electric circuit to produce restrike waveforms as a diagnostic tool)
- 12 kV vacuum CB experimental work
- The related and most important theories and concepts informing the above
- A predictive interpretation technique
- Use of more characteristic features to verify the similarity of simulated and measured waveforms
- Features extraction for database libraries
- Wavelet Transforms.

The methodology for this thesis (as shown in Figure 3.1) is summarised below:

1. Development of a restrike switch model for producing restrike waveform signatures from measured restrike waveform signatures
2. Development of a restrike diagnostic algorithm to detect restrikes on the basis of features extraction from restrike waveform signatures
3. Model applications development for the restrike switch model (presented in the next chapter)
4. Parameter determination and model calibration from the experiments to verify the developed restrike switch model (presented in Chapter 5)
5. Development of a restrike detection algorithm using Wavelet Transforms (presented in next chapter) and recommendation of a non-intrusive measurement using a wide bandwidth antenna for field diagnosis of individual CB.
Chapter 4: Restrike Switch Model Applications and Detection Algorithm Development

The analysis of power systems is more difficult nowadays because of the use of advanced technology for control and monitoring. Therefore, we are obliged to know the complicated transient phenomena from nanoseconds to several seconds, or even minutes. The best way to understand the restrike phenomenon is through real experiments and field experience, but this is costly and impractical to implement in real life for medium and high voltage power networks. The restrike switch model applications in this study used computer simulations as virtual experiments, including predicting breaker restrikes, estimating the interrupter remaining life of SF₆ puffer CBs and vacuum CBs, checking system stresses, assessing point-on-wave (POW) operations, and developing a restrike detection algorithm using Wavelet Transforms. In order to provide examples of the practicality of the proposed methodology, simulation case studies are investigated for the restrike switch model applications development. The next is illustrated with a restrike detection algorithm development for signal processing, feature extraction and database applications using Wavelet Transforms. The restrike switch model applications development are presented in five sections in this chapter, as shown in Figure 4.1.
Figure 4.1. A restrike switch model application and detection algorithm development

4.1 Modeling of restriking and re-ignition phenomena in three-phase capacitor and shunt reactor switching

Capacitor banks and shunt reactors are frequently switched by CBs in MV and HV electricity networks. In recent years, there have been explosive failures due to CB restriking and re-ignition; consequently, there is a need for monitoring techniques that will facilitate the identification and quantification of the onset of more severe restriking. Whilst there have been detailed analyses of single-phase shunt reactor and capacitor bank switching, there is a paucity of information about restriking phenomenon and re-ignition in three-phase circuits for the correlation of system problems with specific waveform characteristics to develop the necessary detection algorithms for proactive monitoring of CBs’ condition.

This section describes the modeling restriking and re-ignition occurring during three-phase capacitor bank and shunt reactor switching, using ATP and network data from AS 4372-1996. Information from the ATP models and data resulting from the simulations are examined with a view to developing an intelligent diagnostic system.
Chapter 4: Restrike Switch Model and Detection Algorithm Development

with logging and alarm features. This modeling method can be easily applied with different data from the different dielectric curves, CBs and networks.

4.1.1 Introduction

Capacitor banks and shunt reactors are frequently switched in MV and HV electricity networks, since their connection to the networks is essential for reactive compensation reasons, improving the power quality locally. In this section, the possibly prejudicial phenomena caused by the switching of capacitor banks and shunt reactors are presented with the modeling of restriking and re-ignition occurring during three-phase capacitor bank and shunt reactor bank switching, using the ATP. Information from the ATP models and data resulting from the simulations are examined with a view to developing an intelligent diagnostic system with logging and alarming features for CB online monitoring.

The remaining subsection of this studies are: Subsection 4.1.2 which provides the ATP simulation results, comparing these with the formulas; Subsection 4.1.3 which presents the methodology and applications; Subsection 4.1.4 which is devoted to discussion; and Subsection 4.1.5 which presents the conclusions.

4.1.2 Capacitor bank switching modeling

4.1.2.1 Single-phase capacitor switching without and with restrikes

Sample system parameters used in ATP simulation studies are as follows:

![Figure 4.2. Capacitor bank single-phase equivalent circuit](image)

[96]
Chapter 4: Restrike Switch Model and Detection Algorithm Development

Figure 4.2 shows a single-phase equivalent circuit for a capacitor bank which is simulated using the ATP on a single-phase and also a three-phase grounded capacitor bank switching circuit, as shown in Figure 4.3.

![Figure 4.3. Single-phase equivalent circuit](image)

In this subsection, a 5 MVar capacitor bank 11 kV bus at a zone substation with a 150 MVA fault level with a load of 10 MVA @0.9 p.f. lag was studied. The major circuit parameters are:

- Source resistance \( R_1 = 0.05 \, \Omega \), inductance \( X_1 = 0.665 \, \Omega \) or \( L_1 = 2.11676 \, \text{mH} \) at 50Hz
- Damping resistance = 100 \( \Omega \) provides damping source transient
- Bus stray shunt capacitance \( C_1 = 2.63 \, \text{nF} \)
- Shunt capacitance to ground \( C_2 = 63.662 \, \text{nF} \) or 5 MVar capacitor bank
- High resistances around switch to damp numerical oscillations 10000 \( \Omega \)
- Discharge resistor \( R_2 = 1000 \, \Omega \)

Restriking: a second switch is added in parallel to the original switch (using low value resistors) and set up such that the first switch is closed at the start of the simulation, and opens at 20 ms. Such an arrangement de-energises the capacitor. The second switch is set up as a flashover switch (i.e., a voltage controlled switch) so that flashover occurs when the voltage across it reaches 13.472 kV or 1.5 p.u. It was noted that the original switch opening was set at 0.02 second and the second switch closing was set at 0.03 second for closing operation; both switch opening and switch opening with restrikes were set at 0.02 second. For simulation of opening restrikes, the time delay was 0.0008 second for trapped charge, whereas for both the time delay for capacitance switching on closing and opening, the time delay was 20 seconds for
no trapped charge. Other CB models such as dielectric recovery and arc resistance may be applied.

*Phenomenon:* As can be seen from Figure 4.4, current in the capacitor is interrupted at a negative-going current zero at 20 ms. High frequency current occurs after a single restrike at about 30 ms. This interruption leaves a d.c. voltage on the capacitor bank and results in a voltage with a d.c. and a.c. component appearing across the CB with a single restrike. Multiple restrikes are obtained to adjust the current in the capacitor, which is interrupted at a negative-going current zero at 10 ms.

\[
\text{TRV oscillating frequency } f = \frac{1}{2\pi \sqrt{(L_1 C_1)}} \quad (4.1)
\]

\[
\text{Inrush current } I_{\text{peak}} = \frac{V_{\text{peak}}}{L_1 \sqrt{C_2}} \quad (4.2)
\]

Using Equation (4.1), the bus-bar capacitance \( C_1 \) is calculated with source inductor \( L_1 \), and the TRV oscillating frequency \( f_0 \) ranges from 10 kHz to 50 MHz [97] for restrike overvoltages. Transient Recovery Voltage (TRV) is relevant for the small amplitude oscillation occurring on the supply side of the CB when the CB
Chapter 4: Restrike Switch Model and Detection Algorithm Development

opens. High frequency current occurs after the end of the restrike voltage. The computer simulations, as per Table 4.1 and Table 4.2, produce very similar waveforms in good agreement with the measured waveforms from the literature, such as a capacitor bank energisation and shunt reactor switching given in references [98] and [99]. The same are also validated using the formulae.

Table 4.1. The comparison of using the formulae and computer simulation for grounded capacitor bank

<table>
<thead>
<tr>
<th>Method</th>
<th>Inrush Current (A)</th>
<th>Oscillation Frequency (Hz)</th>
<th>Transient Recovery Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using the formulae given in (4.1), (4.2) and [100]</td>
<td>50</td>
<td>275</td>
<td>18</td>
</tr>
<tr>
<td>ATP Computer Simulation</td>
<td>38</td>
<td>300</td>
<td>13</td>
</tr>
<tr>
<td>% discrepancy</td>
<td>24</td>
<td>9.1</td>
<td>27.7</td>
</tr>
</tbody>
</table>

4.1.2.2 Three-phase capacitor switching without and with restrikes

The following circuit is simulated using the ATPDRAW program on a three-phase capacitor switching circuit for grounded and ungrounded situations. Figure 4.5 and Figure 4.6 show the equivalent circuit for this capacitor bank. Both examples are based on typical values from [101].

Figure 4.5. ATPDRAW diagram for grounded capacitor bank switching example

Case studies of restrike phenomenon are derived from various simulations of balanced and unbalanced three-phase circuits for capacitor bank model. These case studies cover a range of various pole-opening sequences. The three-phase circuit shown in Figure 4.6 was modeled using ATP. This network consists of a CB
switching an isolated capacitor bank with various supply impedances and various sizes of the shunt capacitor banks.

![ATP DRAW diagram for ungrounded capacitor bank switching example](image-url)

The zero sequence impedance of a lumped capacitor is the same as the positive sequence impedance; i.e., unearthed capacitor bank $C_0=C_1$, where $C_0$ is zero sequence capacitive reactance and $C_1$ is positive sequence capacitive reactance if unearthed $Z_0$ is infinite.

**Case A: Various pole-opening sequences for three-phase restrikes**

Figures 4.7 and 4.8 show the equivalent circuit for this three-phase capacitor bank switching and its phasor diagram. During the restrike period, the change in the potential of the capacitors will be $\sqrt{3}V_p/2$. ($V_p$ is defined as peak voltage). If Phases B and C interrupt at the restrike time, the voltage will be trapped on the capacitors. The voltage at N will be $0.5V_p$ and the maximum phase voltages will be as follows:

**Phase A:** $2.5V_p$ occurring $90^\circ$ after Phases B and C clear and every $360^\circ$ thereafter.

**Phase B:** $(1+\sqrt{3}/2)V_p$ occurring $210^\circ$ after Phases B and C clear and every $360^\circ$ thereafter.

**Phase C:** $(1+\sqrt{3}/2)V_P$ occurring $150^\circ$ after Phases B and C clear and every $360^\circ$ thereafter.
If Phases B and C do not interrupt 90° after Phase A as assumed above, this can lead to a higher voltage. The voltages across Phase A contacts will be $3V_P$ at 180° after Pole A interrupts if Phases B and C have not cleared. If Phase A restrikes when its voltage approaches $2.5V_P$, the behaviour of the circuit is similar to that of the single-phase restrike. A transient oscillatory current will flow between the source and the capacitor bank. The frequency of the current will be $\frac{1}{2\pi\sqrt{(LC)}}$ where $C_1 = C_N + C_A \approx C_N$ (if $C_A >> C_N$):

$$f_0 = \frac{1}{2\pi\sqrt{(LC)}}$$

For a three-phase circuit, the magnitude of the First-Pole-To-Clear power frequency recovery voltage and TRV has increased above the single-phase value by coupling from other phases. The TRV for a three-phase ungrounded fault is calculated as follows:

Three-phase unbalanced fault = $1.5V_F[(1 - \cos[t/\sqrt{(LC)})]$

The First-Pole-To-Clear Factor is 1.5 for a three-phase ungrounded fault, while for an effectively grounded network, the First-Pole-To-Clear Factor is 1.3.
The simulation involves two stages: 
stage 1 simulates the interruption of pole A of a three-phase CB, followed by a restrike which is then cleared. 
stage 2 simulates poles B and C clearing after pole A has cleared. 

In stage 1, the phase A CB was opened while phase B and C CBs remained closed. The voltages across the CBs and capacitors were simulated. When pole A is interrupted, the capacitor bank is charged at 1 \( V_p \) volts, and this voltage is trapped on the capacitor bank. Pole A of the CB restrikes at the next voltage peak and this sudden switching causes the capacitor bank voltage to change rapidly. A high transient current inrush will flow in the circuit, producing a high oscillating voltage or TRV. If the CB is able to clear at the next current zero, a voltage of 2 \( V_p \) volts will be trapped across the capacitor bank, as shown in Figure 4.9. 

When pole A interrupts, the disconnection of the phase A circuit results in an unsymmetrical circuit that consists of phases B and C. The voltage across the capacitor bank \( C_A \) will be equal and opposite in phase, as shown in Figure 4.9, Figure 4.10 and Figure 4.11. 

![Figure 4.9. Voltage waveforms across CB CA, simulating Pole A restrikes](file Ex3A1_20_081.pl4; x-var t)
Stage 2 simulates the phenomenon of Poles B and C clearing after Pole A has cleared. The voltage waveforms across $C_A$ for Phases B and C are equal and opposite in phase, as shown in Figure 4.12, Figure 4.13 and Figure 4.14. If after Pole A had
cleared, and at the next current zero of Phases B and C, both poles successfully interrupted, the charges remaining in both Phases B and C capacitor bank were approximately $3 \, V_p$.

Figure 4.12. Voltage waveforms across CB, simulating Pole B and C restrikes

Figure 4.13. Voltage waveforms across Capacitor Banks B and C, simulating Pole B and C restrikes
Chapter 4: Restrike Switch Model and Detection Algorithm Development

The circuit in Figure 4.8 was modified to see what would happen if only one pole of the CB restrikes. The resulting waveforms are shown in Figure 4.12. There is no permanent increase in voltage, since no path exists for the high frequency oscillation current. This high frequency oscillation current is caused by the closing of the CB (See Example 3 of the notes [101]). This oscillation also causes the fast charging of the capacitor (Note that delta T has been decreased to allow for these high frequency oscillations). This is referred to as ‘the ATP time step’. If the second pole also restrikes, a decent path exists for the high frequency oscillation current, and if the CB switches off after an odd number of oscillations, what will result is a much higher voltage across the capacitor bank than existed before the restrike.

The general conclusion from these simulations is that various pole sequencings can produce voltage escalation in the three-phase circuit.

4.1.2.3 Shunt reactor switching
4.1.2.3.1 Simulation in a single-phase circuit

Below is the circuit (in Figure 4.15), and the circuit data (in Table 4.2).
Supply voltage = 400 kV  
Fault level 25 kA,  
Short circuit impedance = \( \frac{400 \times 10^3}{\sqrt{3}} / 25 \times 10^3 = 9.23 \Omega = 0.0577 \)  

Table 4.2. Circuit data

<table>
<thead>
<tr>
<th>( L_n, C_n, R_n )</th>
<th>R[Ω]</th>
<th>L[mH]</th>
<th>C[μF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>14.7</td>
<td>0.04 ± 0.01</td>
<td></td>
</tr>
<tr>
<td>( R_s, L_s, C_s )</td>
<td>100</td>
<td>0.05</td>
<td>400E-6</td>
</tr>
<tr>
<td>( R_b, L_b, C_b )</td>
<td>2</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>( R_{L1}, L_{L1}, C_L )</td>
<td>10000</td>
<td>2550</td>
<td>0.0019</td>
</tr>
</tbody>
</table>

Note: Supply data refers to AS 62271.110-2006

CB data refers to Ref. [4]

Base 1000 MVA,

Base impedance, \( \Omega = \frac{1}{160} \)

The revised circuit data is shown in Table 4.3 below:
Table 4.3. Revised circuit data

<table>
<thead>
<tr>
<th></th>
<th>R[p.u.]</th>
<th>L[p.u.]</th>
<th>C[p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_mC_mR_m$</td>
<td>0.625</td>
<td>0.0577</td>
<td>4800</td>
</tr>
<tr>
<td>$R_sL_sC_s$</td>
<td>0.625</td>
<td>9.8125E-7</td>
<td>49.06</td>
</tr>
<tr>
<td>$R_bL_bC_b$</td>
<td>0.0125</td>
<td>1.9625E-4</td>
<td>123031</td>
</tr>
<tr>
<td>$R_LL_mC_L$</td>
<td>62.5</td>
<td>5.016</td>
<td>23320</td>
</tr>
</tbody>
</table>

**CB switch models:** the MODEL language in ATP with the TACS switch was used to realise an accumulator and logic operators for the re-ignition control; where the recovery voltage is larger than the dielectric recovery voltage after the current chopping, a voltage comparator is subsequently applied. Dielectric re-ignition is produced by breakdown of the open gap in a CB operation. In practice, this is due to the cooling of the hot gases between the two contacts of the CB until it results in a dielectric re-ignition are of the type shown in Figure 4.16.

![Graph showing single re-ignition across CB](image-url)
Depending on the re-ignition delay, higher values were reached by a higher rate of the rising of the recovery voltage. Flashover in hot gas between the zero interruption current causes re-ignition current for the single-phase case. The multiple re-ignitions are obtained from the appropriate dielectric curve gradient, as shown in Figure 4.17.

**Simulation results and verification:** The ATP model described above has been verified using the formulae, with the following results (Table 4.4):
Table 4.4. Comparison of calculated and simulated phase-to-ground overvoltages and frequency [99]

<table>
<thead>
<tr>
<th></th>
<th>Phase-to-ground overvoltage* (kV)</th>
<th>Frequency* (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATP simulation</td>
<td>320</td>
<td>28</td>
</tr>
<tr>
<td>Using the formulae</td>
<td>350</td>
<td>29</td>
</tr>
<tr>
<td>given in [103]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% discrepancy</td>
<td>11.8</td>
<td>3.5</td>
</tr>
</tbody>
</table>

*The data refer to the first interruption phase

4.1.2.3.2 Simulation in a three-phase circuit

There are different parameters for the shunt reactor model simulation, depending on different types of CBs, such as vacuum CB, chopping current calculated by Smeets [104], the dielectric strength of the breaker gap [4], and the contact separation. The dielectric strength gap or the contact separation depends on the rate of the rise of the recovery voltage, which occurs to the opening contact-system. This varies with the help of the ATP statistic switch.

A three-phase equivalent circuit with Dielectric Strength Reset Model used in the ATP is given in Figure 4.18. The installation includes the shunt reactor bank (consisting of three 120 MVAr single-phase reactors).

![Figure 4.18. Shunt reactor switching](99)
By adjusting the gradient of the dielectric curve, single and multiple re-ignitions were obtained (as per Table 4.5) for single-phase shunt reactor switching. With the help of a random generator in ATP, numbers in the interval [0, 1] were defined for the scattering process like chopping current, re-ignitions and the characteristics of the recovery voltage. Three-phase with statistical switching case using formula for ATP programming is taken from Abramowitz and Seguin’s Handbook of Mathematical Functions (Formula 26.2.23, p.933). A three-phase equivalent circuit with Dielectric Reset Model (used in Figure 4.16) and three-phase waveforms are shown in Figure 4.19 and Figure 4.20.

An example of an obvious feature is observed below:

![Figure 4.19. Voltage waveform for Phase B voltage interruption of reactor switching](image1)

![Figure 4.20. Virtual current chopping feature for Phase B current interruption of reactor switching](image2)

Virtual current chopping is caused by an interaction between two phases, A and C, and is dependent upon the capacitive coupling between the phases. The
computer simulations (as per Table 4.4) produce very similar waveforms in good agreement with the measured waveforms from the literature for shunt reactor switching [99]. These are also validated using the formulae.

4.1.3 Methodology and practical applications

In this computer simulation study, the voltage across the CBs of the capacitor banks and shunt reactors provide electrical waveform signatures. These voltage factors are important to characterize each type of circuit network, such as different types of switching transient such as CBs, networks and dielectric strength curve parameters. The results are:

- Three-phase voltage across CB voltage switch for capacitor bank switching and shunt reactor switching (Figure 4.9 to Figure 4.14, Figure 4.17 and Figure 4.18)
- Practical applications with electrical waveform signature analysis to identify different features for capacitor bank switching with Fourier Transform (Figure 4.19 and Figure 4.20).

The complexity of the classification cannot be fully explained in detail. However, some brief examples of electrical waveform signature analysis are given below. Figure 4.21 and Figure 4.22 show different signatures, such as single restrike and two restrikes for analysis of restriking waveforms. Power spectral density function (PSD) shows the strength of the variations (energy) as a function of frequency. This might be able to give a clue to the location of dielectric strength deterioration by looking at PSD, which would give frequencies of restriking/re-ignition.

The data from ATP simulations are applied in MATLAB, and the same simulated results from different conditions are used for a range of high voltage network conditions for the Self-Organising Map (SOM) training data. A dielectric strength deterioration index, k, is defined to measure the difference between the discrepancy/errors for severe restriking or re-ignitions and the discrepancy/errors for normal restriking or re-ignitions; this difference is used for a quantitative trend index for the CB condition.
Chapter 4: Restrike Switch Model and Detection Algorithm Development

(4.3)

Type 1: Single restrike for capacitor bank switching

![Single Restrike Analysis](image1)

Figure 4.21. Power special density plots show the strength of the single restrike (energy) as a function of frequency

Type 2: Two restrikes for capacitor bank switching

![Two Strikes Analysis](image2)

Figure 4.22. Power special density plots show the strength of the two restrikes (energy) as a function of frequency

4.1.2.4 Discussion

It is seen that the transient waveforms are different for network and dielectric strength parameters for capacitor bank switching and shunt reactor switching in power systems. This difference is characterised by a step change in the voltage, followed by an oscillation as the voltage across the CB equalizes within the system voltage. The oscillation occurs at the natural frequency of the capacitor with the inductance of the power system.

Virtual current chopping is caused by an interaction between two phases, A and C, and is dependent upon the capacitive coupling between the phases. Different
re-ignition results were obtained due to the dielectric strength with different statistical figures for ATP simulations, as shown in Figure 4.19 and Figure 4.20.

Other methods are Fourier and Wavelet analysis, which could be used to identify a different signature and distinguish it from other transient disturbance [105]. The modeling method can be readily applied to determining the features for restrikes and re-ignitions with adjustable parameters, as long as the network, dielectric strength curve and CB data are available. If these data are not available, alternative methods, such as field measurement, need to be used.

4.1.2.5 Conclusion

Based on the analysis of frequency range 10 kHz to 1 MHz for restrike overvoltages due to different source inductance and capacitance using Equation (4.1) for capacitor switching, and different dielectric strength gradient curves and the network data from [106] with different statistical figures for multiple re-ignitions, a simple parallel switch model is proposed for capacitor switching restrikes. A dielectric reset model to simulate multiple re-ignitions while taking statistical effects into consideration, and a framework for a taxonomy of electrical waveform signatures are also proposed. The proposed taxonomy can be used to develop an intelligent diagnostic system with logging and alarm features. It is envisaged that such a taxonomy would evolve continuously with future changes in network topology. Different virtual current chopping features for three-phase shunt reactor switching were obtained due to an interaction between two phases, A and C; this interaction is also dependent upon the capacitive coupling between the phases for ATP simulations.

The framework proposed here, however, forms the basis for individual CB signature and taxonomy study. Action research is being carried out to use Wavelet Analysis for features extraction. Although the overvoltage estimations of the capacitor bank switching and shunt reactor switching have been checked by formulae to confirm the validity of the ATP studies, many simulated scenarios are really required for the development of a database for on-line monitoring. The sensitivity analysis studies and the evaluation of the waveforms were not easy to implement without data from real utility scenarios.
4.2 A data-base of ATP simulated waveforms of shunt reactor switching cases with vacuum CBs on motor circuits

This section presents a database of ATP simulated waveforms for shunt reactor switching cases with vacuum breakers in motor circuits following interruption of the starting current. The targeted objective is to provide multiple re-ignition simulated data for diagnostic and prognostic algorithm development, but also to help ATP users with practical study cases and component data compilation for shunt reactor switching. This method can be easily applied with different data for the different dielectric curves of CBs and networks. This subsection presents design details and discusses some of the available cases and the advantages of such simulated data.

4.2.1 Introduction

High voltage motors are exposed to transient overvoltages during switching operations by vacuum CBs in power distribution systems; this leads to dielectric failures [95] due to multiple re-ignitions. The vacuum CBs are inclined to interrupt small inductive currents not in the natural current zero but rather to chop off the current. This current chopping causes a large time derivative of the current and, because of this inductive circuit, it appears that high overvoltages occur. The level of the overvoltages depends on parameters such as the elements of the electric circuit, the type of inductive load and the characteristic of the CB.

The results show that the variation in these parameters can produce significant differences in overvoltages magnitude for system switching transients [107]. The results also show the possibility of failure of motor insulation due to uneven voltage distribution in the motor winding, or possible vacuum CB failure. This offers opportunities for condition monitoring of system transients, extending a vacuum CB life, identifying impending failures, and identifying maintenance requirements as needed. Cost savings through deferred maintenance can reduce costly unplanned outages by identifying impending failures before they occur.

The main difficulty in developing the database of ATP simulated waveforms was the lack of certain important parameters of the elements of the system model, and the lack of a valid model of the termination impedance presented by the induction motor for an accurate overvoltage analysis. This subsection reports the
simulated transient waveforms following interruption of the starting current. The advantages of such simulated data are that they have been carried out using equivalent circuits which simulate various components of the system, using the Electromagnetic Transient Simulation (EMTDC) program, and the International Electrotechnical Commission (IEC) model of standard test circuit [108]. This also has been investigated for validity by performing laboratory tests for a relatively severe case.

This subsection aims to demonstrate how switch features can estimate remaining life in motor insulation and vacuum CBs by evaluating the risk of damage due to overvoltages arising from multiple re-ignition and surge impedance. A database of ATP simulated waveforms of shunt reactor switching cases with vacuum CBs on motor circuit and the restriking features of the waveforms are presented to test a new detection measurement technique for a single-phase restrike breakering using a vacuum CB at Ergon Laboratory.

4.2.2 Motor circuit for overvoltage determination

Figure 4.23 represents the structure of a relatively severe case with respect to overvoltages and will cover the majority of service applications. Values of circuit parameters are shown in Table 4.5[107].

![Figure 4.23. Three-phase equivalent circuit of cable connected motor system AS/IEC 62271-110 circuit](Image)
Chapter 4: Restrike Switch Model and Detection Algorithm Development

Table 4.5. Parameters of 6.6 kV motor circuits [107]

<table>
<thead>
<tr>
<th>Load Circuit</th>
<th>Freq (kHz)</th>
<th>R(Ω)</th>
<th>L(mH)</th>
<th>C_p(nF)</th>
<th>Zo(kΩ)</th>
<th>Is(A)</th>
<th>Rp(kΩ) η=1.6</th>
<th>Rp(kΩ) η=1.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>7.62</td>
<td>118.8</td>
<td>2.130</td>
<td>7.460</td>
<td>100</td>
<td>11.95</td>
<td>13.44</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>7.62</td>
<td>118.8</td>
<td>0.947</td>
<td>11.200</td>
<td>100</td>
<td>17.92</td>
<td>20.16</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>2.54</td>
<td>39.6</td>
<td>6.396</td>
<td>2.488</td>
<td>300</td>
<td>3.98</td>
<td>4.48</td>
</tr>
<tr>
<td>4</td>
<td>15</td>
<td>2.54</td>
<td>39.6</td>
<td>2.843</td>
<td>3.732</td>
<td>300</td>
<td>5.97</td>
<td>6.72</td>
</tr>
</tbody>
</table>

As shown in the above table, four load circuits are simulated, two for 100 A (at natural frequencies of 10 kHz and 15 kHz), and two for 300 A. The parameters of R, L, R_p, and C_p for different load conditions are simulated.

Modeling of the stochastic vacuum CB

![Figure 4.24. Signals between MODELS and ATP [4]](image)

A stochastic breaker model is based on a range of credible parameters, including statistical overvoltage studies (as stated in Ref.[1]). A simple switch model (Type 13) is used, and is controlled by means of a logic imposed in MODELS, simulating the multiple re-ignitions with the following values (taken from [4]) for ATP database simulated waveforms:

- Slope of recovery strength = 20 to 30 kV/ms
- Velocity of contacts = 1 to 5 m/s

125
Chapter 4: Restrike Switch Model and Detection Algorithm Development

- Gap distance = 3 to 5 mm
- Chopping current = 1 to 5 A
- Quenching capability = 60 to 100A/µs
- Phase angle displacement = 0° to 359° with 1° interval.

With the help of a random generator in ATP, numbers in the interval [0 to 1] were defined. With random numbers, the value of the desired standard-deviation of the inverse error function (inverf(x))[109], [110], the chopping current and re-ignition are calculated taking statistical scatter into consideration. This models stochastic behaviour of the dielectric breakdown. By feeding the models a realistic string of simulated data, a reasonable confidence is gained in the real-world situation showing a similar behaviour to the real-world input data. This holds only if the presumed independence and Gaussian assumptions are true. The confidence can be increased with the results being compared with measurements from experiments.

4.2.3 Framework of the simulation

TRV is the voltage across the opening contacts of an opening CB immediately after the arc is extinguished. The actual shape of the transient is determined by the connected lumped and distributed inductive and capacitive parameters defined by the equipment connected. For successful interruption, the breakdown voltage of the interruption medium must always exceed the recovery voltage. If the TRV peak value is above the breaker rating, the increasing TRV across the gap will restrike the arc and break down the interruption medium. Checking the dielectric condition and the wear of the arcing contacts will give important information regarding the dielectric withstand of the CB.

The probability of occurrence of re-ignitions is related to the slope of the recovery voltage strength between contacts and with the TRV. Figure 4.25 shows an example where the re-ignition will occur if the arc time – that is, the time between mechanical separations of the contacts and the instant of current chopping – is less than 0.8 ms approximately. It also shows the slope of the recovery voltage strength considered in this simulation and the TRV between contacts of the vacuum breaker when the starting current of the motor is interrupted, obtained with the assumed values of the dielectric parameters and the digital model.
Chapter 4: Restrike Switch Model and Detection Algorithm Development

Figure 4.25. Slope of recovery dielectric strength and TRV between arcing contacts

The overall framework of the developed software simulation package is an
interactive structure using MATLAB and ATP, as shown in Figure 4.26.

MATLAB

Motor Circuit Models

Circuit Configuration Settings

Restriking Scenarios Settings:
Without restriking scenarios settings

Database (mat)

Signal Processing

Diagnostic & Prognostic Algorithm

Motor Risk of failure Results

ATP

Modelling in ATPdraw (.adp)

Modified ATP input file (motor.atp)

Template ATP input file (.atp)

Transient Data (.mat)

Figure 4.26. Database development for diagnostic and prognostic algorithm framework

MATLAB is a widely used general purpose modeling and simulation tool and
ATP is a free version of EMTP. The existing ATP software does not have the
capability to automatically generate the scenarios in a batch. This is very
inconvenient in studies that require simulation of thousands of scenarios. MATLAB
is a powerful programming and simulation software system. It can be used to
implement flexible control of the ATP simulation and interface used to produce simulated waveform data. The entire software consists of two parts: simulation of motor circuits and database production. In the part devoted to simulation of motor circuits, the motor circuit is built in ATPDRAW, as shown in Figure 4.27, with data shown in Table 4.6.

![ATP DRAW Diagram](image)

**Figure 4.27.** ATPDRAW for the motor circuit

**Table 4.6.** Circuit parameters as per AS 62271.110

<table>
<thead>
<tr>
<th>Circuit Parameters</th>
<th>Supply Circuit A</th>
<th>Supply Circuit B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source voltage</strong></td>
<td>6.6 kV</td>
<td>6.6 kV</td>
</tr>
<tr>
<td><strong>Starting current</strong></td>
<td>100 A</td>
<td>100 A</td>
</tr>
<tr>
<td><strong>Power factor</strong></td>
<td>≤ 0.2</td>
<td>≤ 0.2</td>
</tr>
<tr>
<td><strong>Supply capacitance</strong></td>
<td>0.044 µF</td>
<td>1.6 µF</td>
</tr>
<tr>
<td><strong>Related power of short circuit source</strong></td>
<td>20 MVA</td>
<td>20 MVA</td>
</tr>
<tr>
<td><strong>Bus inductance</strong></td>
<td>2 µH</td>
<td>2 µH</td>
</tr>
</tbody>
</table>
A template .atp file without any events is then generated, as shown in Figure 4.28.

The system components and their parameters are set in MATLAB. The user defines motor scenarios through the interface in MATLAB. For each scenario, the MATLAB program will load the template .atp file and create a temporary file by modifying the settings of the template .atp file. After ATP is executed, the transient waveforms for each scenario are then produced for simulated database development.
When applied to different motor circuits, the software only needs to rebuild the ATP template and update the system configuration settings in MATLAB. The other parts need not be changed. The steps are:

1. **General Settings**: Supply data, motor circuits, and parameters.
2. **Data Input**: Load the source data file, which is generated by simulation of the power systems, into MATLAB program.
3. **Data Extraction**: According to the requirement of the algorithm, extract the useful data from the source data file for ATP database simulated waveforms.

### 4.2.4 Simulation and results

Based on heuristics gained through Dr. David Birtwhistle’s many years of experience and practice, the restrikes can be measured from the phase-to-ground voltages on both sides of a CB against time. The measure is to determine the peak voltage buildup from the restrikes and to identify which pole is restriking from these motor starting operations. Other restriking features are power spectral density (PSD), the numbers of the restriking (NOR) pulses, and the restriking time duration (RTD) of the pulses. PSD is used for the fixed frequency 10 kHz and 15 kHz and the time duration of the impulse magnitude for the motor circuits. From this practice, each phase overvoltage magnitude and the restriking features from different modes of reignition waveforms were obtained with ATP and MATLAB program computation, including virtual chopping and voltage escalation, as shown in Table 4.7 and Table 4.8 below.
Table 4.7. Peak voltage buildup for detecting restrikes

<table>
<thead>
<tr>
<th>Simulation condition</th>
<th>Frequency of high frequency current (kHz)</th>
<th>Time (ms) to reach peak voltage A, B and C</th>
<th>Peak voltage buildup-phase A, B and C to ground (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11A</td>
<td>10</td>
<td>21, 18, 24</td>
<td>9.5, 9.8, 9.0</td>
</tr>
<tr>
<td>12A</td>
<td>15</td>
<td>21, 18, 24</td>
<td>8.7, 10, 6.5</td>
</tr>
<tr>
<td>21A</td>
<td>10</td>
<td>21, 18, 24</td>
<td>9, 10, 6.3</td>
</tr>
<tr>
<td>22A</td>
<td>15</td>
<td>21, 18, 24</td>
<td>10, 8.2, 6.2</td>
</tr>
<tr>
<td>11B</td>
<td>10</td>
<td>21, 18, 24</td>
<td>9.0, 10.0, 8.0</td>
</tr>
<tr>
<td>12B</td>
<td>15</td>
<td>21, 18, 24</td>
<td>11.3, 10.0, 8.0</td>
</tr>
<tr>
<td>21B</td>
<td>10</td>
<td>21, 18, 24</td>
<td>9.3, 9.5, 9.0</td>
</tr>
<tr>
<td>22B</td>
<td>15</td>
<td>21, 18, 24</td>
<td>10.9, 8.9, 8.9</td>
</tr>
</tbody>
</table>

ATP computation was carried out as follows:

1) Re-ignition at the crest value of TRV, or re-ignition was simulated.
2) The high frequency re-ignition current is greatly affected by the capacitance of the device coupled to the power supply side of the CB for switching the motor, as shown in Table 4.6 for Supply Circuits A & B. Thus, their values were varied in computation.
3) The level of surge voltage to ground was also computed to identify the occurrence of restrikes.
Table 4.8. Power spectral density indicating the wear

<table>
<thead>
<tr>
<th>Simulation with Peak Phases A, B and C Voltage (kV)</th>
<th>NOR (Nos.) for Phases A, B, C</th>
<th>RTD (ms) for Phases A, B, C</th>
<th>Average Power Spectral Density (PSD) via Welch x10^7 for Phases Current A, B, C</th>
</tr>
</thead>
<tbody>
<tr>
<td>9, 10, 6.3</td>
<td>5, 3, 3</td>
<td>0.019, 0.015, 0.015</td>
<td>2.3193, 2.1994, 2.1994</td>
</tr>
<tr>
<td>10, 8.2, 6.2</td>
<td>3, 0, 26</td>
<td>0.016, 0, 0.0021</td>
<td>1.636, 2.3944, 1.0911</td>
</tr>
<tr>
<td>10.3, 9.4, 8.5</td>
<td>9, 8, 6</td>
<td>0.0023, 0.0019, 0.0035</td>
<td>2.6767, 2.0033, 1.603</td>
</tr>
<tr>
<td>9.4, 8.9, 6.4</td>
<td>3, 4, 8</td>
<td>0.0017, 0.0026, 0.0035</td>
<td>2.1253, 1.8041, 1.1019</td>
</tr>
<tr>
<td>9, 10, 8</td>
<td>3, 4, 6</td>
<td>0.0016, 0.00073, 0.0032</td>
<td>1.9886, 2.3878, 1.4437</td>
</tr>
<tr>
<td>11.3, 10, 8</td>
<td>4, 2, 6</td>
<td>0.004, 0.00014, 0.00032</td>
<td><strong>3.5773</strong>, 2.4374, 1.4298</td>
</tr>
<tr>
<td>9.3, 9.5, 9.0</td>
<td>6, 4, 7</td>
<td>0.0024, 0.0018, 0.0037</td>
<td>2.2329, 2.1098, 1.8368</td>
</tr>
<tr>
<td>10.9, 8.9, 8.9</td>
<td>4, 7, 10</td>
<td>0.0020, 0.0022, 0.0036</td>
<td>2.0934, 1.797, 1.758</td>
</tr>
</tbody>
</table>

For surge voltages upon current chopping, the results in Table 4.9 show the relative PDF increase, indicating a maximum high-frequency surge voltages of around 11.3 kV. This will threaten the insulation of the CB and the motor, as shown in Figure 4.29, Figure 4.30 and Figure 4.31.
As it is very difficult to record multiple re-ignition of the high frequency switch across the vacuum CB and the motor terminal, ATP was used to simulate the multiple re-ignitions. In the common case, when a motor is operated directly by the vacuum CB, the occurrence of multiple re-ignitions when breaking the starting current can produce high frequency overvoltages that stress the inter turn insulation.
of the motor, as shown in Figure 4.31. Note that the model does not correctly describe the motor flux decay so post break voltages will not be fully correct.

In order to compare the ATP computation on restriking switch features against the switch features obtained from another new restrike detection technique, measurement was carried out using both the broadband active antenna and capacitive coupling passive antenna at Ergon (Virginia, Queensland, Australia). Measurement was done using two oscilloscopes; hence, there are two types of data: Captured waveforms from the first scope (Agilent 54624) and binary data from the second scope (Yokogawa DL9240).

Restrikes measured by CH1, CH2 and CH3 are similar in frequency and pattern, but have variation in terms of magnitude. The restrikes measured results for Figure 4.32 and Figure 4.33 are similar to Figure 4.30 and Figure 4.31. Both voltage and current switch are matched for both laboratory measurement and ATP simulation. For clearer relations to be identified between the voltages measured and the ATP determinations, faster sweep velocity instruments are required to record the high-frequency results. Analysis of high frequency detected by the active antenna on opening can validate the power supply angle for number of restrikes, and the restriking time duration against the average power spectral density via Welch coefficient for the wear of the CB.

The captured waveforms are in .bmp format and consist of passive antenna and active waveforms, supply side voltage and load side voltage. The recorded waveforms are given below.

Background
Switching tests on reactor circuit at Ergon Laboratory.
Agilent Oscilloscope
CH1 – Passive/Active Antenna  CH2 – Supply Side Voltage  CH3 – Load side Voltage  CH4 – HF Earth current
1 – Without capacitor installed at the load side to reduce oscillation on supply side.
Opening at 3kV – Print 00,01
Whenever a switching operation is determined to be abnormal, such as slow opening of a vacuum CB, over-voltages waveforms are obtained with ATP suitable for engineering analysis. As the abnormal opening is of necessity being best diagnosed by a signal processing technique with MATLAB program computation, a set of feature vectors – including numbers of restrikes (NOR), as shown in Figure 4.34, restriking time duration (RTD), as shown in Figure 4.35, and power spectral density (PSD), via Welch coefficient of the impulse magnitude, as shown in Figure 4.36 – characterize the deterioration of a CB. More accurate results were shown, taking into consideration different power supply angles for the PSD. Examples of the results are as follows:
One approach to determining remaining life is to compare PSD that indicates deterioration. Remaining life is estimated by comparing the worst case stress on the CBs with AS/IEC 62271.110-2005 circuit. Cumulative data includes averages and extreme values from simulated data against actual insulation and the number of start and stop operations. The database is used to determine the statistical significance of any changes in dielectric stress, expressed in terms of percentage of remaining life and the average number of switching operations over time. The electric wear is proposed to be expressed as a percentage of life times 100. For example, current operation resulting in 1% loss of life would be recorded as 1. If a trend is evident, accurate prediction is proposed for further work on the statistical analysis with an expert system or neural network for decision making procedures. If no trend is evident, it will be necessary to establish an acceptable bound or a baseline target on the basis of the latest simulated data against the actual insulation deterioration.

4.2.5 Conclusions

A database ATP of simulated waveforms with restriking features of shunt reactor switching cases using vacuum CBs on motor circuits was obtained with AS/IEC 62271.110-2005, as suggested by IEC. The restriking features are identified by ATP computation on peak voltage buildup, and the PSD signal processing
Chapter 4: Restrike Switch Model and Detection Algorithm Development

technique with MATLAB program. The features are identified by the number of restrikes, the restriking time duration and average power spectral density via Welch on the impulse magnitude, taking into consideration different power supply angles. These are especially useful in the database development where the worst case scenarios are calculated for the remaining life estimate.

An ATP MATLAB software simulation framework has been developed to produce database simulated data. Thousands of scenarios can be simulated at one time. The structure of the software benefits from both the programming flexibility of MATLAB and the simulation efficiency of ATP. Both the restriking voltage and current waveform were matched for both the laboratory measurement and the ATP simulation. The results can be further validated with faster sweep speed instruments in a laboratory measurement. The sensitivity analysis has been included for the restriking features due to the variations in the power supply angle. This will be used for future work in diagnostic and prognostic algorithms development with the expert system or neural network for recognition of results. A real case study of the statistical overvoltages and risk-of-failure resulting from switching of an induction motor by a vacuum CB is proposed to validate the developed diagnostic and prognostic algorithms.

4.3 Mayr’s arc equation for SF$_6$ CB degradation and its remaining life prediction from restrike waveform signatures

Failure of SF$_6$ puffer CBs during shunt reactor switching has been reported [111] and the high-frequency re-ignition currents cause ‘parasitic arcing’ in the CB nozzle. This phenomenon leads to gradual deterioration of the nozzle that may eventually result in a puncture of the nozzle material and failure of the interrupter [112].

For a majority of CBs in service, the POW of contact opening or closing is a random operation, and transient simulation is initiated because the process under study is complex and it is necessary to simulate the worst-case scenario for estimating the remaining life of the SF$_6$ CBs. The modeling process using the ATP-EMTP software package is therefore proposed to confirm this with site measurement waveforms. The “preventive switching” strategy is performed at the modeling level
Chapter 4: Restrike Switch Model and Detection Algorithm Development

by using computer simulation-based observations of the CB’s behaviour. To assess the behaviour of the SF₆ puffer CB, various scenarios – i) topology changes, ii) switching angle changes and iii) situations involving re-ignition/restrikes – are generated and studied using simulation results. By quantitative simulation of the CB behaviour for as many scenarios as possible as a database, the knowledge will be acquired and impending problems can be identified.

System voltages monitoring the magnitude and frequency of occurrence of system restrike currents over time, using on-line analysis and comparison with a values database, will be used as the diagnostic algorithm to determine the impending failure. High frequency current magnitude inference from ATP simulations with the prognostic algorithm will determine the remaining lifetime; this may result in an improved expectancy of the SF₆ puffer CBs to reduce their maintenance cost. These are the objectives of this subsection which presents modeling details and the research methodology for developing diagnostic and prognostic algorithms. The outcome of this subsection will be a new model for maintenance of CBs which will result in savings and prevention of electricity supply interruption.

4.3.1 Modeling of the SF₆ CB

There are two parts to the SF₆ puffer CB model: Mayr’s arc equation [118] and the CB model. The first part, Mayr’s arc equation[113], is as follows:

\[
\frac{dG}{dt} = \frac{G}{\tau} \left( \frac{P}{\theta} - 1 \right)
\]  

(4.12)

where 
- G- Arc conductivity
- \( \tau \) - Arc time constant
- P- Arc power loss
- \( \theta \) - Arc power

Typical values \( P = 4 \times 10^6 \) and \( \tau = 1.5 \times 10^{-6} \)

Using ATPDRAW, Mayr’s equation is simulated in a CB arc model and Dielectric Recovery model to determine the deterioration of a dielectric strength. The mathematical operation of an arc model is done by Transient Analysis of Control System (TACS) function, and feedback continuously operates in the simulated system. The modeling arc, the dynamic refreshing function, can get more precise simulation results. In this subsection, a CB arcing effect at the opening of the shunt
reactor is simulated by this model. The simulated results are compared with published results to evaluate the CB model. It is hoped that the measurement of voltage and current waveforms, with the MAYR arc model equation, and the voltage and current data can determine the deterioration of the dielectric strength with the equation parameters P and τ of the internal CB.

It is proposed to use the MODEL language in ATP-EMTP, co-ordinating with the TACS switch, to simulate the arc dynamics for Mayr’s nonlinear differential equation. In Figure 4.37, the states of the CB voltage and the arc current input to the Mayr’s model are shown. The arc conductance and the TACS switch states are then determined, and output to control the CB switch SW is shown. The time-controlled switch is to control zero current. The upper part is arcing time before zero current, and the lower part is post-zero current.

Figure 4.37. Schematic diagram of the proposed extended Mayr’s equation-based arc model, including ATP-EMTP TACS SW(Switch) control and dielectric recovery control unit for post-arc monitoring

Method

Refer to [114] where the CB model is using Transient Analysis of Control System (TACS) by taking off the voltage and current point of the network with Algebraic and Logical variables and Transfer functions.

Steps using ATPDRAW
Step 1: Take off the voltage with TYPE 90 and current signal level with TYPE 91
Step 2: Use TYPE 60 to determine if the current is zero or not; if the current is zero (i.e., pre-zero period), go to Step (A) to find resistance; if the current is not flowing through the circuit (i.e., post-zero period), go to Step (B) to find the resistance.
Step (A)
A1. Using TYPE 98 to calculate V=V1- V2; gj=I /|V|
A2. Using TYPE 98 to calculate \( P(g_j) \) and \( r(g_j) \)
A3. Using TYPE 58 to calculate Integral \( gj+1(GG) \)
A4. Using TYPE 98 to calculate \( Rj+1(RR) \)

Step (B)

B1. Using TYPE 98 to calculate \( V=V1-V2 \). For initial value, 0.05 \( \Omega \) is assumed due to the practical measurement value between 0.02 \( \Omega \) and 0.06 \( \Omega \)
B2. Using TYPE 98 to calculate \( P(g_j) \) and \( r(g_j) \)
B3. Using TYPE 58 to calculate Integral \( Rj+1(RR) \)

Step 3: using TYPE 98 to calculate the V arc, then using coupling to electric network for determination, as shown in Figure 4.38.

![Figure 4.38. Universal arc representation of modified Mayr’s model](image)

The following equations are used for the model:

\[
P(R) = P_0 \cdot \rho^\beta = 4E-6 \cdot g^{0.68}
\]
\[
\tau(R) = \tau_0 \cdot \rho^\beta = 1.5E-6 \cdot g^{0.17}
\]
Reset CNSA = \( (i(t) ** 2 / P(R) - G) / \tau(R) \)
Reset CNSV = \( (R - v(t) ** 2 / P(R) / \tau(R) \)

\[140\]
The second part is the CB model: the MODEL language in ATP with the TACS switch was used to realise an accumulator and logic operators for the re-ignition control, where the recovery voltage is larger than the dielectric recovery voltage after the current chopping; a voltage comparator is applied subsequently. A flow chart of the voltage comparator is given in Figure 4.39 below:

![Flowchart of the voltage comparator](image)

Figure 4.39. The flowchart of the voltage comparator

[113]

4.3.2 Summary of SF₆ breaker diagnostic and prognostic algorithms

The proposed SF₆ breaker diagnostic and prognostic algorithms are shown below in Table 4.9.
Table 4.9. Diagnostic and prognostic algorithms for SF6 breaker

<table>
<thead>
<tr>
<th>Features</th>
<th>SF&lt;sub&gt;6&lt;/sub&gt; puffer CB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of occurrence</td>
<td>Number of restrikes/re-ignition from the voltage switch by measuring phase to earth voltage</td>
</tr>
<tr>
<td>Amplitude</td>
<td>High frequency current magnitudes</td>
</tr>
<tr>
<td>Time</td>
<td>Time to breakdown i.e. current zero to re-ignition/restrike</td>
</tr>
<tr>
<td>Worn parts</td>
<td>SF&lt;sub&gt;6&lt;/sub&gt; gas contamination or particles &amp; Teflon nozzle &amp; contacts</td>
</tr>
<tr>
<td>Detection algorithms</td>
<td>Arc Power, Arc Time Constant and Conductivity Phase to earth voltage and the number of re-ignition/restrikes and frequency of occurrence of system restrike/re-ignition current over time</td>
</tr>
<tr>
<td>Statistical model</td>
<td>Dielectric strength variation on the basis of normal distribution for the breakdown voltage</td>
</tr>
</tbody>
</table>

1. The literature survey of parameters for modeling, such as parasitic capacitance and inductance to improve ATP simulation with parameters for ATP modeling, shows: $C_s=300 \text{ pF}$ and $L_s=5\times10^{-5} \text{ mH}$ to adjust the simulated waveforms for the actual site measurement waveforms as follows:

![Arc Voltage (kV) vs Time (µs) graph](image_url)

Figure 4.40. Simulated ATP switch (red in colour) and a field switch (blue in colour) waveforms [115]
Chapter 4: Restrike Switch Model and Detection Algorithm Development

Figure 4.41. Three-phase simulated circuit for site

Figure 4.42. Three-phase simulated re-ignition voltage

Figure 4.43. Three-phase simulated re-ignition current to predict I2t losses
Chapter 4: Restrike Switch Model and Detection Algorithm Development

2. Using ATP simulations, the high frequency current switch to predict losses [107, 116], the remaining life of a Teflon nozzle will be predicted $I^2t$ losses. It will be verified by physical observation of damage done to a Teflon nozzle, and wearout (mechanical strength) will be related to the nozzle’s remaining life.

3. To estimate the rate of degradation based on the envelope of the withstand dielectric curve, the following will be addressed:

   A. Estimation of the standard deviation to determine the statistical variation of dielectric strength (With the help of the Monte-carlo capability in Matlab, a program is determined to simulate the occurrence of each re-ignition/restrike.)
   
   B. Feeding of the data into an ATP model to produce a simulated database for on-line system voltage monitoring and restriking current (This will produce a prediction of the impending failure rate and a rate of electrical degradation against experimental measurements and site evaluation.)

4.4 A restrike switch model for shunt capacitor bank switching with POW assessments

Medium and high voltage CBs are subject to electrical stresses with restrikes during capacitor bank operation. Stresses are caused by the overvoltages across CBs, the interrupting currents and the rate of rise of recovery voltage (RRRV). Such electrical stresses also depend on the types of system grounding and the types of dielectric strength curves. The aim of this simulation study is to demonstrate a restrike switch model for a SF₆ CB that considers the types of system grounding (grounded and non-grounded), and the performance accuracy comparison on the application of the cold withstand dielectric strength and the hot recovery dielectric strength curve (including the POW assessments) to make a decision about the life extension of the interrupter.

The simulation of SF₆ CB stresses in a typical 400 kV system was undertaken and the results in the applications are presented. The simulated restrike waveforms produced with the identified features using Wavelet Transforms can be used for restrike diagnostic algorithm development to locate a substation with breaker restrikes. This study found that the hot withstand dielectric strength curve has less magnitude than the cold withstand dielectric strength curve for restrike simulation.
results. Computation accuracy improved with the hot withstand dielectric strength, and POW controlled switching can extend the interrupter life of a SF$_6$ CB.

4.4.1 Introduction

Ref. [117] reported that a controlled function that was employed for a reactor switching failed, and that repetitive re-ignitions caused compounding damage in the nozzle and the final punching which lead to the catastrophic failure. This was due to inadequate arcing time which resulted in high voltage transients and nuisance tripping, and indicated the current limitation of inaccurate POW controlled switching operation. Also, CBs are subject to electrical stresses with restrikes during capacitor bank operation such as no-load transmission lines, no-load cables, capacitor banks and chopping currents of reactors.

Breaker restrikes are unwanted occurrences and the practical means of obtaining the restrike waveforms is to use an analytical modeling of the power transient behaviour. After producing the restrike simulated waveforms with the restrike switch model and the network data using ATP-EMTP simulations, the identified features using wavelet transform can be used to locate a substation with breaker restrikes. The measured restrike waveforms in Ref. [8] can then be modeled with POW assessment to make a decision about the life extension of the interrupter. The motivation behind this section is to show the restrike switch model using ATPDRAW [118] for checking the relevant standard of compliance and producing restrike simulated switch for diagnostic purposes. It will demonstrate POW controlled switching for asset management application.

The dielectric strength recovery characteristics are inherent to the CBs, and the process of recovering dielectric strength is a cold recovery voltage known as the ‘cold withstand dielectric strength’. There has been little previous research on determining an accurate dynamic dielectric recovery characteristic suitable for the CBs under consideration in this previous research. To demonstrate the restrike switch model according to effects of grounding and the restrike computation accuracy comparison considering the cold withstand dielectric strength curve and the new hot dielectric strength curve, a simple power network model is established, including 750 kV source, cables, a capacitor bank 220 MVar 400 kV and a transmission line circuit. The capacitor bank is introduced in the network to simulate the stresses of capacitive
current and predict the rare occurrence of restrikes. POW controlled switching is shown to reduce the interrupted currents, thus achieving the life extension of a SF₆ interrupter.

4.4.2 Background theory

Capacitor banks are used to improve voltage regulation in a power network and reduce losses through reduction in reactive current. Before the capacitor is switched off, the capacitor bank is fully charged equal to the peak supply voltage. After half a cycle, the supply voltage is reversed, thus making the voltage across the CB twice the peak value of the supply voltage. When the CB is in a closed position, the load voltage is higher than the supply voltage. This leads to a voltage jump at supply side of the CB with a phenomenon called ‘Ferranti effect’. Energizing a single capacitor bank could generate inrush current with a high frequency, causing restriking with parasitic arcing during opening. This is due to the dielectric strength performance of the gap. This has been identified as a cause of CB failures under reactor switching application, using a single-interrupter SF₆ CB [119, 120]. Therefore, a similar effect is expected for capacitor bank switching and POW controlled switching applied to extend the maintenance interval of nozzle and contact [10].

Restriking in the interrupting device can greatly increase the recovery voltage values over those imposed on the switch if no restriking takes places [100]. The recovery voltage should comply with breaker rating specified by the requirements of IEEE Standard C37.04-1999 and IEEE Standard C37.09-1999 (Institute of Electrical and Electronics Engineers Standards Association, 1999a, 1999b). Table 5, Clause 4.107.3 of AS 62271.100:2005 (SAA) is applied in systems with a voltage above 400 kV to check the capacitive current magnitude.

4.4.3 Simulation models and cases

In order to demonstrate the applicability of the performance comparison for the cold and hot withstand dielectric curves and the POW recommendation resulting from the SF₆ CB operation, ATP-EMTP simulations were performed for a simple case of a transmission type 1600 kVA transformer (700/400 kV) switching to a 400 kV transmission network. The schematic diagram illustrating the case analysed is shown in Figure 4.44.
4.4.3.1 Specification and modeling of equipment

A simple power system is modeled using some examples from ATPDRAW manual 5.6 [118]. The system includes a transmission line connected to equivalent network through a switch.

The method of modeling a SF₆ CB’s behaviour as a dielectric reset switch is taken from the literature [22] and uses Equation 4.4, Figure F.1 (Cold dielectric strength curve for SF₆ CB) and Figure G15 (Hot dielectric strength curve for SF₆ CB) for computation.

For a single SF₆ puffer interrupter CB, the chopping current level \( i_{ch} \) is given by the equation
\[
  i_{ch} = \lambda \frac{C_t}{F} \tag{4.4}
\]

\( C_t \) is the total capacitance in parallel with the breaker (F) and \( \lambda \) is the chopping number for a single interrupter (\( \lambda F^{0.5} \)).

The transformer represented by ATP BCTRAN model and the surge capacitance utilized was tested at 0.06 \( \mu \)F, 0.022 \( \mu \)F and 0.01 \( \mu \)F. The busduct connections are \( L = 0.05 \) mH and \( C = 0.0026 \) \( \mu \)F. The source impedances are \( R = 2 \) \( \Omega \).
and \( L = 63.7 \) mH and the damping resistor \( R = 200 \) Ω The connection between the source and the transformer was modeled as a short (100m) cable of a transmission line, and outgoing overhead transmission lines have been modeled with the frequency dependent distributed parameter model JMARTI, allowing analysis of the effects of the travelling voltage wave along the transmission line.

### 4.4.3.2 Simulation cases

In order to simulate stresses of a \( \text{SF}_6 \) CB, a restrike switch model with a dielectric reset switch using the hot withstand dielectric strength curve and the cold withstand dielectric strength curve, applications have been introduced. In every application, the simulation is carried out for a grounded and ungrounded connection. The three main parameters – peak voltage, interrupting current and rate of rise of recovery voltage (RRRV) – are taken into account. The applications of CBs in this work are for:

1. Switching grounded capacitor bank
2. Switching ungrounded capacitor bank
3. POW controlled switching with the aim being to minimise inrush current.

### 4.4.3.3 Simulation conditions

In order to simulate the restrikes for capacitor switching, the simulation time step and applied models must follow the relevant guidelines [87]. The simulation time step is determined by the expected frequency \((f)\) within the range 20 to 100 kHz. The simulation time step can be determined from

\[
\Delta = \ldots \quad (4.5)
\]

The simulation time step of 1 µs is applied. The CB is opened at 3.563 ms within 5 ms re-ignition window.

### 4.4.4 Simulation results

The parameters considered in the simulations include crest voltage across CB, interrupting current and rate of rise of recovery voltage (RRRV), as well as the types of system grounding. Voltage, current and recovery voltage rise-time waveforms for various schemes examined are shown in Figures 4.45 to 4.55.
4.4.4.1 Performance comparison for the cold and hot withstand dielectric strength curves for grounded and non-grounded capacitor bank connection

Figure 4.45. Voltage across breaker (110/40/50 kV) for cold withstand dielectric strength curve non-grounded connection

Figure 4.46. Current across breaker (2000/1500/1100 A) for cold withstand dielectric strength curve non-grounded connection

Figure 4.47. TRV rise time (0.4/0.1/0.05 kV/µs) for cold withstand dielectric strength curve non-grounded connection
4.4.4.2 Cold withstand dielectric strength curve grounded connection; no POW

Figure 4.48. Voltage across breaker (35/15/45 kV) for cold withstand dielectric strength curve grounded connection

Figure 4.49. Current across breaker (800/600/500 A) for cold withstand dielectric strength curve grounded connection

Figure 4.50. TRV rise time (0.13/0.08/0.1 kV/µs) for cold withstand dielectric strength curve non-grounded connection
4.4.4.3 Hot withstand dielectric strength curve grounded connection; no POW

Figure 4.51. Voltage across breaker (45/0/28 kV) for cold withstand dielectric strength curve non-grounded connection

Figure 4.52. Current across breaker (80/120/200 A) for cold withstand dielectric strength curve non-grounded connection

Figure 4.53. TRV rise time (0.9/0.4/0.7 kV/µs) for cold withstand dielectric strength curve non-grounded connection; no POW
4.4.4.4 Hot withstand dielectric strength curve grounded connection

Figure 4.54. Voltage across breaker (18/16/18 kV) for hot withstand dielectric strength curve non-grounded connection

Figure 4.55. Current across breaker (220/100/110 A) for hot withstand dielectric strength curve non-grounded connection

Figure 4.56. TRV rise time (0.13/0.08/0.3 kV/µs) for hot withstand dielectric strength curve non-grounded connection
Chapter 4: Restrike Switch Model and Detection Algorithm Development

From the POW controlled switching recommendation in the mentioned applications, it can be concluded that:

- Hot withstand dielectric curve gives less interrupting current than cold withstand dielectric curve for both grounded and non-grounded capacitor bank switching.
- Hot withstand dielectric curve gives fewer restrikes in terms of crest voltage, interrupting current and RRRV.
- The single capacitor bank breaking current, as rated in Table 5 (Clause 4.107.3 of AS 62271.100:2005), is the maximum capacitor current that a CB is capable of interrupting at its rated voltage without exceeding the permissible switching over current of 400 A. The results are summarised in Table 4.10 and Table 4.11. ATPDRAWT is a tool to check the TRV rise-time compliance with AS2006-2005.

Table 4.10. Grounded capacitor bank switching performance

<table>
<thead>
<tr>
<th>Simulation cases</th>
<th>Cold withstand dielectric strength</th>
<th>Hot withstand dielectric strength</th>
<th>Average improvement accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak U (kV)</td>
<td>110/40/50 35/15/45</td>
<td></td>
<td>52.5%</td>
</tr>
<tr>
<td>Inrush current (A)</td>
<td>2000/1500/1100 800/600/500</td>
<td></td>
<td>58.7%</td>
</tr>
<tr>
<td>TRV (kV/µs)</td>
<td>0.4/0.1/0.05 0.13/0.08/0.1</td>
<td></td>
<td>43.6%</td>
</tr>
</tbody>
</table>

Table 4.11. Non-grounded capacitor bank switching performance

<table>
<thead>
<tr>
<th>Simulation cases</th>
<th>Cold withstand dielectric strength</th>
<th>Hot withstand dielectric strength</th>
<th>Average improvement accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak U (kV)</td>
<td>45/0/28 18/16/18</td>
<td></td>
<td>28.7%</td>
</tr>
<tr>
<td>Inrush current (A)</td>
<td>80/120/240 220/100/110</td>
<td></td>
<td>2.3%</td>
</tr>
<tr>
<td>TRV (kV/µs)</td>
<td>0.9/0.4/0.7 0.13/0.08/0.3</td>
<td></td>
<td>74.5%</td>
</tr>
</tbody>
</table>

4.4.4.5 POW controlled switching recommendation

The proposed POW recommendations referred to in Ref. [121] use the controlled switching to reduce the inrush current in order to increase CB life for an interrupter. The optimum POW at 50 degrees with reference to a 0 degree supply angle is shown in Figures 4.57 to 4.60 and in Table 4.13 and Table 4.14.
Figure 4.57. Current across breaker (800/1000/1200 A) for cold withstand dielectric strength curve grounded connection

Figure 4.58. Current across breaker (800/900/1200 A) for hot withstand dielectric strength curve grounded connection

Figure 4.59. Current across breaker (80/100/240 A) for cold withstand dielectric strength curve non-grounded connection
Chapter 4: Restrike Switch Model and Detection Algorithm Development

Figure 4.60. Current across breaker (80/100/230 A) for hot withstand dielectric strength curve non-grounded connection

Table 4.12. Inrush current for grounded capacitor bank switching performance

<table>
<thead>
<tr>
<th>Simulation cases</th>
<th>Cold withstand curve</th>
<th>Hot withstand curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>No POW average current (A)</td>
<td>1533</td>
<td>1200</td>
</tr>
<tr>
<td>POW average current (A)</td>
<td>1200</td>
<td>633</td>
</tr>
<tr>
<td>Interrupting current Improvement</td>
<td>21.7%</td>
<td>47.25%</td>
</tr>
</tbody>
</table>

Table 4.13. Inrush current for non-grounded capacitor bank switching performance

<table>
<thead>
<tr>
<th>Simulation cases</th>
<th>Cold withstand curve</th>
<th>Hot withstand curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>No POW average current (A)</td>
<td>146</td>
<td>143</td>
</tr>
<tr>
<td>POW average current (A)</td>
<td>143</td>
<td>140</td>
</tr>
<tr>
<td>Interrupting current Improvement</td>
<td>2%</td>
<td>2%</td>
</tr>
</tbody>
</table>

The POW controlled switching assessment in the mentioned applications concludes that:

- Hot withstand dielectric curve gives less interrupting current than cold withstand dielectric curve for both ground and non-grounded capacitor bank switching; and
- ATPDRAW is a tool that can model the measured restrike waveforms to check the life extension of a breaker because it can compute the current value.
Chapter 4: Restrike Switch Model and Detection Algorithm Development

Usually, current interruptions take place at different current ratings. Therefore, in order to estimate the interruption life, the lower current interruptions are simply extrapolated into full rating [25], as shown in Table 4.14.

<table>
<thead>
<tr>
<th>Percentage of rated fault current</th>
<th>Number of interruptions</th>
<th>Equivalent interruptions at 100% fault current</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>50%</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>50%</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>100%</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
<td>3.25</td>
</tr>
</tbody>
</table>

Table 4.14. Simplified linear extrapolation

The deterioration is estimated from the cumulative energy dissipated in interrupters by the restriking currents. The method proposed by [25] to estimate the remaining lifetime of a CB is based on interrupting the current magnitude to obtain the erosion characteristics. The test data to see some dependencies of nozzle and contact mass losses on the interrupting current can be in terms of $\int idt$ and $\int i^2dt$.

Cumulative energy/current dissipated in interrupters is indicated for mass loss of nozzle - interrupter wear determinations (curves interpretation):

$$\text{Mass loss limit} = N_{\text{allow}} \times \text{Mass loss at breaking current}$$  \hfill (4.6)

When the allowable number of interruptions at any percentage of rated short-circuit current is known, the remaining interrupter lifetime can be determined [25] using the following equation:

$$\text{Remaining interrupter lifetime(\%)} = \left[ 1 - \sum_{i} \frac{N_{\text{allow}} \times I_{SCi}}{N_{\text{allow(max)}} \times I_{\text{SC(max)}}} \right] \times 100$$ \hfill (4.7)

$N$ is the number of interruptions at current $I_{SC(i)}$

$I_{SC(max)}$ is rated short-circuit current

$N_{\text{allow(max)}}$ is the allowable number of interruption at $I_{SC(max)}$
Therefore, the reduction of the interruption current can extend the interrupter life, as supported by Table 4.14 and Equations 4.6 & 4.7. Therefore, the reduction of the interruption current can increase the CB life, as supported by Table 4.15. The TRV rise-time waveforms, Figures 4.44 to 4.55, are checked to comply with breaker rating specified by the requirements of IEEE Standard C37.04-1999 and IEEE Standard C37.09-1999 and Table 5 (Clause 4.107.3 of AS 62271.110-2005), which is applied in systems with a voltage above 300 kV to check capacitive current magnitude.

Table 4.14 is used to estimate the remaining life of a CB for an interrupter. However, power systems are often complex and some of the parameters are difficult to determine. For this reason, there is an uncertainty in how well the restrike switch model resembles reality. In order to calibrate the model and have a more accurate parameter estimation, site measured waveforms are needed to calibrate the restrike switch model. Moreover, there are many other components, such as transformers and cables, that require accurate modeling in order to produce simulated waveform signatures for comparing with measured waveform signatures. That is why the simulated results show the applications but do not compare them to any measured results from the literature for discussion.

4.4.5 Conclusion

Stresses of an SF₆ CB in terms of overvoltages across CBs, interrupted currents and RRRVs are demonstrated in the simulations as follows:

- A literature validated restrike switch model with the power network data using ATPDRAW can be applied to predict a breaker with restrikes.
- The hot withstand dielectric strength curve has lower magnitude than the cold withstand dielectric strength curve for restrike simulation results to improve computation accuracy; and
- It is evident that POW controlled switching can reduce the interrupted currents and thus increase the life of a SF₆ CB.

In conclusion, the restrike switch model, using ATPDRAW, is proved through simulation to be an effective method to make an assessment for POW controlled switching at power networks, and is complementary to the existing evaluation
method based on published standards. Site evaluation work is recommended so that the CB for interrupting a capacitor bank can also be used for interrupting a no-load transmission line and a no-load cable in power networks.

4.5 A CB restrike detection algorithm using ATP and Wavelet Transforms

A novel non-intrusive restrike detection algorithm using ATP (Alternative Transient Program) and Wavelet Transforms is proposed. Wavelet Transforms are the most commonly used in signal processing, which is divided into two tests: restrike detection and energy level based on deteriorated waveforms in different types of restrike. A ‘db5’ wavelet was selected in the tests as it gave a 97% correct detection rate evaluated using a database of diagnostic signatures. This was also tested using restrike waveforms simulated under different parameters, which gave a 92% correct diagnostic responses. The detection technique and methodology developed in this research can be applied to any power monitoring system with slight modification for restrike detection.

4.5.1 Introduction

Efficient and prompt detection and classification of power quality waveforms facilitates maintenance and control of the power networks and improves system reliability. For this purpose, transient recorders such as power quality meters have been installed at different locations in the system to capture various types of power quality waveforms. After being recorded, the power quality waveforms are usually transmitted to the control centre and stored in a database and can be accessed for further analysis [83].

Most of the studies in power systems consider an operating frequency of 50/60Hz and the models of the systems components are designed for these power frequencies. Because dealing with very high frequencies is always difficult, there are very few studies in this research area [4]. If very fast transient behaviour is to be analysed, the adequacy of the traditional models must be reviewed and new solutions found. The difficulties lay in the fact that very fast transients are not confined to a certain frequency. The frequency range is so broad that different models are needed
depending on the phenomenon to be investigated. A mathematical CB model is applied for restrike prediction using the ATP to examine a worst case condition in a power network; that is, generating restrike waveform signatures. However, we cannot diagnose using ATP simulation alone for detection algorithms because we need another tool to detect the restrike signal.

Ref. [83] sets out to detect the restriking current after current zero for a restrike hardware method. The spectrum is analysed with the Discrete Fourier Transform by a radiometric measurement method. The interpretation process includes signal processing, feature extraction and decision-making according to Ref. [8]. Due to the difficulty of measuring current at extra high voltages such as 400 kV transmission line, there exists an opportunity to develop the detection algorithm with a restriking voltage profile using ATP for producing simulated data with selected features that are detected by Wavelet Transforms. The main goal of this contribution is to develop a novel restrike diagnostic algorithm using ATP and Wavelet Transforms as a non-intrusive restrike online detection method.

The structure of this section is as follows: Subsection 4.5.2 describes an existing approach for a restrike detection algorithm and the novel restrike detection algorithm using Wavelet Transforms which is implemented with an input from ATP simulations [122]. This detection algorithm detects the probability of re-ignitions/restrikes. In Section 4.5.3, tests and results are presented, and conclusions are stated in Section 4.5.4.

4.5.2 Existing approach for restrike detection algorithm

There are very few papers on restrike detection algorithms. Studies by Kasztenny et al. [83] are the exception and their algorithm is presented below.
The restrike events are used to prevent shunt capacitor unit and shunt reactor unit failure with the following algorithm [83]:

1. The power network is installed where the breaker is detected with restrikes.
2. The sample rate is set to an appropriate level, such as 128 samples per cycle.
3. Voltage or current triggering is required.
4. The algorithm is set to recognize a signature based on a database that exceeds at least 150% of nominal, has high-frequency content, and occurs on multiple cycles.
5. The monitor flags events that meet all criteria and alerts the utility using e-mail, pager, or other means for review and action.

As was presented in previous chapter, restriking voltages can be due to the different cases such as parasitic capacitance, contact opening velocity, chopping current value, dielectric strength variation, arcing time (between breaker opening time and arc extinction), breaker angle, inductance value between vacuum CB and the transformer load source impedance and high frequency current quenching capacity. In this particular restrike case, the breaker restrike diagnostic utilizes
wavelet analysis for feature extraction and a rule-based expert system for decision making, as shown in Figure 4.62.

![Diagram](image)

Figure 4.62. Using Wavelet Transforms for diagnostic algorithms development with experimental data

4.5.3 Novel approach for restrike detection algorithm

4.5.3.1 Overall structure of the restrike detection algorithm

The wavelet transform is a signal decomposition procedure [82] which decomposes a signal into various levels with different time and frequency resolution. At each level $j$, we can split the original signal $A_j$ and $D_j$. Here $A_j$ is the “approximation part” and represents the low frequency components of the signal. $D_j$ is the “details” part and represents high frequency component.

The results from the DWT (Discrete Wavelet Transform) depend on the selection of mother wavelet. This is especially important if a given wavelet is used to analyse a specific class of signals, such as voltage restrikes in a CB. If we use a wavelet that is similar to the signal, we can expect to do a good job of detecting the features present in the switch. Generally, fast transients are better detected more effectively by longer wavelets [82].

As shown in Figure 4.63, the $D_1$ plots in all three figures show a spike when a pole of the CB restrikes, while the $D_2$ and $D_3$ plots show the transient behaviour that characteristically occurs after Pole A has cleared.
Wavelet Selection

Selection of suitable wavelet is important for reliable detection of restrike phenomenon. A primary objective of this work is to identify the wavelet which gives the best detection performance, while still having a reasonable computational complexity. If we want to detect the sudden increase in voltage across the busbar capacitor, we must use wavelets with moments [123]. The wavelet transform is equivalent to the procedure of multi-resolution smoothing, followed by a derivative.
operation on the smoothed signal. If a wavelet has one moment, then the local maxima correspond to the locations where sudden changes occur. In fact the more moments a wavelet has, the better it can characterize local irregularities. However, this would increase the computation complexity and so we need to find the most suitable wavelet to use.

The detection scheme is summarized as follows:

1. Perform simulations with ATP [122] for restrike waveforms feature identification that would indicate a restrike.
2. Perform DWT on the simulated waveforms.
3. For each sample in D1, extract the first level D1(i)(with \( i = 1,2\ldots N \), where N is the total number of samples in D1). Ignore the spikes at both ends of D1 which are caused by edge distortion of the wavelet transform and compare the remaining values in D1(i) with a preset threshold value \( \gamma \).
4. The transient energy of the re-ignition is calculated by the formula as,
   \[
   E = \sum_{i}^{M} X_i^2
   \]
   \( i \) is the point where spike is detected, and M is the number of waveforms used to calculate the energy of the transient response after restrikes (In this work, M was selected to be 160 for a given sample rate by visual comparison of all simulation results).
5. If the value of E in 4 exceeds the energy threshold value \( E_{th} \), it is claimed that a restrike has occurred. Otherwise, the spike detected is not used by a restrike and it is necessary to go back to Step 3.
6. If neither the threshold for \( \gamma \) nor threshold for transient energy \( E_{th} \) is exceeded after the 4000 waveforms, it is concluded that no restrikes have occurred.

This detection scheme, as shown in Appendix-B Figure B.1, has been tested with simulated data to find the best fit “mother wavelet”, and to choose threshold value of the spike \( \gamma \) used on D1 and the energy threshold value \( E_{th} \) used on D2 and D3.
4.5.3.4 Tests and results of Wavelet Transforms

This subsection discusses the process of selecting the best-fit mother wavelet and its results. It also discusses the various schemes and test results obtained using wavelet analysis for detection of CB restrikes.

**Wavelet Selection**

In order to select a wavelet that best suits the diagnostic for the restrikes of CB, different types of wavelet length from the common wavelet families were tested. In the tests, the wavelets with moments from 5 different families have been considered. These are:

1. Daubechies (db)
2. Symlet (sym)
3. Coiflets (coif)
4. Biorthogonal (bior)
5. reverse-biorthogonal (rbior).

Daubechies wavelets have been widely used in investigating several power transients, such as impulsive transient and oscillatory transient [123]. Daubechies wavelet, including Symlets and Coiflets, are orthogonal wavelets. Biorthogonal and reverse biorthogonal wavelets consist of two separate wavelet functions, one for decomposition and another for reconstruction [123]. The most suitable wavelet must have the general characteristic of compact support, which is better for detecting short transient.

Two phases of screening tests were conducted. The objective of the test was to select the most-suitable mother wavelet for detecting the restrikes. This is an initial screening test. There are various and many types of wavelet available for use. The objectives of the test are to select the suitable wavelets from the family of wavelets and to find out how effectively each of the wavelets detected the presence of the restrikes. A wavelet that provides a high coefficient at Detail 1 of the DWT to indicate restrikes will be preferable as it ensures a more accurate diagnostic.

The wavelet sensitivity is related to how similar the wavelet is to produce transient switch by the restrike process. It was determined based on a subjective evaluation of how well the wavelet was able to pick up the restrikes information in the Level 1 or Detail 1 ($D_1$) of the wavelet decomposition. It was achieved by visual
inspection. For instance, Figure 4.64 shows a sample of voltage switch across the capacitor, $C_2$, as shown in Figure 4.3. Figure 4.65 shows a poor result of wavelet transform with a low coefficient of 0.17, whereas Figure 4.66 shows a good result of wavelet transform with a high coefficient of 0.39. Although DWT performed by both wavelets were able to detect the restrikes at the peak, as shown in the Figure 4.68 and Figure 4.69, the wavelet that provided a higher coefficient to indicate restrikes was preferable. Tests where 30 sets of data were tested on different types of mother wavelet were conducted.

![Figure 4.64. Example of voltage waveform across C2 from Figure 4.3](image1)

![Figure 4.65. Poor result using db1 at Detail 1](image2)
Wavelet that produced a coefficient greater than 0.2 from the DWT would be identified as a good candidate for CB restrikes. From the ranking, the wavelets that are in the top three ranks are:

- db5, db6 and db10
- sym2, sym3, sym4 and sym7
- coif1 and coif2
- bior2.2, bior3.1 and bior5.5
- rbio3.1 and rbio5.5.

The objective of the second test is to examine the transient’s energy level of the wavelet decomposition at its Level 2 or Detail 2 ($D_2$) that provides the information of the transient’s signal. The test was carried out based on visual inspection of how similar the transient oscillation at $D_2$ was to that of an expected result. Test results are given below.

**Results of first test**

The 30 sets of data were used again in the second phase of testing. The result was obtained by visual inspection. It was ranked first by the total number of good
diagnostics in Detail 3 of DWT. From the ranking, the top rank wavelets are based on Table 4.15:

- db5, db6, db10
- sym3, sym7
- bior5.5
- rbio5.5

**Results of both tests**

The DWT is implemented via filter. The shorter wavelet gives better time localisation of the restrikes, as there are fewer past values included in the filter ‘windows’ when the sharp peak change is detected. In other words, the shorter wavelet is more sensitive to the sudden jump of magnitude in D1, but has poor performance on transient response in D3 and vice versa. Ideally, a short wavelet such as db2 (four filters coefficient) would be used instead of db10 (twenty filters coefficient) in order to provide the best time accuracy.

The shortest wavelet in nature is the most suitable for transients diagnostic; however, the analysis shows that db2 wavelet was only capable of detecting 26 of the 30 tests. The longer wavelets, such as db2 and db3, are more sensitive to the transients which occur after the restrikes. It is not practical to use two different lengths of wavelet, where the shorter wavelet is used in the D1 analysis and the longer wavelet is used in D2 analysis. Therefore, the best wavelet selected must have the good diagnostic in both the first and second test. We selected the most suitable wavelet which was good in the diagnostic of peak value and transient energy. The number of good diagnostics was represented in the percentage of diagnostic, P₁ and P₂:

\[
P₁ = \frac{\text{number of good diagnostics of spikes}}{\text{Total number set of test}}
\]

\[
P₂ = \frac{\text{number of good diagnostics of transients}}{\text{Total number set of test}}
\]

<table>
<thead>
<tr>
<th>Rank</th>
<th>Wavelet</th>
<th>#Good Diagnostic (out of 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Db5</td>
<td>29</td>
</tr>
<tr>
<td>1</td>
<td>rbio3.1</td>
<td>29</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>2</td>
<td>bior2.2</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>bior3.1</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>bior5.5</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>rbio5.5</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>Sym3</td>
<td>28</td>
</tr>
<tr>
<td>2</td>
<td>Sym7</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>Coif1</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>Coif2</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>db10</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>Db6</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>Sym2</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>Sym4</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>bior2.4</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>bior2.8</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>bior3.3</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>bior3.5</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>bior6.8</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>coif3</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>coif4</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>coif5</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>db2</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>rbio2.6</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>rbio2.8</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>rbio4.4</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>rbio6.8</td>
<td>26</td>
</tr>
<tr>
<td>5</td>
<td>bior3.9</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>bior4.4</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>db4</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>rbio2.2</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>rbio2.2</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>rbio2.4</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>rbio3.3</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>rbio3.7</td>
<td>25</td>
</tr>
</tbody>
</table>
From the ranking, the wavelets that are in the top three ranks are:

- db5, db6 and db10
- sym2, sym3, sym4 and sym7
- coif1 and coif2
- bior2.2, bior3.1 and bior5.5
- rbio3.1 and rbio5.5.

The objective of the second test is to examine the transient’s energy level of the wavelet decomposition at its Level 2 or Detail 2 (D₂) that provides the information of the transient’s signal. The test was carried out based on visual inspection of how similar the transient oscillation at D₂ was to that of an expected result. Results are given below.

4.5.3.5 Results of first test

The 30 sets of data were used again in the second phase of testing. By visual inspection, the result was obtained, as shown in Table 4.16. It ranked first by the total number of good diagnostics in Detail 3 of DWT.
Table 4.16. Second phase of screening wavelet testing result

<table>
<thead>
<tr>
<th>Rank</th>
<th>Wavelet</th>
<th>#Good Diagnostic (out of 30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Db5</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>Sym7</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>Sym3</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>rbio5.5</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>Db6</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>db10</td>
<td>30</td>
</tr>
<tr>
<td>1</td>
<td>bior5.5</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>Sym4</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>Sym2</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>Coif2</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>bior2.2</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>Coif1</td>
<td>28</td>
</tr>
<tr>
<td>3</td>
<td>bior3.1</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>rbio3.1</td>
<td>0</td>
</tr>
</tbody>
</table>

From the ranking, the top rank wavelets are:

- db5, db6, db10
- sym3, sym7
- bior5.5
- rbio5.5

4.5.3.6 Results of both tests

The DWT is implemented via filter; the shorter wavelet gives better time localisation of the restrikes, as there are fewer past values included in the filter ‘windows’ when the sharp peak change is detected. In other words, the shorter wavelet is more sensitive to the sudden jump of magnitude in D1, but has poor performance on transient response in D3 and vice versa. Ideally, a short wavelet such as db2 (four filters coefficient) would be used instead of db10 (twenty filters coefficient) in order to provide the best time accuracy.

The shortest wavelet in nature is the most suitable for transients diagnostic; however, the analysis shows that db2 wavelet was only capable of detecting 26 of the 30 tests. The longer wavelets, such as db2 and db3, are more sensitive to the
transients which occur after the restrikes. It is not practical to use two different lengths of wavelet, where the shorter wavelet is used in the D_1 analysis and the longer wavelet is used in D_2 analysis. Therefore, the best wavelet selected must have the good diagnostic in both the first and second test. By reviewing the results, as shown in Table 4.14 and Table 4.15, we selected the most suitable wavelet which was good in the diagnostic of peak value and the transient energy. The number of good diagnostics was represented in the percentage of diagnostic, P_1 and P_2.

\[
P_1 = \text{number of good diagnostic of spikes} \\
\text{Total number set of test} \\
P_2 = \text{number of good diagnostic of transients} \\
\text{Total number set of test}
\]

The results are tabulated and shown in Table 4.17 and Table 4.18.

### Table 4.17. Probability of first test result, P_1

<table>
<thead>
<tr>
<th>Rank</th>
<th>Wavelet</th>
<th>#Good Diagnostic (out of 30)</th>
<th>Probability, (P_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Db5</td>
<td>29/30</td>
<td>0.97</td>
</tr>
<tr>
<td>1</td>
<td>rbio3.1</td>
<td>29/30</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>bior2.2</td>
<td>28/30</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>bior3.1</td>
<td>28/30</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>bior5.5</td>
<td>28/30</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>rbio5.5</td>
<td>28/30</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>sym3</td>
<td>28/30</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>sym7</td>
<td>28/30</td>
<td>0.93</td>
</tr>
<tr>
<td>3</td>
<td>coif1</td>
<td>27/30</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>coif2</td>
<td>27/30</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>db10</td>
<td>27/30</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>db6</td>
<td>27/30</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>sym2</td>
<td>27/30</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>sym4</td>
<td>27/30</td>
<td>0.90</td>
</tr>
</tbody>
</table>
The probability of having the good detection in both the first and second test can be calculated as $P_3$, where $P_3 = P_1 \times P_2$. The results are tabulated and shown in Table 4.19.

### Table 4.18. Probability of second test result, $P_2$

<table>
<thead>
<tr>
<th>Rank</th>
<th>Wavelet</th>
<th>#Good detection (out of 30)</th>
<th>Probability, ($P_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Db5</td>
<td>30/30</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>sym7</td>
<td>30/30</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>sym3</td>
<td>30/30</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>rbio5.5</td>
<td>30/30</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>db6</td>
<td>30/30</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>db10</td>
<td>30/30</td>
<td>1.00</td>
</tr>
<tr>
<td>1</td>
<td>bior5.5</td>
<td>30/30</td>
<td>1.00</td>
</tr>
<tr>
<td>2</td>
<td>sym4</td>
<td>29/30</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>sym2</td>
<td>29/30</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>coif2</td>
<td>29/30</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>bior2.2</td>
<td>29/30</td>
<td>0.97</td>
</tr>
<tr>
<td>3</td>
<td>coif1</td>
<td>28/30</td>
<td>0.93</td>
</tr>
<tr>
<td>3</td>
<td>bior3.1</td>
<td>28/30</td>
<td>0.93</td>
</tr>
<tr>
<td>4</td>
<td>rbio3.1</td>
<td>0/30</td>
<td>0.00</td>
</tr>
</tbody>
</table>

### Table 4.19. Final result of wavelet selection, $P_3$

<table>
<thead>
<tr>
<th>Rank</th>
<th>Wavelet</th>
<th>Probability, ($P_3 = P_1 \times P_2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Db5</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>Sym7</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>Sym3</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>rbio5.5</td>
<td>0.93</td>
</tr>
<tr>
<td>2</td>
<td>Bior5.5</td>
<td>0.93</td>
</tr>
<tr>
<td>3</td>
<td>Bior2.2</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>Db6</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>Db10</td>
<td>0.90</td>
</tr>
<tr>
<td>4</td>
<td>Bior3.1</td>
<td>0.87</td>
</tr>
<tr>
<td>4</td>
<td>Sym4</td>
<td>0.87</td>
</tr>
<tr>
<td>4</td>
<td>Sym2</td>
<td>0.87</td>
</tr>
<tr>
<td>4</td>
<td>Coif2</td>
<td>0.87</td>
</tr>
<tr>
<td>5</td>
<td>Coif1</td>
<td>0.84</td>
</tr>
<tr>
<td>6</td>
<td>rbio3.1</td>
<td>0.00</td>
</tr>
</tbody>
</table>
From Table 4.19, the highest rank of the wavelet is \( \text{db5} \), with the probability 0.97 or 97% detection in both the first and second test. Therefore, \( \text{db5} \) is selected for the best fit wavelet selection.

**Selecting the threshold values**

After the process of wavelets screening, the \( \text{db5} \) was selected. The next step would be selecting the appropriate threshold values of detecting the spike, \( \gamma \) (at Detail 1) and energy level, \( E_{th} \) (at \( D_2 \) or \( D_3 \)) based on \( \text{db5} \) wavelet transform.

**Selecting the Threshold Value, \( \gamma \) at Detail 1**

As we know, a sharp change was presented when the restrike events occurred. The wavelet decomposition at Detail 1 was able to locate the occurrence of the restrikes well. Therefore, determining the threshold value \( \gamma \) is important, as it would affect the performance or accuracy of the diagnostic. In this analysis, 135 sets of data were used in testing for selecting the best suitable threshold value, \( \gamma \). The result is shown in Figure 4.67.

![Probability vs Threshold for db5](image)

Figure 4.67. Probabilities of diagnostic and false alarm at Detail 1, \( \text{db5} \)

A successful detection is defined as ‘the eventual detection of the spike caused by restrikes’, whereas false alarm diagnostic is defined as ‘the false detection that does not indicate a restrikes’. The spike in \( D_1 \) is caused by the sudden change of voltage. Besides CB restrikes, other conditions, such as the initial current zero
Chapter 4: Restrike Switch Model and Detection Algorithm Development

interruption, also produce a small change in voltage. The small change is picked up by the wavelet and indicated in the D₁ of wavelet decomposition. This contributes to the false alarm.

From the graph shown in Figure 4.68, the optimum threshold value of 0.15 would be recommended as the probability of correct detection up to 99%, and the probability of false detection would be as low as 1%. Although threshold value of 0.05 and 0.1 might give 100% of diagnostic, they also showed high percentages of false alarm. As a compromise, the threshold value 0.15 was selected.

**Selecting Eth for Detail 2 or 3**

The process of checking the energy at Detail 2 or Detail 3 was to improve the performance of the detection scheme. Figure 4.68 compares the probability of detection for using only Detail 2 and Detail 3, and Detail 2 or Detail 3. The results showed that the probability of detection using Detail 2 or Detail 3 gave the highest probability of detection.

Figure 4.69 shows the probability of detection verses energy level at Detail 3 or Detail 2, or Detail 2 or Detail 3. The 135 sets of data were tested with threshold value 0.15. From the graph in Figure 4.68, the threshold energy Level 10 was selected as the probability of detection is 92%, with zero percentage probability of false detection.

![Graph](image.png)

Figure 4.68. Comparison of using energy Level D2, D3 and D2 or D3

As shown in the Figure 4.69, the probability of detection was 99%. After implementing the threshold of the energy, the probability of detection was decreased to (99-92)/99= 0.071 or 7.1%. However, as it was worthwhile to implement the
checking as a compromise on the false detection, the $E_{th}=10$ was selected. Finally, both $\gamma$ and $E_{th}$ were determined. The restrikes detection scheme for the single-phase was completed.

![Graph of Probability vs Energy for db5 with Threshold = 0.15](image)

Figure 4.69. Probability of detection vs energy level at D2 or D3

The detection algorithm was tested with waveforms simulated under normal capacitive switching, restrikes, and false recording conditions.

4.5.4 Conclusions

In this section, the restrike waveforms were simulated using ATP to model single-phase capacitor bank switching for features extraction. The signature test showed that when a restrike occurs, the voltage suddenly collapses, and this causes rapid changes and high frequency oscillating voltage after the final interruption. The test also shows that a wavelet transform is very effective to characterise the transient phenomenon associated with CB restrikes. A detection algorithm was developed based on the two major characteristics observed in restrike waveforms. Wavelet transform was used to analyse how the original restrikes switch decomposes into different levels or details. Detail 1 shows the sharp change caused by the restrikes, while both $D_2$ and $D_3$ provide the information on the high frequency transient voltage.

The best fit mother wavelet and the selection of threshold values for the detection procedure were also tested. The first screening test was conducted on the basis of visual inspection of Detail 1, while the second screening test was chosen on the basis of the mother wavelet that gives the best similarity to the high frequency
transients. If a wavelet has one moment, then the local maxima correspond to the locations where sudden changes occur. In fact, the more moments a wavelet has, the better it can characterize local irregularities. However, this would increase the computation complexity and so we needed to find the most suitable wavelet to use. ‘db5’ was selected as it achieved a 97% correct detection rate evaluated through a database.

The second stage of the development focused on selecting the appropriate threshold values of detecting the spike at Detail 1, and energy level at D2 or D3 based on db5 wavelet transform. From the test results based on 135 sets of data, the threshold for D1 delivered 99% correct detection value and threshold values for transient energy. Both D2 and D3 gave 92% probability of detection with zero result. This was achieved on the basis of restrike waveforms simulated under different network parameters.

The detection algorithm was developed on the basis of the simulated results in the ATP. However, in a real power system, multiple restrikes may occur before the CB successfully operates. The detection technique and methodology developed in this research can be applied to any power monitoring system with slight modification. Future field implementation of the parameter estimate and calibration of the restrike model for SF6 CBs at 275 kV is proposed.

4.6 Using Wavelet Transforms for a diagnostic algorithm development with measured data

As db3 had been selected visually from the results of the first test with good quality waveform for 10 samples, only the second stage of the development was repeated to select the appropriate threshold values of detecting the spike, at energy level at D4 or D5 based on db3 wavelet transform, as shown in Figure 4.70. From the test results based on 5 sets of data, the threshold for D4 and D5 gave overall 90% probability of detection, as shown on Figure 4.71. This was achieved on the basis of
10 numbers of restrike measured waveforms from an 11 kV experimental work.

Figure 4.70. Typical wavelet decomposition of a measured restrike waveform

Figure 4.71. Probability of detection vs energy level at D4 or D5
4.7 Summary

This chapter has presented restrike switch model applications and algorithm development with the following:

- Four (4) simulation case studies including three-phase restrike model simulations, database monitoring, prediction of nozzle and contacts deterioration for SF₆ CB capacitor current switching, and a SF₆ puffer CB with POW recommendations to demonstrate the model applications of a restrike switch model.

- Use of Wavelet Transforms as a restrike detection algorithm for both simulated and measured waveforms.

Laboratory measurement of restrike waveform signatures determines the vacuum CB parameters as a risk condition monitoring and calibrates the restrike switch model, and this is presented in next chapter.
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

One of the measures that can be used to gauge the quality of the inter-gap insulation in a vacuum CB is the escalation of the voltage across the breaker contacts associated with restrikes during opening. The gradient of the envelope formed by the gap escalating voltage is one of the key parameters that is investigated experimentally on a 12 kV vacuum CB in this research. Changes to the breaker opening velocity versus the gap voltage escalation was also investigated. It is shown in this chapter that a change in opening velocity of the vacuum CB produced a corresponding change in the slope of the gap escalation voltage envelope.

A wide bandwidth antenna calibration was also developed with applications for field implementation of restrike detection due to the breaker deterioration. An ATP-EMTP model of the experimental setup was developed. The ATP breaker model use in this work is able to include restrikes using the A, B, C and D restrike characteristic parameters. A calibration process is established for the ATP-EMTP model so as to get the experimental measured waveforms as close as possible to the simulated waveforms, and the measurements are compared with the computer simulations for the development of a predictive interpretation technique. A predictive interpretation technique is a computer model assessing switching device performance which allows one to vary a single parameter at a time (such as the variable contact opening velocity), which is often difficult to do experimentally.

This chapter presents a restrike switch model with contact velocity computation for a 12 kV vacuum CB recloser with theoretical studies, experimental tests and model simulations and, as shown in Figure 5.1, following with the last chapter for the restrike switch model applications and detection algorithm development. It describes a 12 kV vacuum CB laboratory experimental process for the development of a calibration technique, including the process details, layout,
instrumentation and simulation tools. The experimental and simulated results are presented so that the measured results are used for the parameter determination of the restrike switch model as well as the model evaluation. The simulation model can also be used to test the behaviour of the vacuum CB model and compare it with the tests made for a predictive interpretation technique. As these parameters are determined by the opening process of the vacuum CB, the analysis will be on vacuum CB open operations.

Both measured and simulated results obtained as part of the research project will be discussed and compared with the literature. First, a description and comparison of the measured and simulated waveforms when opening a vacuum CB recloser for a restrike switch model, then a generalised vacuum dielectric curve model for 12 kV vacuum CBs and next parameter variation for degradation waveform features are given. Finally, the procedures needed for field implementation are described.

The simulations are performed in ATP-EMTP, and a model of the laboratory setup is created using a high frequency power transformer model with data for similar type and size SWER transformers with the simulated data from the literature. This makes the results of the simulations less accurate, but is used so as to complete the simulations within the time limitations of the research project.

5.1 Introduction

Circuit breaker (CB) diagnostic has not been fully incorporated into its routine maintenance procedure due to lack of expertise in advanced data analysis and lack of data repository to provide useful statistical results [82]. The problem is that the original data being monitored and recorded by the power system is usually hard to interpret [82]. The current state of the art for the CB diagnostic techniques is using non-intrusive techniques such as vibration analysis, RTR-84 Circuit Breaker Response Recorder and Intelligent Optical Fiber Monitoring of Oil-Filled Circuit Breakers [82]. Current trends in online CB condition monitoring have not used restrikes as a diagnostic tool for CBs. Also, there are many limitations in performing measurements of restrikes in the field and there is a need for non-contact techniques such as radiometric measurement for restrike detection [8]. The objective of this
thesis is to use restrike characteristic parameters as a CB diagnostic tool and the radiometric measurement for field implementation of restrike detection.

The dielectric and arc quenching capability, as measured by Glinkowski [31], have been used for restrike/re-ignition computation by many researchers [4],[20], [34], and [95]. These characteristics can fully represent the gap dielectric characteristic and the critical current slope during the first millimetre of contact separation [4] by Equations 3.17 and 3.18.

In order to investigate the hypothesis that a model breaker parameter dielectric voltage gradient ‘A’ can be used as a vacuum CB diagnostic tool, a simple 12 kV vacuum CB experiment is investigated for parameter determination. The parameters of the model are inferred from the experimental measurements and can be sufficiently accurate such that the key features of the dielectric response are matched. The model parameters associated with slow opening velocity are matched with the experimental results. The experimental setup describes the equipment used, measurement and control process. The voltage and current signals are measured from the breaker terminals and the returning earth. An antenna calibration process is established to compare the measured results and the investigations involve system studies, laboratory experiment and computer simulations for the development of a predictive interpretation technique. On the basis of these considerations, the following points have been elucidated:

- The restriking phenomena are found when switching off an inductive circuit or a transformer circuit.
- The contact velocity, the slope of dielectric strength and the high-frequency current quenching were all measured.
- The data obtained were used as the basis for simulations as well as the verification of the restrike switch model.
- In the last series of the model applications and algorithm development, a simulation procedure was established to match the measured waveform data close to the simulated waveform data.

5.1.1 Model calibration

As it is impractical to have 275 kV equipment and laboratory facilities to perform experiments for a better understanding of the restrike phenomena, there is a
need to determine parameters of a 12 kV vacuum CB recloser and calibrate the restrike switch model for a predictive interpretation technique. A 12 kV vacuum CB single-phase experiment for inductive load switching tests was performed, as shown in Figure 5.1. A laboratory test set-up was designed to reproduce measured restrike waveforms with features close to the simulated waveforms that would be experienced when disconnecting a power transformer from the network. The disconnection of the transformer with an inductive load on the LV side was found to cause a more severe restrike voltage escalation than switching the unloaded transformer only.

Figure 5.1. Parameter determination and model calibration of a restrike switch model

An 11 kV single-phase circuit was found to be easier to implement, and sufficient enough to model the restrike breaker and the withstand dielectric strength and the high frequency current quenching capability for a 12 kV vacuum CB recloser. A methodology for the systemic calibration of the restrike switch model is outlined as follows; the feedback loop between estimating sensitive parameter and calibration is usually where severe difficulties arise, as shown in Figure 5.2.

Figure 5.2. A methodology for a systematic parameter determination and calibration of the restrike switch model
5.1.2 Theoretical studies of the vacuum CB restrike behaviour

In order to capture the measured waveforms for the simulated waveform information, it is necessary to have a theoretical analysis of the simulated circuit so that an approximate value of the component is estimated.

![Simulation circuit analysis](image)

Figure 5.3. Simulation circuit analysis

- $C_p$, $L_p$: Parasitic capacitance and inductance of the CB
- $L_s$: Equivalent system inductance
- $L_o$: Bus work inductance
- $C_s$: System capacitance; CB bushing and buswork
- $C$: Reactor equivalent capacitance; CB bushing, reactor bushing, winding cap

In order to estimate the value for the very high frequency components of the laboratory setup, a mathematical analysis is carried out with the simultaneous solution of circuit differential equations. For the period of restrike and that of extinction of the vacuum CB, the following sets of equations are described:

![An analytical calculation of re-ignitions/restrikes](image)

Figure 5.4. An analytical calculation of re-ignitions/restrikes a) Sample circuit for computation; b) Part of the circuit that determines the high frequency component

During the re-ignition period, the switch is in closed position; when the arc is extinct, the switch opens and the branch $R_s - L_s - C_s$ forms part of the circuit. The studied circuit is displayed in Figure 5.3. The set of equations for the period of re-ignition is:

\[
\text{(5.1)}
\]
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

The high frequency component in this period depends mainly on the capacitances and the inductance in Figure 5.3.

The period of arc extinction is described including Equations 5.2, 5.3 & 5.4 and two other equations below:

\[
\text{(5.5)}
\]

\[
\text{(5.6)}
\]

In Equation 5.5 and Equation 5.6, \( u_s \) is the voltage of the vacuum CB’s source side when vacuum CB is open. When the switch is closed, this voltage is equal to the source side voltage \( U_{cs} \). These equations can be simplified if the frequency of restrikes is much higher than the source frequency. The Equations 5.5 and 5.6 can be solved accurately by means of a fourth order Runge-Kutta method. The current part is determined by the \( R_s-L_s-C_s \) branch and the voltage equation is:

\[
\text{(5.7)}
\]

where \( t_{off} \) is the instant when the high frequency current zero is reached and \( U_b(t_{off}) \) is the recovery voltage at this time instant. In Equation 5.7 it is assumed that \( L_s \) and \( C_s \) are constant and linear. According to the last equation, the current through the breaker is:

\[
\text{(5.8)}
\]

where \( \delta = \) and \( d = \), \( \) and \( t > t_{off} \)

However, it is too complicated to solve the above equations from first principle. ATP simulations were used to estimate the required LC components for the available resources in the laboratory experiments, such as the maximum loading current 10 A for the set-up transformer.
5.1.3 Laboratory experimental tests

A laboratory setup for parameter determination of a vacuum CB recloser was made. The setup was completed and modified from the circuit by Lopez-Roldan et al. [43]. Expected typical results, including slow opening velocity for similar circuit arrangement, have been obtained for parameter determination as a breaker risk condition. In this research project, the setup is used to examine how the vacuum CB behaves and interacts with the system. These studies are also used to determine the dielectric envelope, the contact opening velocity and the high frequency zero current quenching slope of the vacuum CB that are used in the simulation model.

Figure 5.5. Laboratory test setup

TXR- transformer
HF – high frequency
PFCT – power frequency current transformer
HFCT – high frequency current transformer
HBVD – high bandwidth voltage divider

The components used in the laboratory setup are shown in Table 5.1.
Table 5.1. Equipment data for measurement test

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains supply</td>
<td>220 V, short circuit limit 10A</td>
</tr>
<tr>
<td>Single-phase step-up transformer</td>
<td>10 k VA, 250 V/12.7 kV, 3 % impedance</td>
</tr>
<tr>
<td>Capacitance for stabilising voltage during switching</td>
<td>1000 pF</td>
</tr>
<tr>
<td>Load transformer</td>
<td>5 k VA, 250 V/12.7 kV, 3.5% impedance</td>
</tr>
</tbody>
</table>

The vacuum CB model that is used in this project takes into account the following stochastic properties of the vacuum CB:

- Current chopping ability
- Recovery of dielectric strength
- High frequency current quenching.

In the test setup used to determine the parameters of the vacuum CB, only one phase of the vacuum CB is connected and measurements are performed on this phase. In order to supply the vacuum CB with high voltages, a step-up transformer is used and the measurements are performed on the high voltage side of the transformer. Only one capacitive load is used to load the system; this load is 1000 pF. This means that the current running through the vacuum CB recloser during the capacitor tests is rather limited. When analysing the results of the vacuum CB tests, the main focus is on determining the parameters for the vacuum CB model. As these parameters are mainly determined by the opening process of the vacuum CB the analysis is of vacuum CB open operations. As the parameters are mainly described by the very fast transients created by the vacuum CB, the main work is concentrated in this area. The simulations are performed in ATP, and a model of the laboratory setup follows.

5.1.3.1 Layout of the test setup

Figure 5.5 outlines the circuit arrangement. A step-up transformer (10 kVA, 250 V/12.7 kV) is used to adjust the low voltage of the mains supply to a more suitable high voltage between 2 and 11 kV, simulating the network source voltage which depends on the POW switching. A capacitor of 1000 pF is needed to be added for keeping the source voltage stable during the switching. A vacuum CB recloser
rated 12 kV, as shown in Figure 5.6, is chosen to switch the transformer load 5 kVA with the maximum 10 A loading current. We were only able to supply the 250 V side with 10 A through the variac as this was all we could get out of the building supply. The transformer could draw up to 40 A on the 250 V side if we had the current. This limited our HV current to 0.2 A well below the chopping current for this type of vacuum CB. After the simulations, the results show the simulated switch for data analysis for determining the trend of the vacuum CB electrical degradation, and for predicting its failure if the pattern of the degradation behavior can be found.

Figure 5.6. Sectional diagram for 12 kV vacuum CB recloser [124]
A more detailed description of the high voltage components and the control and measurement components, as shown in Figure 5.5, is given in the following two sections.

**High Voltage Setup**

The step-up transformer is a HV transformer with a voltage rating of 10 kVA 250 V/12.7 kV. The transformer has a nominal current of 10 A and is rated at 12.7 kV. The step-up transformer is on the primary side connected to the building electricity supply and, therefore, supplied with 240 V. The secondary side of the step-up transformer is connected to the vacuum CB and the switching transformer rated at 5 kVA. The transformer is an oil filled type transformer. On the secondary side of the transformer, 117 mH (measured at 120 Hz LC meter) inductances are connected. The vacuum CB used in this project is a 12 kV Schneider Electric Australia vacuum CB recloser. In the tests done for this research project, the current will not come close to the rated current. The vacuum CB can also be unlatched electrically by means of the point-on-wave (POW) control circuit box. The control is designed to provide independent pole closing timing control by the holding magnetic latches to the opening contact at appropriate for peak value across the breaker open under the pressure of the contact and opening springs. The loads chosen for the setup are a 1000 pF 40 kV capacitor and an inductive load.

**POW control circuit design and construction**

The POW control box, as shown in Figure 5.7, was designed and constructed by Dr. Shawn Nielsen and was adjusted for breaker opening to obtain maximum TRV as well as to enable the repeatability of the experimental results. The power supply for the box is derived from an external 12V AC plug-pack transformer. The rectifier uses common 1N4004 diodes for half wave rectification to provide 50 Hz operation signal, and the BC539 transistor can be used for small signal NPN devices. Both counters are divided by 10 and 2 Nos. 4018 CMOS for generating 1Hz synchronous signal with main supply frequency. Full wave rectification is provided for IC 7812 to supply 12 V DC supply for the circuit. 4 nos. 555 Timer ICs are used for debounced circuit, triggering pulse width and delayed time to achieve the supply control angle, as shown in Figure 5.8. The box is die cast aluminum to avoid the electromagnetic interference, as shown in Figure 5.7.
Figure 5.7. POW control circuit schematic diagram
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

Measurement and Control

This breaker control panel, as shown in Figure 5.9, is used for closing the breaker. As seen in Figure 5.10, the Item 1 yellow control knob communicates with the step-up transformer for the output voltage, as indicated in Figure 5.11. of the laboratory setup. In Figure 5.9, a screen shot of the control drive is shown. The oscilloscope Tektronix P6015A has 4 channels that show the measurements done on the high voltage system, as shown in Figure 5.9. The high frequency current measurement is by means of High Voltage Partial Discharge (HVPD) High Frequency Current Transformers (HFCT), as shown in Item 2 of Figure 5.9, and taps off the signal from recommended load impedance 50 Ω to the input of the oscilloscope, as shown in Figure 5.9. The current transformer HFCT 140/100 is wired one turn for secondary and channel amplitude 2.2 V for input, which is equal to 0.4545 A/ V or 0.909 A per division. A 50Hz CT in the current path (the HFCT does not register 50Hz currents) to see what the angle between the supply voltage and current is before opening. We need a current zero to occur at maximum supply voltage amplitude to get the largest TRV.
Contact opening velocity measurement

A contact position transducer is installed at the bottom of the plate for contact opening velocity measurement, as shown in Figure 5.8; this is supplied from a 240/12V AC power step-down transformer. In the open position the resistor is 9 kΩ, and in the closed the resistance is 4.4 kΩ.

Figure 5.9. Contact travel transducer is installed at the bottom of the breaker plate

Figure 5.10. Details showing all the resistances and the control mechanism
Figure 5.11. Input to control output voltage and HV CRO probe connected to source side of transformer

Figure 5.12. Remote control of supply voltage and high frequency current transformer measurement
Objectives of the experiments:

1. To capture re-ignition/restrike waveforms during single-phase shunt reactor switching to determine the restrike switch model parameters such as the contact opening velocity, dielectric envelope and ABCD parameter
2. To experimentally determine the parameters of a vacuum CB recloser for the improvement of the accuracy of the restrike switch model with contact velocity computation, and to verify the dielectric envelope produced during re-ignition against the generalised model for 12 kV vacuum dielectric strength curve
3. To experimentally determine the internal RLC parameters of a vacuum CB recloser and two power transformers for the restrike switch model simulation
4. To verify the hypothesis that a model breaker Parameter ‘A’ is a function of the contact opening velocity which can be used as a condition parameter for a vacuum CB
5. To develop a predictive interpretation technique for CB diagnostics after the restrike switch model calibration to use a ‘what if’ scenario for different operational conditions.

Measurements were carried out using two digital oscilloscopes. Procedures were developed with a view to applying these same procedures for future field implementation with parameter determination and calibration to evaluate the restrike switch model. Details of these procedures are as follows.

5.1.3.2 Procedures

Setting up

In Phase 1:

1. The location and spacing of the test equipment and the circuit were laid out in accordance with relevant Australian Standards and the operation was in accordance with the QUT HV Laboratory Safety Operations Procedures for HV equipment for switching procedures.

2. The earthing connection with earthing cable was connected to the step-up transformer, as shown in Item 3 of Figure 5.9.

3. Power was supplied from the autotransformer to the measuring equipment via power cord.

4. The control cubicle was the device that controlled the closing times of the vacuum CB recloser.

5. A wiring connection was made for the circuit and measurement points, including the measuring co-axial cable to measuring equipment.

6. A visual and physical inspection of the connection was carried out and then the insulation was tested to ensure proper connection. Before making the connection, all the external parts were cleaned, and megger test on vacuum CB recloser terminals was checked without making any connections.

7. All HV components were inside the Faraday cage and the HV test light sign came on once energised (and would trip off in case of fault).

8. A technician was nominated as a Safety Observer and to ensure the functional check of RCD for the Faraday Cage.

Phase 2 involved measurements and recording.
Performing measurement:

1. The experimental work involved simple EMI measurements during the restrikes. This meant having one channel available on the oscilloscope to record the radiated signal from the breaker using a simple monopole antenna close to the breaker. This signal could then be investigated for correlation to determine the zero current quenching position measured by the antenna and the high frequency current waveforms measured by HFCT during the restrike, as well as the calibration for field evaluation of restrike occurrence. For details of the passive antenna, see Ref.[8].

2. The oscilloscopes and the digital voltage were switched on before carrying out any measurement.

3. Measurements outside the HV working areas with the live HV equipment were carried out.

4. The author took the measurement outside the Faraday Cage.

5. Transient signal on 1st closing operation of vacuum CB recloser was measured.

6. The oscilloscope was switched on before carrying out any measurements.

7. Upon confirmation from the Technician, the vacuum CB recloser was CLOSED.

8. The author downloaded and recorded the data, making adjustment and then preparing for the next measurement.

9. Transient signal on the first opening operation of the vacuum CB recloser was measured by pressing the red button on the POW control box.

10. Steps 6 to 9 were repeated for vacuum CB recloser opening operation.

Records consisted of:
1. A list of waveforms – Voltage phase-to-earth across load and current across vacuum CB
2. Tests form – oscilloscope settings
3. Photographs.

5.1.3.3 Preparatory calibration tests

5.1.3.3.1 Triggering signals and CROs connection arrangement
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

The following figure is the interconnection arrangement amongst CROs, antenna and POW control box:

![Diagram showing interconnection arrangement between CROs, antenna, and POW control box.]

**Figure 5.14. CROs Channel interconnection arrangement**

**Tektronix DPO 4034 CRO**
- Channel 1 – Antenna for current switch (divided by 100 for the multiplier setting)
- Channel 2 – Breaker source side terminal
- Channel 3 – Breaker load side terminal
- Channel 4 – High frequency current (divided by 100 for the multiplier setting)

**Rigol DS 1204BCRO**
- Channel 1 – Breaker contact movement (unit multiplier setting)
- Channel 2 – Supply current switch (unit multiplier setting)
- Channel 3 – Contact opening signal capturing
- Channel 4 – Vacant

The POW control box setting is 53 ms, including breaker opening time 38 ms and the time delay 15 ms. Triggering signal is activated by the red push button, as shown in Figure 5.8 on opening to Tektronix DPO 4034 CRO and then external triggering is connected to Rigol DS 1204BCRO. The antenna is interfaced with 50 Ω T-piece connector to Tektronix CRO and Channels 2, 3 and 4 are interfaced with 1 Ω T-piece connector to Tektronix CRO. Unit multiplier setting is applied to Channels 2 and 4 of Rigol DS 1204 BCRO. The noise of the capture process (shielding earthing) is minimized because of the few turns for the current transformer.
Significant inductance in the connection in the HV loop, particularly in the HFCT earthing setup, can be reduced with wide copper straps to improve the high frequency response of the setup. Any reduction of any stray inductance and capacitance that can interfere with the measurements, such as wide copper straps to improve the high frequency response of the setup, need to be addressed.

When the vacuum CB contact separates and the vacuum arc extinguishes, a TRV will arise across the two contacts. This TRV is a critical parameter in the interruption process, the TRV can either cause the arc to be re-established or it can lead to successful interruption. The TRV magnitude is a critical factor for obtaining restrike waveform signatures. In order to minimize the time required for obtaining the restrike waveform signatures, a POW control circuit box is built to get the contact openings to produce the maximum TRV across the breaker contacts.

5.1.3.4 Experimental Results

In the experiments, the following issues were noted:

1) There appeared to be significant inductance but very little capacitance in the connections in the 11 kV High Voltage loop, particularly in the HF current transformer earthing setup. This caused significant ringing in the measured restrike currents with very high frequency about 35 MHz, resulting in the recombination effect with bounded frequency from the adjacent waveforms.

2) Power frequency current waveforms and high frequency chopping current were not measured due to the unavailability of the Rogowski current transducer of type CWT03.

In order to ensure the quality of the measured data, appropriate steps were taken to clean the data, such as using a moving average with 101 span for restrike voltage data. The restrike current waveforms were cleaned using a standard Matlab signal processing filter including FIR Equiripple Low Pass filter Density factor of 20, $A_{\text{pass}} = 1$ dB, $A_{\text{stop}} = 80$ dB, $f_{\text{pass}} = 100$ MHz and $f_{\text{stop}} = 200$ MHz. Quality voltage and current waveforms are shown in Figure 5.18 to justify the selection. The contact opening velocity was calculated with a 10 point moving average from the displacement position of the voltage transducer. The network analyser used was the Rohde & Schwarz ZVL Network Analyser (9 kHz-6 GHz) Model ZVL for the impedance and phase measurement for the breaker and the two power transformers.
Vacuum CB parameters, such as RRDS (A and B) and di/dt (C and D), were obtained experimentally. Varying the moving contact velocity was achieved by adding slow damping at the end of the piston for the slowing effect, as can be seen in Figure 5.15.

Figure 5.15. Slow contact opening velocity by inserting a wedge and a wooden plate at the piston end

Figure 5.16. Contact travel measurement from the position transducer for normal contact opening at 1.9 m/s for Figure 5.13

The x-axis is the time of contact travel, y-1 axis is the contact distance travel captured by RIGOL CRO Channel 1, and y-2 axis is the velocity obtained by the intersection of a 10 point moving average of the voltage waveform (purple in
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

colour). The contact signal is captured by RIGOL CRO Channel 3, as shown the brown opening contact signal.

![Contact Signal](image)

Figure 5.17. Contact travel measurement from the position transducer for slow contact opening at 1.5 m/s for Figure 5.13

The method for the measurement results was the same as in Figure 5.16. These results infer different contact opening velocities, which indicate the degraded condition of the breaker compared with the measured waveforms. Then, simulated waveforms were obtained to diagnose the breaker condition for a predictive interpretation technique.

Effect of rate of rise of dielectric strength

The rate of rise of the dielectric strength depended on how fast the breaker contacts opened. All other parameters remaining constant, if the rate of rise was increased, the breaker reached a higher dielectric strength faster and the probability that the breaker quenched the arc at first power frequency current zero increased. This is demonstrated in Figure 5.18 (below) which shows breaker voltage for a rate with rise of A=57.71V/µs. The green line is obtained by Matlab curve fitting tool to represent a straight line Equation (3.17) \( V(t) = A*t + B \), where A and B are the parameters.

199
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

Figure 5.18. Effect of rise of dielectric strength from measured data. Dielectric envelope at contact opening velocity 1.9 m/s with travelling distance about 0.266 mm

Checking the calculated contact velocity

Velocity —
Displacement $S = V \cdot t + u$
$S = 1.9 \cdot t$
$V_{\text{vacuum}} = V(t) = 6.258 \times 10^7 \cdot t + 448$
Slope $m = 3.32 \times 10^7 \text{ V/m}$ or $3.32 \times 10^4 \text{ V/mm}$

Table 5.2. Comparison of breakdown voltage per mm up to 4 mm at the time of contact opening

<table>
<thead>
<tr>
<th>Author</th>
<th>Osmokravic [125]</th>
<th>Helmer [45]</th>
<th>Experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown strength (V/mm)</td>
<td>4k V/mm to 39kV/mm</td>
<td>30 kV/mm</td>
<td>33.2 kV/mm</td>
</tr>
</tbody>
</table>

This is in good agreement with the breakdown strength $3.32 \times 10^4 \text{ V/mm}$ from our experiments.

$U = A(t - t_{\text{open}}) + B$
$A = 6.258 \times 10^7 \text{ V/s} = 6.258 \times 10^6 \text{ V/s} = 62.58 \text{ V/µs}$
$B = 448 \text{ V}$

Table 5.3. Comparison of contact opening velocity

<table>
<thead>
<tr>
<th>Author</th>
<th>Glinkowski [126]</th>
<th>Wong [34]</th>
<th>Experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise of rise(V/s)</td>
<td>0.5x10^6 V/s to 1.7 x10^7 V/s</td>
<td>0.2x10^6 V/s to 5.0 x10^7 V/s</td>
<td>6.258 x10^7 V/s</td>
</tr>
</tbody>
</table>
It was also found that this was also in keeping with the $3.32 \times 10^4$ V/mm result in the experiments. Therefore, a contact opening velocity was added onto the ATP model program as below:

\[
\text{Displacement(s)} = v \times (t - \text{topen})
\]

\[
U := 3.32E4 \times v \times 1.0E3 \times (t - \text{topen}) + 448
\]

When a vacuum CB recloser reignites during opening operation, voltage escalation occurs and inductive current interruption process can terminate in one of the three cases \[19\]. Voltage escalation sometimes continues until there is a flashover or insulation failure somewhere in the circuit. This implies it goes on for ever for some cases. The following three cases current interruption will occur:

a. The breaker can successfully interrupt at one of the high frequency current zeros. This is referred to as ‘termination mode A’.

b. The breaker fails to interrupt the high frequency current, and interruption is accomplished in one of the next power frequency zero crossings. This is designated as ‘termination mode B’; however, this could not be observed in this experiment.

c. The breaker fails to interrupt and may cause harm to itself and/or the load to which the transformer is connected.

Dielectric envelope is one of the main elements of any vacuum device. An important parameter of the device, such as dielectric strength of a vacuum gap, is considered the restrike occurrence if the transient recovery voltage exceeds the instantaneous breakdown voltage of the dielectric strength.

**Determining the high Frequency quenching capability**

Before determining the HF quenching capability of the vacuum CB, many considerations of the approach were made. The two main considerations were how to determine the constant C that appears in Equation (3.18), and the second was how to set the opening time of the VCB, $t_0$. The value of C can be described as ‘the rate of current change in di/dt with respect to time’. The value is therefore found by finding the slopes of the HF current between a maximum and a minimum point and describing the slopes as a function of time. The time used to find C is in Equation (3.18), given as $t - t_0$. The time $t_0$ should be the opening time of the breaker, but since this time was not known with reference to the particular time captured in the CRO, it was decided to set $t_0$ as the time when the HF current started appearing. When
calculating the value of RRDS, the time $t_0$ was set to zero; however, in this case, the beginning time of the HF current was chosen, since this time had to be used anyway when finding the value of $D$. The value of the constant $C$ could now be calculated from the measurements of the HF currents.

![Figure 5.19](image)

*Figure 5.19. High frequency current at the contact of opening to find Parameter ‘D’ using last quenching points of the last two data markers at zero current quenching*

Finding the slope between the last two data markers at zero current quenching is seen in Figure 5.17, with the green line calculation shown in Figure 5.18. The two points are (4.048e-7, 84) and (3.87e-7,24.04) for the slope calculation.

$$D = \frac{[84 - (-24.04)]}{(3.87e^{-7} - 4.048e^{-7})} = 7.6829 \times 10^9 \text{ A/s or 7682.9 A/µs or 76.829 A/µs (after correction)}$$

Frequency ($f$) = $\frac{1}{T} = 1/(3.87e^{-7} - 4.048e^{-7}) = 72.46 \text{ MHz}$

As shown in Figure 5.20, the green line is $|\text{di/dt}|$ and the blue line is the current. The point $X = 6.0.0007995$ s is the $|\text{di/dt}|$ at current equal to zero at point $Y = 6.112e+9$, as below:
The slope $\frac{di}{dt}$ just prior to arc extinction determines whether the breaker can interrupt the high frequency current or not. This is called ‘critical current slope’, a parameter that is hard to determine. If the critical slope is $B$, then the probability $p$ of arc quenching can be found by the following expression [4]:

$p = 1, \frac{|di/dt|}{B} < B$

$p = 2 - \frac{|di/dt|}{B}, B < \frac{|di/dt|}{B} < 2B$

$p = 0, \frac{|di/dt|}{B} > 2B$

The Parameter ‘$D$’ value was found outside the literature range 100 to 600 A/$\mu$s by both methods. Therefore, the Greenwood method [126] was followed, using Matlab to find the Parameters ‘$C$’ and ‘$D$’, as shown in Table G.9 and Figure 5.19. Each calculation represents a $di/dt$ at zero current point from the highest to the nearest zero point below. The unit for the slope Parameter ‘$C$’ is A/s$^2$ and the unit for the rate of change of current Parameter ‘$D$’ at $t=0$ is A/s.
The rate-of-change of the current at a current zero determines whether or not there is a successful extinction. The high frequency quenching capability of typical vacuum CBs after contact separation is represented by Equation 3.18:

$$|\frac{di}{dt}| = C(t - t_{\text{open}}) + D$$

where $t_{\text{open}}$ is the moment of contact separation.

The values of the constant $C$ can be either positive $0.31 \times 10^{12}$ A/$\mu$s$^2$ or negative $-0.34 \times 10^{12}$ A/$\mu$s$^2$ and $D$ from 100 to 600 A/$\mu$s. However, the curve giving $|\frac{di}{dt}| = 148.7 \times t + 2.2 \times 10^9$; that is, the $C$ is the slope positive 148.7 A/$\mu$s$^2$ where at last $|\frac{di}{dt}| @ I=0$ and $D$ is 229 A/$\mu$s at which black “o” $|\frac{di}{dt}|$ arc quenching is within either positive slope or negative slope. There is no quenching region outside the slopes, as shown in Figure 5.22. Different ABCD parameter for normal and slow contact opening are shown in Table 5.4; however, both are outside the Table 5.4 or Parameter ‘D’ below the minimum 100 A/$\mu$s. The possible reason for such high $\frac{di}{dt}$ is either a very low capacitance in the circuit or cable reflection from the circuit.
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

The above concludes that average ABCD parameters will generate different restrike waveform signatures; however, only Parameters ‘A’ and ‘B’ are input into ATP for the results, as shown in Figure 5.27 and Figure 5.29.

**Restrikes**

During the opening operation of a vacuum CB, the dielectric strength of the gap increased as the contact separation distance increased. This was due to either slow contact opening or insulation deterioration where the gap tended to break down and an arc was established before real galvanic isolation occurred. The gap dielectric strength between them increased as a function of time, and a ‘race’ between the transient recovery and the dielectric strength developed.

A number of restrikes can happen in the gap during opening. The effect of restrikes is illustrated in Figure 5.18, where very steep breaker step voltages are shown to have developed, due to high frequency current quenching. As is shown in Figure 5.18, the higher the quenching capability, the larger the number of re-ignitions. This is because of the high transient recovery voltage across the breaker and interrupting currents with high \( \frac{dt}{di} \) at the same time.

Zero arc quenching current is also clearly shown in Figure 5.21. On the other hand, when the quenching capability was smaller, the current was not always chopped during the high frequency period; this led to an increase in conduction period of the high frequency component (smaller number of re-ignitions). The latter
Case might cause failure of interruption. Each subsequent restrike introduces higher and higher load side over voltages due to the increased and continuous transfer of energy between the inductance and the capacitance on the load side due to the restrike and extinction respectively, as shown in Figure 5.18.

High frequency current zero quenching determination was based on the following:

- The recombination effect occurred after high frequency current quenching at current zero. This was due to the fact that it was not possible to obtain a clean damped oscillation.
- Behaviour differed between the high frequency signal and the neighbouring signal with varying peaks of different frequency, as shown in Figure 5.23. This was due to the post-arc current induced from the stray capacitance and inductance circuit[127].
- The post-arc current has a travelling wave with a swing effect.

![Figure 5.23. High frequency current quenching from measured data where the circle is the high frequency current zero quenching](image)

5.2 Modeling of restrikes/re-ignitions behaviour analysis

A power system is formed by many different kinds of components and equipment. The purpose of this section is to describe a general modeling methodology for the components of the system under study. For this reason, the

206
components analysed correspond to the laboratory setup formed by a supply, a step up transformer, a vacuum CB recloser, a power transformer and an inductive load.

Component values that are needed to be measured to match the actual value for ATP simulations:

1. 12 kV vacuum CB recloser under high frequency for restrike occurrence
2. One high voltage capacitor under high frequency
3. A step-up transformer and power transformer load
4. Inductive load 117 mH measured using a 120 Hz RLC meter.

5.2.1 Modeling for the power supply source

The most common way of modeling a power supply is by an AC voltage source and a series source inductance. If the system under analysis is being fed by a source inductance and if the source is not permanent supply, such as a generator source, then some other considerations such as source reactance, inductance of the connecting cables and busbar capacitance must be taken into account.

5.2.2 Modeling for a 12 kV vacuum CB recloser– measurements and results

In this section, the measurement setup designed and instrumentation used to measure the impedance and phase over a wider frequency range is described using PI model for series RLC circuit values, as detailed in Appendix D. When dealing with overvoltage determination and small current switching, the restrike switch model has to include HF re-ignition components, depending on the properties of the vacuum CB recloser and the surrounding network. The vacuum CB is modeled by:

• the withstand voltage characteristic of 12 kV vacuum CB recloser
• HF current quenching capability.

For the transient analysis, the dielectric withstand is approximated using Equation 3.17: \( U_b = A(t - t_0) + B \). It is an envelope formed by this equation both positive and negative slope as shown in Figure 5.21. The constant A determines the voltage slope and is related to the velocity of the contacts separation. This voltage slope is the measure of the rate of rise of the dielectric strength (RRDS). The values of the constants A and B vary for the different vacuum CBs. For this research, the actual dielectric envelope for a 12 kV vacuum CB recloser was used. Vacuum
dielectric strength curves and the slope di/dt high frequency quenching zero current capacity are determined from experiments and are also used in ATP simulations shown in section for both normal contact opening velocity and slow opening velocity.

The chopping current $I_{ch}$ depends mainly on the contact material, but also important is the surge impedance of the load side [4]. Surge impedance $Z$ is the transformation of an inductive energy into electrostatic energy following the decay of the transient. This is caused by the interaction of the load stray capacitance $C_L$ and the inductive load $L_L$[11]. i.e. $Z= \ldots$

Had there been no re-ignition/restrike, the TRV would have risen to a magnitude given by [11]:

$$V = I_{ch} \ldots$$

However, if the TRV exceeds the dielectric strength of the breaker, re-ignition/restrike will occur, as shown in Figure 5.18. In these determinations however, we consider the chopping current constant at 3 A [4]. The characteristics describing whether or not re-ignition occurs are [4]:

From Equation (3.18) $\frac{di}{dt} = C(t - t_{open}) + D$

where $t_{open}$ is the moment of contact opening. The $di/dt$ represents the arc quenching capability of the vacuum CB respectively. The value of the constants were obtained from the experiments.

5.2.3 Modeling for the existing power transformers – measurements and results

In this section, the measurement setup is designed. The instrumentations used to measure the impedance and phase over a wider frequency range is described in detail in Appendix E. The measurement, results and their analysis are discussed and, finally, the model is validated by comparing the measured results with the corresponding simulated results.
5.2.4 Results evaluation

1) The tests could only be started when all the required parameters to be measured had been identified and the ability to measure them with confidence assured. Once again, issues regarding time and amplitude resolution needed to be looked at, reduction of any stray inductances and capacitances that could interfere with the measurements needed to be addressed. From the experiments, the measurement are:

a) Input and output voltage on the switch terminals
b) High frequency current in the HV loop (HV loop chopping current is estimated 0.2 A due to the limited availability of measurement instrumentation)
c) Travel of the contacts
d) Antenna output, as shown in Figure 5.24.

2) Once the voltage between the contacts and the high frequency restrike currents were measured accurately and clearly with sufficient time and amplitude resolution, we could calculate the A, B, C and D parameters from varying the inductive current from 2 A to 10 A.
Analysis of the experimental results was carried out for ATP simulations. The experimental results were: contact opening velocity, load current, the dielectric voltage gradient $A$ (V/s), initial voltage $B$ (V), high frequency current slope $C$ (A/s$^2$)
and zero current quenching D (A/s) as breaker condition features (as shown in Appendix C).

1. The dielectric envelope characteristics of the dielectric strength between the contacts are different when it is subjected to TRV of different steepness which causes continuous repetitive restrikes. Both Parameters ‘A’ and ‘B’ for Equation (3.17) and ‘C’ and ‘D’ for Equation (3.18) are approximately a straight line for the first millimeter after the contact opening.

2. As discussed in the literature [8], the high frequency current slope can be measured with high frequency current transformer (HFCT) or antenna and the slope is a breaker condition feature. High frequency current is a hypothesis of the breaker risk condition for SF₆ CBs. This is still to be proven in future work.

3. Different operational conditions have different high frequency current oscillation due to the change of L and C values that can be used as a predictive interpretation technique for CB diagnostics, as shown in Appendix G.

4. The number of restrike occurrences and their time can be validated with the results from the antenna and the high frequency current transformer measurement. Also, the di/dt magnitude relationship between the antenna and the high frequency current transformer (HFCT) was established, as shown in Figure 5.24.

5. The wide frequency bandwidth of the antenna must be adequate to cover the frequency range of restrike between 100 kHz to 100 MHz, as shown in the resonant measurement results for RLC values in the breaker and the two power transformers in Appendices D and E.

6. The sudden drop in the voltage due to the slow opening velocity indicates a slow velocity mechanism measurement to give a degree of contact degradation from the model parameter and the contact opening velocity, as shown in Figure 5.27. Also, there is only a very slight change of the slope for the rate of change of high frequency current for both normal and slow contact opening velocity, as shown in Figure 5.28. The Parameters ‘A’, ‘B’, ‘C’ and ‘D’ for both normal and slow behave differently depending on the secondary current load increasing, as shown in Figure 5.29 and Figure 5.32.
7. Although the HF quenching capability of the vacuum CB is inconsistent with Greenwood’s experimental results [43], the result varied greatly; this was also expected because of the low current levels in the tests and the recombination effect on the forced current zero. The HF quenching capability was therefore set to standard values in the simulations to obtain the simulated waveforms close to the measured voltage waveforms [128].

<table>
<thead>
<tr>
<th>Table 5.4. Comparison between Greenwood’s and the experimental results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenwood’s experimental results</td>
</tr>
<tr>
<td>A (V/s)</td>
</tr>
<tr>
<td>B (V)</td>
</tr>
<tr>
<td>C (A/s2)</td>
</tr>
<tr>
<td>D (A/s)</td>
</tr>
</tbody>
</table>

8. The calculated high frequency quenching current parameter results from the experiments deviated from the literature results due to the absence of a ‘clean’ damped oscillation. Instead, the high frequency current quenching has a travelling wave with a swing effect.

9. In the setup, we could only get 10 A out of the supply. Therefore, the breaker 50 Hz current was very low, probably below the chopping current. As such, we could not get a current zero at quenching.

10. The POW switching was done to get the “chop” current openings to occur at maximum voltage. This allowed the TRV to exceed the gap dielectric strength for restrike occurrence.

The withstand voltage of the gap increased proportionally to the square of the distance between the contacts [4]; however, for the first millimeter of the contact separation this dependence can be taken as linear, as shown in Figure 5.18. As the dielectric breakdown phenomenon is of a stochastic nature, for the very same vacuum CB there will be some differences in the dielectric withstand. This difference varies with the normal distribution and a 15 % standard deviation can be assumed [4]. For an easier comparison of vacuum CBs that have different dielectric withstands in theoretical analysis of the vacuum CBs, only the mean value of the dielectric withstand is taken into account. The high frequency current quenching results were different to those in the literature [126].
Figure 5.27. Comparison of normal and slow velocity at the first few micro-seconds
Figure 5.28. Comparison of normal and slow rate of change of current at the first few micro-seconds

Figure 5.29. Comparison of normal and slow breaker Parameter ‘A’
Figure 5.30. Comparison of normal and slow breaker Parameter ‘B’

Figure 5.31. Comparison of normal and slow breaker Parameter ‘C’
5.2.5 Model evaluation

In this section, the validity of the models is checked by comparing the features/parameters of the waveform signatures measured directly on the breaker. The voltage computed was obtained from the measures using Equations (3.17) and (3.18). The accuracy of the parameters of this model used in ATP greatly depends on the accuracy of the measured voltage and current waveforms; hence, it is very important to check if these measurements are accurate enough to give the accuracy requirements for the model to be developed using this measurements. Also, it depends on the models and the parameters used for the breaker and the power transformers. The restrike switch model was evaluated on the basis of similar gradient feature for both voltage and current waveforms for normal and slow contact operation velocity, and on the basis of similar results from the literature.

The following experiments have been performed:

i. Normal contact opening

ii. Slow contact opening

1. Normal opening velocity 1.9 m/s waveforms
Chapter 5: Analysis of Results for Parameter Determination and Model Calibration

Figure 5.33. Voltage waveforms for normal contact opening velocity: measurement vs simulation

Figure 5.34. Current waveforms for normal contact opening velocity: measurement vs simulation
2. Slow contact opening velocity 1.5 m/s waveforms

Figure 5.35. Voltage waveforms for slow contact opening velocity: measurement vs simulation

Figure 5.36. Current waveforms for slow contact opening velocity: measurement vs simulation
The restrikes observed during the simulations were consistent with those in the single-phase experiments presented in Maialen Boya’s experimental results [76]. A straight line is fitted through the maximum voltage points of the restrike chain, as shown in Figures 5.31 to 5.34. A straight line is fitted through the voltage points at flashover of the contact gap. This is the point at which the gap voltage has reached a value that exceeds the dielectric strength of the gap. This validates the hypothesis that ATP is used to estimate the dielectric strength failure rate and interrupter risk condition as a function of the breaker model ABCD parameter and a function of contact opening velocity. The same Parameter ‘D’ but different Parameter ‘C’ and contact opening velocity indicate the mechanism measurement to give a degree of contact degradation.

5.3 Discussion

The parameters used to model the vacuum CB in the ATPDRAW model were determined on the basis of the literature and a series of tests. The results were analysed and the ABCD breaker model parameters and the contact opening velocities were calculated. The limitations of the work are also covered in this section.

The chopping current was the first parameter of the model that was treated. The current chopping phenomenon was hard to observe at high voltage levels because of the high current transients created at these levels. At lower voltage levels, the chopping current was seen quite clearly and an attempt at calculating the current chopping level of the vacuum CB was made. Since the laboratory setup conducted a current which was under the current chopping level of the breaker, the value of these parameters could not be determined for this breaker. The parameters of the chopping current were therefore chosen as standard values, which should give a current chopping level of 3 A at power frequency and 0.2 A at high frequency (by trial and error method) in the simulation model. The results were acceptable in comparison with the measured waveforms on the basis of similar voltage gradient.

An analysis of the re-ignitions/restrikes of the vacuum arc was made in order to determine the dielectric withstand of the vacuum CB. The analysis of the re-ignitions/restrikes showed that the vacuum CB has a RRDS of 10 to 67 V/µs. This value corresponds to the suggested value range of RRDS when testing vacuum CBs.
The value of the RRDS gives a maximum dielectric withstand of the vacuum between the vacuum CB contacts of 30 to 43 kV/mm. The dielectric withstand of vacuum is between 20 kVrms/mm and 30 kVrms/mm [8]. The mean value in this research is 33.2 kVrms/mm; therefore, the found values for the RRDS of the vacuum CB seem to be acceptable.

The HF current quenching capability of the vacuum CB was also examined and two methods of determining the simulation parameters were introduced. When the HF current quenching capability is considered to be constant, its values should lie between 100 A/s and 600 A/s [34], which indicates that the result found in this research is different because it is very difficult to determine the quenching capability of a vacuum CB as a linear function with respect to time in the experiments [4]. The difference between the calculated value and the expected value is most likely to be caused by: the current level in the system, very little capacitance in the circuit, the cable reflection in the circuit, and by the effect of the stray inductance and capacitance on the HF interrupting capacity of the vacuum CB. Also, it is expected that tests conducting larger currents will give better results of the HF current quenching capability of the vacuum CB. For this reason, the value of the HF current quenching capability was therefore chosen as $C=1.00E+12$ A/s$^2$ for normal velocity and $C=1.6E+12$ A/s$^2$ for slow velocity, and model $D=190E+06$ A/s was chosen as standard values in the simulation model.

The two parameters play a big role in the creation of restrikes in the vacuum CB. The re-ignitions/restrikes in the vacuum CB are created whenever the dielectric strength is exceeded by the TRV and the high frequency quenching capability. The RRDS during an opening operation was found to be 33.2 kVrms/mm. The parameters for determining the current chopping level could not be found, as the current in the test setup was under the current chopping level of the vacuum CB. An attempt at finding the HF quenching capability of the vacuum CB was made, but the results varied; this is also expected because of the low secondary inductive current level in the tests. The parameters of the current chopping and the HF quenching capability were therefore set to standard values in the simulations for obtaining the simulated waveforms close to the measured waveforms.

Initial guesses for the network components values were made, then set to optimise the guessed RLC component values to minimise the square error for the
vacuum CB and the transformer parameters. There is a difference between the measured values and the model values for the vacuum CB recloser and the two power transformers. It is difficult to obtain the exact simulated waveform as the measured waveform; this is due to the measurement errors and the unknown parameters, such as chopping current value and connection inductance. Dielectric behaviour for vacuum different from SF$_6$, and different parameters such as high frequency transient current monitoring will be investigated for SF$_6$ CBs.

5.3.1 A restrike switch model with contact velocity computation

A restrike switch model was modified with contact opening velocity computation for vacuum CB recloser. The aim was to predict the breaker restrike risk for the prevention of an interruption of the distribution and transmission of the distribution and transmission of electricity supply system for a replacement of a SF$_6$ CB. The results of the comparisons between measured and simulated restrike waveform after calibration indicate that the proposed model can be a useful tool for breaker restrike prediction and CB diagnostics, taking into account the compromise between accuracy and simplicity.

5.3.2 A generalised vacuum dielectric model for 12 kV vacuum CBs

The RRDS for the first 4 mm is approximately 50 V/µs and then the RRDS for the next 6 mm is 30 V/µs for the generalised 12 kV vacuum dielectric curve model. This is shown in Appendix F, Figure F.18, in comparison with Figure 5.37; the difference is between 2 and 50 V/µs. This is also a useful tool for restrike prediction for vacuum CBs if we do not have the actual dielectric envelope from the experiments or the manufacturers.

5.3.3 A predictive interpretation technique for CB diagnostics

After calibration by trial and error method for the unknown parameter for the restrike switch model, as shown in Section 5.2.5, parameters are varied one at a time and a predictive interpretation technique for ‘what if’ simulations is presented for CB diagnostics. With the application of online condition assessment of medium and high voltage CBs in mind, a novel method for diagnosis was developed. This method –
which has been named the "simulated restrike breaker diagnosis" (SRWD) – simply replicates the real measured waveform data with simulated waveform data for a feature extraction database, as shown in Appendix G.

5.3.4 Evaluation of the hypotheses

The experimental and simulation results have validated the main hypothesis and amended it as follows:

The restrike switch model Parameter ‘A’ is related to a normal and a slowed case of the contact opening velocity and the escalation voltages which can be used as a diagnostic tool for a vacuum circuit-breaker (CB) at service voltages between 11 kV and 63 kV. The escalation voltages continue until there is a flashover or insulation failure somewhere in the circuit due to inductive current interruption by vacuum strength and interrupter risk condition as a function of the breaker model ABCD parameter. The same Parameter ‘D’ but different Parameter ‘C’ and contact opening velocity indicate the mechanism measurement to give a degree of contact degradation.

Other hypotheses are supported by the literature:

**Hypothesis 1a:** A CB restrike can be predicted if there is a similar type of simulated and measured waveform signature [43].

**Hypothesis 1b:** A CB model parameter/feature is a diagnostic tool to interpret the breaker risk condition from the transient waveform signatures and escalation voltages as a function of the breaker model characteristics for breaker performance [34].

**Hypothesis 1c:** A computer simulation can provide a breaker risk predictive interpretation technique. This is supported by the computations verified by laboratory experiments [72] and [129].
5.4 Summary and implications

This chapter investigated the generation of high voltage transients from a 12 kV vacuum CB recloser. The investigation was concerned with theoretical research, experimental tests and simulations studies.

The different physical phenomena – the dielectric strength and the HF current quenching capability – of a 12 kV vacuum CB recloser were investigated. These phenomena were all described using a mathematical model and the model included parameters which determined the behaviour of the 12 kV vacuum CB recloser as well as the breaker performance. Methods for finding the model parameters from test results were determined and a series of tests were performed on the vacuum CB recloser.

The result of the parameter tests showed that the parameters for determining the current chopping level could not be found, as the current in the test setup was under the current chopping level of the vacuum CB. An attempt to find the HF current quenching capability of the vacuum CB recloser was made, but the result was variable; this is also expected because of the low secondary current levels in the tests. The parameters of the current chopping and the HF current quenching capability were therefore set to standard values in the simulations.

The dielectric envelope, contact opening velocity and voltage rise per mm for Parameter ‘A’ and Parameter ‘B’ of the vacuum CB restrike waveform model were inserted in an ATPDRAW model of a vacuum CB. The model of the vacuum CB was used in a simulation model that represented the complete laboratory setup and the hypotheses were validated with simulations and experiments.

In order to determine the parameters for modeling the dielectric strength curve and the HF current quenching capability, new tests at higher current levels should be made. In order to get more precise simulation results, an improvement of the simulation model is also required. A description of the antenna magnitude calibration procedures has been developed with applications for field implementation, as shown in Figure 5.24.

The CB diagnosis in the field is based on the capturing of real restrike waveforms from the radiometric measurement method using a passive antenna. A
wide bandwidth antenna calibration based on the current magnitude and energy level was also developed with applications for field implementation of restrike detection. This is an alternative means for a relatively deterioration detection of Parameter ‘A’. ATP is applied to obtain similar simulated waveforms for analysis and prediction. This will be achieved by comparison of the measured waveforms and the simulated waveforms. Then, the simulated waveforms are processed to extract the parameters with reference to the model breaker parameter, contact opening velocity, breaker RLC component values and the circuit data, as shown in Appendix F.
Chapter 6: Conclusions and Future Work Proposal

The main results and general conclusions from the previous chapters and potential extensions of this research are presented in this chapter.

6.1 Fulfillment of thesis goals

As stated in Chapter 1, two main goals were established for this thesis work:

- To use the A, B, C and D characteristic restrike parameters as a diagnostic tool for vacuum CBs (A change in these parameters indicates a change in the breaker conditions)
- To measure the characteristic restrike parameters via a non-intrusive antenna.

The proposed restrike switch model with contact opening velocity computation has been shown to reliably predict the risk of the occurrence of restrikes in the experiments. The analysis of experimental calibration tests has been applied to identify the parameters determination for breaker degradation and the roles in restrike risk prediction. Further work is required to develop the restrike switch model applications and test the proposed method for more specialized cases, such as those near large generators or on series-compensated lines and 275 kV power networks (as per Appendix A).

The experiments conducted as part of this thesis have provided valuable insight into the parameters determination of a 12 kV vacuum CB. The results covered only a limited range of operations. It was also shown that it is possible to obtain a useful model of the interrupter wear rate and thereby provide a restrike detection algorithm with a means to update its expected opening times with accumulated interruptions. After each interruption, the interrupter is perceived as more severe than before. The result receives even more support when the interruptions are viewed cumulatively.
However, a visual inspection of the accumulated interruption identifies the relationship between the breaker stresses relating to the interrupter lifetime.

6.2 Novel contribution of the work

The main novel contribution of this work is that it uses simulated restrike waveforms guided by measured restrike waveforms to analyse a breaker restrike detection problem, using restrike phenomena as a diagnostic tool to predict a breaker performance for a predictive interpretation technique.

The proposed restrike switch model with contact opening velocity computation has been shown to perform well according to its intended functions to predict a breaker performance, by distinguishing normal and slow contact opening velocity within the modeled framework. The restrikes observed during the simulations were not only consistent with Dr. Lopez’s single-phase experimental results presented in the CIGRE 2002 paper [43] and Maialen Boya’s experimental results [76], but also include the case where the contact opening velocity was slowed effect on the restrike parameters.

Restrikes occur due to the transient recovery voltage exceeding the withstand dielectric strength of a breaker. Transient recovery voltage is the voltage computed across the breaker from the power system data. The simulation research method is ATP-EMTP software as an analytical tool for transient power network. The restrike switch model is the derived empirical curve for SF₆ CBs and the dielectric reset CB model with contact opening velocity computation. Power network data is needed to produce restrike simulated waveforms using ATP-EMTP for breaker restrike risk prediction in the power networks. This improves the accuracy of the computer simulations compared with the existing cold dielectric curve for SF₆ CBs. Modeling the restrike measured switch is a non-intrusive prediction technique for medium and high voltage CBs in support of reliable, cost effective and sustainable electrical power utilization.

The complete restrike switch model with contact opening velocity computation is, however, infeasible to implement for large systems (such as industrial systems or power networks). One reason is that the empirical data, such as contact opening velocity, would have to be experimentally determined for the specific CB used in the
simulations. This adds extra complexity and the amount of extra knowledge gained from such an implementation is minimal, unless the purpose is to study the CB itself for failure. Secondly, the system is fairly large, and statistical data for individual CBs tend to play a smaller role in the aggregate. Finally, when the effects of re-ignitions/restrikes are to be studied, only the basics of the CB characteristics are important (main phenomena). Whether three or four re-ignitions are observed is irrelevant since each individual CB will behave differently in a real system, and the complete behavior is dependent on many different parameters. The purpose of modeling is hence to have a good approximation that can be used as a source of transients and feature extractions for diagnostic algorithm development.

From ATP simulations, an improvement of computer accuracy is achieved, compared with the cold dielectric curve and using hot dielectric strength empirical curve development for SF₆ CBs.

A generalized dielectric curve model for 12 kV vacuum CBs covers more than 1 millimetre to produce the restrike waveforms and a useful tool for restrike risk prediction for 12 kV vacuum CBs.

Restriking waveform is one of the power quality problems that has not been tested with the Wavelet Transforms in the literature. The Wavelet Transforms are very good for visualization of the signal in different frequency bands. In this research, the simulated and measured restrike waveforms and their causes are analysed using Matlab software for automatic detection before any ATP-EMTP system restrike computation studies. This is a novel approach in this area.

Five simulation studies with practical model applications development on the basis of the literature review, which distinguishes what has been done from what needs to be done.

Experimental investigation of a 12 kV vacuum CB diagnostic was carried out for the parameter determination, and a passive antenna calibration was also successfully developed with applications for field implementation to validate the breaker restrike model and the hot dielectric strength empirical curve development for SF₆ CBs.

This research has developed a predictive interpretation technique using computer modeling and simulations for CB diagnostics to predict a breaker
performance for improving asset management by diagnosing the medium and high voltage CB condition.

6.3 Future work proposal

As there has been little previous published work focused on these restrike detection problems, there is significant scope for further work in this area. The following outlines proposals for possible future research areas grouped into four main areas from Subsections 6.3.1 to 6.3.4, though not in any specific order of importance. Other related work proposals are given in Subsections 6.3.5 to 6.3.9.

6.3.1 Restrike switch model development proposal

Table 6.1 provides a summary of the main items presented in this section and the following subsection, relating to future work on the application of the restrike switch model, parameter determination and algorithm robustness. As summarized in Chapter 5, there are a number of synergies to be found between the parameter determination required for the restrike switch model and for detection schemes, such as busbar connection.
Chapter 6: Conclusions and Future Work Proposal

Table 6.1. Summary of restrike switch model development proposal

<table>
<thead>
<tr>
<th>Work packages</th>
<th>Future work proposals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Models of current in CB</td>
<td>Virtual current chopping between other phases due to inductive and capacitive couplings from the source side</td>
</tr>
<tr>
<td>Parameter determination</td>
<td>Parasitic capacitance</td>
</tr>
<tr>
<td>Parameter sensitivity</td>
<td>Busduct connection particularly for SF6 CBs</td>
</tr>
<tr>
<td>Diagnostic algorithm</td>
<td>Investigate alternative methods such as self-organisation map for diagnosis</td>
</tr>
</tbody>
</table>

6.3.2 Parameter variation sensitivity analysis

The performance of the proposed model has been tested in simulations for POW and slow contact opening effects. However, additional model parameter variations can arise under both normal and faulted power system conditions, which should be investigated in relation to their restrike risk conditions.

6.3.3 ATP implementation and simulations on large scale power system models

Table 6.2 below summarizes the proposed power system models applied for the development of the restrike switch model. The proposed model has been developed and tested using a very simple power system model, intentionally chosen as a starting point for the research. However, any practical application of the restrike switch model requires the algorithm to be developed and tested with power system models that reflect both the scale and dynamics of large scale power systems.

Table 6.2. Summary of power system modeling proposal

<table>
<thead>
<tr>
<th>Work packages</th>
<th>Future work proposals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power system modeling short term development</td>
<td>Multi-source, multiple line model, for the investigation of parallel breaker operations.</td>
</tr>
<tr>
<td>Power system modeling medium term development</td>
<td>Specific modeling for &quot;special&quot; cases, e.g. near large generators/machines, series compensated lines, distributed generation.</td>
</tr>
<tr>
<td>Power system modeling long term development</td>
<td>Modeling of mutual line coupling, frequency and voltage changes during operational switching, dynamic current phase angle behaviour, &quot;ideal&quot; versus &quot;actual measured&quot; reference voltages for fault current modeling.</td>
</tr>
</tbody>
</table>
6.3.4 Automatic diagnostic algorithm for restrike waveforms using a self-organising map

Chapter 4 of this thesis provided a single-phase example of the algorithm performance using signal processing techniques, and demonstrated that the algorithm for restrike detection was able to perform adequately. While restrike recordings are a useful alternative source for simulation testing, it is difficult to obtain a comprehensive set of such data for all possible cases. In addition, sampling rates used by different restrike recorders can vary widely, and conducting an efficient and comprehensive testing using restrike recordings can involve a substantial amount of time and collation of the recordings into formats that can then be readily used for simulation purposes. In addition, there can often be the problem that not all operational data relating to a case and its interruption are readily available from the one data source; e.g., power system data may not always be directly included in recordings focused only on current and voltage waveform recording. The phase angle and measurement ratio errors inherent in the recording system should also be considered, as shown in Table 6.3.

Table 6.3. Summary of staged field trialling for SOM development proposal

<table>
<thead>
<tr>
<th>Work packages</th>
<th>Future work proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations with restrike recordings</td>
<td>Build a &quot;reference library&quot; of actual field restrike recordings for use in simulation testing and comparison with artificial power system restrike modeling performance.</td>
</tr>
<tr>
<td>Passive trialling</td>
<td>Observe restrike prediction accuracy and overall algorithm robustness.</td>
</tr>
<tr>
<td>Active trialling</td>
<td>Set-up for actual CB control for the detection of electrical wear, using the restrike detection algorithm.</td>
</tr>
</tbody>
</table>

6.3.5 Single-phase laboratory experiments and simulations for a restrike switch model parameter determination and calibration

These laboratory experiments were the first stage of a long-term experimental project in which a real branch (with real parameters) of a restrike switch model is to be examined. Although, before running the tests there was a certain concern about whether the single-phase configuration would give problems or not, it has been demonstrated that it works, but not perfectly. Moreover, it can be useful to have
single-phase experiments because the coupling between phases cannot occur and, thus, the results are easier to examine.

The comparison of the measured results with the simulated results has shown that there is a fair degree of similarity, but they are not exactly the same. The divergence could be due to the following facts:

- The model used gives the possibility of enabling/disabling the current chopping. If the chopping is enabled (that is the case of these simulations), then the current is always chopped no matter the power frequency. In reality, current chopping is only observed at power frequencies so, if the current is chopped also at higher frequencies, the consequent TRV after each current zero is steeper than in reality and the re-ignition number and frequency increases. In simulations, the re-ignition density is higher.
- The cold withstand curve is deduced from the measurements and modeled as a two point linear curve. However, the real withstand is not linear and it also depends on the hot gap withstand characteristics.
- The oscillation frequencies of the supply side and of the load side (separately) of the circuit are higher in simulations than in reality. This is evidence that some parameter/s has/have not been correctly chosen. One possibility is that if the above limitations are resolved, it should be extended to three-phase simulation for model calibration so that virtual current is taken into account for restriking behaviour.
- Due to the limitation of the experimental setup, it is difficult to obtain a realistic inductive load model for the variable inductance.
- Small capacitance, one quarter wavelength reflection, stray inductance and capacitance have affected the results for the high frequency rate of change of high frequency current quenching values.
- It is difficult to obtain an exact simulated waveform as a measured waveform due to the measurement errors and unknown parameters, such as chopping current value and connection inductance.
- The re-combination phenomenon on the post-arc current has a travelling wave with a swing effect for di/dt results. Post-arc restrike current modeling indicating vacuum CB performance is recommended for future work.
6.3.6 A generalised dielectric curve model for vacuum CBs other than the rating 12 kV vacuum CBs

This thesis has introduced a generalised dielectric curve model for 12 kV vacuum CB, and the methodology can be applied to other ratings. The studies on generalised dielectric curve model for vacuum CBs other than 12 kV and the evaluation are left for future work.

6.3.7 Arc Equation for vacuum CBs

This thesis has successfully applied Mayr Arc Equation to calculate the SF₆ CBs’ parameters such as time constant and power loss, with simulated waveforms against manufacturer data as a diagnostic parameter for breaker degradation conditions at 50/60 Hz power supply. An equation is recommended to be derived for the diagnostic purpose of a vacuum CB degradation condition at 50/60 Hz power supply.

6.3.8 Hot withstand dielectric model for vacuum CBs

An interesting phenomenon derived from multiple re-ignitions is that the gap does not have time to recover from re-ignition to re-ignition and its withstand decreases. The reason is that when an arc is extinguished, conducting particles precedent from the CB contacts are still floating in the gap and they reduce the withstand capability of the gap.

The decreased withstand is known as ‘hot withstand capability’ and is also recommended for further work.

6.3.9 Other signal processing techniques which can be used for feature extraction and classification of simulated restrike waveforms

Other than Section 6.4.4 with the self-organising map technique, there are many signal processing techniques to develop a restrike detection system such as artificial neural network and Kalman filter-based segmentation method.
6.4 Concluding remarks

The restrike switch model with contact opening velocity computation and its model applications and diagnostic algorithm using Wavelet Transforms to predict a breaker performance are summarised in Table 6.4 and Table 6.5.

Table 6.4. Summary of the techniques developed in the thesis

<table>
<thead>
<tr>
<th>Technique</th>
<th>Algorithm</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>A restrike switch model with contact opening</td>
<td>Hot dielectric strength empirical curve</td>
<td>• Breaker restrike risk prediction</td>
</tr>
<tr>
<td>velocity computation</td>
<td>development for SF₆ CBs</td>
<td>• Remaining life prediction to apply a developed formula from the literature</td>
</tr>
<tr>
<td></td>
<td>A generalised vacuum arc dielectric strength</td>
<td>• POW controlled switching investigation</td>
</tr>
<tr>
<td></td>
<td>curve model development for 12 kV vacuum CBs</td>
<td>• Checking system stresses in compliance with relevant standards</td>
</tr>
<tr>
<td></td>
<td>Envelope extraction for restrike risk</td>
<td>• Signal visualisation, suitable for signal exploration of degraded insulation</td>
</tr>
<tr>
<td></td>
<td>prediction</td>
<td>• Providing features for condition assessment</td>
</tr>
<tr>
<td></td>
<td>Predictive interpretation technique (as shown in Appendix G)</td>
<td>• Producing signatures to evaluate the signal processing and analysis techniques</td>
</tr>
<tr>
<td>A restrike detection algorithm development</td>
<td>Wavelet Transforms</td>
<td>• Breaker restrike diagnostic based on their causes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Automatic detection of restrike waveforms for simulated and measured data</td>
</tr>
</tbody>
</table>
Restrike is an abnormal electric arcing phenomenon for a breaker opening, which has a similar effect to that of lightning on air insulation or a heart attack on a human being. It is an indication of possible interruption failure of a CB. In this thesis, restrike waveform signatures are replicated with mathematical modeling using ATP and analysis of the breaker operational performance with parameters determination such as time constant, power loss and contact velocity. The concept itself appears to be obvious at first, but the reality of achieving such a prediction has been often considered too difficult to be viable. While computer simulations have solved many operational problems in the power industry over time, the advances in modeling and simulations allow us to predict operational problems, equipped with new and powerful tools. However, there are still many gaps in the representation of computer simulations to solve operational problems, such as the need for more detailed equipment modeling and improvement in measurement techniques.
While potential direct benefits to CB maintenance development have been identified from the application of computer modeling and simulations, it is possible that continued research in this area may provide additional benefits in associated areas for predicting the viability of other power equipment with restrike waveform signatures. The best measure of the success of this research will be whether it stimulates further research in this area to lead not only to better solutions, but also to an improved body of reference material with respect to non-intrusive techniques for medium and high voltage CBs in support of reliable, cost effective and sustainable electrical power utilization.

Future work is also recommended to include the development of diagnostic and prognosis algorithms for other power equipment that can be used to detect the signs of catastrophic events before they occur. These algorithms will greatly enhance power monitoring hardware and software and will allow engineers to mitigate problems on the power network before they become severe.
References


Symposium on Discharges and Electrical Insulation in Vacuum -Tours, pp. 602-605, 2002.


242


J. Bachiller, et al., "Switching of shunt reactors -theoretical and practical determination of high-voltage circuit breaker behaviour," Colloquium of CIGRE Study Committee 13, Florianopolis (Brazil), September 1995.


J. Bachiller, et al., "Switching of shunt reactors -theoretical and practical determination of high-voltage circuit breaker behaviour," Colloquium of CIGRE Study Committee 13, Florianopolis (Brazil), September 1995.


[131] J. A. Bachiller, et al., "The Operation of Shunt Reactors in The Spanish 400 kV Network-Study of The Suitability of Different Circuit Breakers and


Publications arising from the thesis

Published Conference papers


Published Journal Paper

Journal Papers under review


Appendix-A
Future Field Implementation Proposal

Chapter 5 has tested the dielectric curve model for a 12 kV vacuum CB, but it is very difficult to implement the same for SF₆ CBs with experimental work. Having validated the restrike switch model from the literature and experiments, it is proposed to validate the model with field implementation. This proposal is organised as follows: Section I – Introduction; Section II – Project Support; Section III – Specific Plan; and Section IV – Proposed Contributions.

I. Introduction

Ramli [8] measured the restrikes/re-ignition during shunt reactor switching using capacitive coupled antennas and active broadband antenna. He completed the single-phase laboratory experiment at Ergon Laboratory, Virginia (Queensland, Australia) and the three-phase exploratory three-phase capacitor bank switching measurement at Blackwall Substation. It is suggested that it should be possible to use simulated restrike waveform diagnosis for the evaluation of the developed hot withstand dielectric recovery model for the SF₆ circuit-breakers and then extend the research work to provide the evaluation of the developing diagnostic and prognostic algorithms with further system testing, using non-intrusive methods for measuring restriking activity.

A database will be established using the phase to earth voltage and the number of re-ignition/restrikes for online monitoring of re-ignition/restrikes. The advantage of the simulated input data is that it will have a similar behaviour to the online waveforms. This is only if the presumed independence and Gaussian assumption of the SF₆ dielectric strength are valid. Using the database as a part of an expert system for online monitoring, impending problems can be identified in advance. After services with such condition indicators, an improved life expectancy of the SF₆ puffer circuit-breakers can be expected.

It is proposed that the research project will cover the following:

(i) Equipment Familization and Data Collection 1) Substation layouts would be examined in order to enable the equivalent circuits of the systems to be studied. 2) Test reports of the CBs for shunt reactor
switching and capacitor switching duty and other relevant conditions would be examined and 3) Relevant power network data would be collected.

(ii) *Electromagnetic Transient Simulation Studies* Models of selected installations will be constructed and re-ignition/restriking conditions will be simulated. Special consideration would be given to determining the magnitude of high-frequency restriking current and voltages.

(iii) *Site Evaluation* Results from ATP-EMTP studies using previous site data [25] will be used for exploratory investigation. After estimating the number of the re-ignition and restrikes from the selected installation, the SF₆ CBs will be internally examined against the calculated deterioration.

II. Project Support

The following support is required:

1. Laboratory tests if required to reconfirm the ATP-EMTP simulated results
2. Equipment – data acquisition system and test gears
3. Identification of test sites
4. Field substation and plant data
5. Arrangement of internal examination of SF₆ CB internally after restrikes being detected to confirm and identify any deterioration match with the prediction.

III Specific Plan

A. To estimate the remaining life using energy loss and mechanical damage to the Teflon nozzle after restrikes/re-ignition, collect experimental waveforms/data for normal power frequency and transient voltage and current waveforms for predication of failure in terms of arc energy dissipation.

The used values of the curves and times in the model were taken from literature data[22], and the network data is taken from Australian Standard AS4372-1996.

The 400 kV with short-circuited current 60 kA gives

Inductance= \(\frac{400}{\sqrt{3} \times 60} = 3.85 \ \Omega\) or 12.3 mH i.e. less than 10% of shunt reactor inductance

Source capacitance= 0.03 µF i.e. more than 10 times load capacitance
Reactor capacitance = 1.9 nF

Reactor inductance = 2.55 H

Reactor resistance with 173A = 1330 Ω

Phenomenon: Depending on the ignition-delay, higher values were reached by a higher rate of the rising of the recovery voltage. Flashover in hot gas between the zero interruption current may cause re-ignition current for the single-phase case.

Simulation results and verification: The ATP model described above will be verified using the formulae with the following proposed results:

1. The literature survey on parameters for modeling such as parasitic capacitance and inductance to improve ATP simulation with parameters for ATP modeling
2. Match using ATP simulations the high frequency current switch to predict losses
3. Following the paper [116], the remaining life of a Teflon nozzle will be predicted I^2t losses
4. It will be verified by physical observation of damage done to a Teflon nozzle and wearout (mechanical strength) will be related to the nozzle’s remaining life.

B. To estimate the rate of degradation based on the number of restikes/re-ignition, it will be necessary to:

1. Calculate the number of high frequency re-ignition/restrikes with reference to each phase voltage, as shown in Figure 4.42
2. Estimate the standard deviation to determine the statistical variation of dielectric strength (With the help of the ATP Program, Monte-carlo capability in Matlab Program is determined to simulate the occurrence of each re-ignition/restrike.)
3. Feed the data into an ATP model to produce a simulated database for on-line system voltage monitoring and restriking current (This will produce a prediction of the impending failure rate and a rate of electrical degradation against experimental measurements and site evaluation.).

IV. Proposed Contributions
Three main contributions from this research project are proposed:

a. Diagnosis: Development of a database which will show phase-to-earth voltage across a SF$_6$ CB and the numbers of restrikes/re-ignitions; this data can be used to monitor breaker restrikes online.

b. Prognosis: Use of an ATP program to calculate the high frequency magnitude current inside a CB to estimate the cumulative energy current inside a circuit-breaker to estimate the cumulative energy inside a SF$_6$ CB to predict a nozzle’s lifetime.

c. Model evaluation: Validation of an ATP statistical model which will determine the statistical dielectric strength behaviour of a SF$_6$ circuit-breaker and improve the accuracy of computer simulations.
Appendix-B
Scheme of restrikes to determine breaker risk level

N= number of sample
M= number of sample used to calculate the energy of transient respond
γ = threshold of the spike in D1
E_{th}= threshold of transient energy

Figure B.1. Scheme of restrikes
Appendix-C
Summary of the breaker ABCD parameter experimental results

1. ABCD parameter determination for a vacuum breaker recloser

Table C.1. Summary of measurement results for different operation conditions from cold determination of dielectric strength and high frequency current slope to be used for computer simulations

<table>
<thead>
<tr>
<th>contact opening velocity (m/s)</th>
<th>Load Current (A)</th>
<th>A (V/s)</th>
<th>B (V)</th>
<th>C(A/s²)</th>
<th>D (A/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>10</td>
<td>6.10E+07</td>
<td>577.0</td>
<td>4.37E+02</td>
<td>2.64E+09</td>
</tr>
<tr>
<td>1.9</td>
<td>9</td>
<td>8.13E+07</td>
<td>1013.0</td>
<td>2.56E+02</td>
<td>3.05E+09</td>
</tr>
<tr>
<td>1.9</td>
<td>8</td>
<td>6.65E+07</td>
<td>600.0</td>
<td>1.04E+02</td>
<td>4.88E+09</td>
</tr>
<tr>
<td>1.9</td>
<td>7</td>
<td>6.30E+07</td>
<td>375.0</td>
<td>1.49E+02</td>
<td>2.20E+09</td>
</tr>
<tr>
<td>1.9</td>
<td>6</td>
<td>6.00E+07</td>
<td>554.0</td>
<td>1.13E+02</td>
<td>6.61E+09</td>
</tr>
<tr>
<td>1.9</td>
<td>5</td>
<td>7.54E+07</td>
<td>174.0</td>
<td>1.75E+02</td>
<td>3.02E+09</td>
</tr>
<tr>
<td>1.5</td>
<td>10</td>
<td>7.32E+07</td>
<td>370.0</td>
<td>8.00E+01</td>
<td>1.18E+09</td>
</tr>
<tr>
<td>1.5</td>
<td>9</td>
<td>7.07E+07</td>
<td>613</td>
<td>8.00E+01</td>
<td>1.34E+09</td>
</tr>
<tr>
<td>1.5</td>
<td>8</td>
<td>6.82E+07</td>
<td>855.0</td>
<td>8.00E+01</td>
<td>1.49E+09</td>
</tr>
<tr>
<td>1.5</td>
<td>7</td>
<td>6.00E+07</td>
<td>450.0</td>
<td>4.84E+01</td>
<td>1.17E+09</td>
</tr>
<tr>
<td>1.5</td>
<td>6</td>
<td>5.00E+07</td>
<td>89.0</td>
<td>5.44E+01</td>
<td>9.26E+08</td>
</tr>
<tr>
<td>1.5</td>
<td>5</td>
<td>4.70E+07</td>
<td>69.0</td>
<td>7.64E+01</td>
<td>7.32E+08</td>
</tr>
</tbody>
</table>
Appendix-D
PI Model of the vacuum circuit breaker

The internal RLC circuit of a vacuum CB is represented by a series RLC circuit \( \pi \) model using vector impedance measurement to find the component value. We can only measure impedance magnitude and phase.

![Diagram of PI model](image)

Using vector network analyzer, we can measure \( Z_A(f) \); \( Z_B(f) \) and \( Z_C(f) \), leaving all other terminals open circuit.

\[
Z_A(f) = \frac{Z_1(f)}{(Z_2(f)+Z_3(f))} \\
Z_B(f) = \frac{Z_2(f)}{(Z_1(f)+Z_3(f))} \\
Z_C(f) = \frac{Z_3(f)}{(Z_1(f)+Z_2(f))}
\]

Using these 3 equations, we can find the 3 unknown \( Z_1(f) \), \( Z_2(f) \) and \( Z_3(f) \) with Matlab.
Use Simulink to find $Z_A$, $Z_B$ and $Z_C$ of a circuit and work back to the circuit parameters.
The model results are as follows:

With the measured data for the 12 kV vacuum CB for open circuit – Zabo, Zago and Zbgo – where g = ground, where Zabo= impedance across terminal a and b with secondary open-circuit, where Zago= impedance across terminal a and ground (g) with secondary open-circuit and where Zbgo= impedance across terminal b and ground (g) with secondary open-circuit. The actual measurement are below:
The original π network is transformed into “T” network

\[ Z_A = Z_1 + Z_2 \]
\[ Z_B = Z_2 + Z_3 \]
\[ Z_C = Z_1 + Z_3 \]

\[ C = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{bmatrix} \]
\[ A = [ \ ]; \]

for \( i = 1:1000 \)
\[ B_i = [Z_B(i,1);Z_C(i,1);Z_A(i,1)] \]
\[ A_i = inv(C) * B_i \]
\[ A(:,i) = A_i \]
end

\[ Z_{1T} = A(1:1000); \]
\[ Z_{2T} = A(1001:2000); \]
\[ Z_{3T} = A(2001:3000); \]

where \( Z_{1T} \) = impedance across terminal \( Z_2 \) & \( Z_3 \) and \( bd \), where \( Z_{2T} \) = impedance across terminal \( a \) and \( Z_1 \) & \( Z_3 \) and where \( Z_{3T} \) = impedance across terminal \( c \) and \( Z_1 \) & \( Z_2 \).
Transforming back into the original circuit:

\[ Z_{1\pi} = \frac{(Z_{2T} \cdot Z_{3T}) + (Z_{2T} \cdot Z_{1T}) + (Z_{3T} \cdot Z_{1T})}{Z_{3T}} \]

\[ Z_{2\pi} = \frac{(Z_{2T} \cdot Z_{3T}) + (Z_{2T} \cdot Z_{1T}) + (Z_{3T} \cdot Z_{1T})}{Z_{1T}} \]

\[ Z_{3\pi} = \frac{(Z_{2T} \cdot Z_{3T}) + (Z_{2T} \cdot Z_{1T}) + (Z_{3T} \cdot Z_{1T})}{Z_{2T}} \]
Z2pi=R across breaker ≈2.5 ohm from the above diagram Y=2.464 ohm
L2pi=Inductance across breaker = 6 μH

C2pi=Capacitance across breaker = 20 nF from green line Y=2.023e-10 at 35 MHz.
C1pi=C3pi = Capacitance to ground = 32 nF from red line Y=3.2e-10 at 35 MHz.
The above results are validated by putting the RLC values onto the transfer function, and it was found that the difference between the pi model value and the transfer function value is most likely to be caused by the complicated breaker model.
similar to the transmission line and the instrument load as well as the co-axial cable modeling. It is expected that more detailed modeling of coaxial cables and equipment load will give better results of the RLC model parameter of the vacuum CB. For this reason, the value of the RLC model parameter was set at the PI model measured value in the simulation model.
Appendix-E

A high frequency power transformer model

The transformer transient model proposed by Kikkert [93] is the circuit shown in Figure E.1 below, and the circuit and data is evaluated with Simulink, as in Figure E.2.

Figure E.1. An ATP high frequency transformer model [93]

Figure E.2. A high frequency power transformer circuit model for simulation
Figure E.3. Model evaluation results for ABB transformer

Figure E.4. Model evaluation results for Power King transformer
Measurement setup

Vector Network Analyser was used to measure the impedance over a wider frequency range and is described in detail. The measurements and results along with their analysis are discussed and, finally, the model is validated by comparing the measured results with the corresponding calculated and Matlab simulated results. The measurements done on the single phase transformer were an important step to the modeling of one-phase transformers which represent the step-up transformer (TX1) and the load transformer (TX2).

3. Measurement setup load transformer (TX1)

Transformer TX1 (Figure E.5) in the experimental setup is the representation for one of the step-up transformers. It is a 10 kVA, 0.25 V/12.7 kV, 3% impedance step up transformer with low voltage side connected in and high voltage side. The transformer data, as it is shown in the name plate data, is given in Table E.1.
Table E.1. ABB single-phase SWER transformer nameplate data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>K. V. A.</td>
<td>10</td>
<td>50</td>
<td>12700</td>
<td>0.79</td>
<td>250</td>
<td>40</td>
<td>3 %</td>
</tr>
</tbody>
</table>

4. Measurement setup load side transformer (TX2)

The load side transformer TX2 (Figure E.6) is a 5 kVA, 12700 V/250 V distribution transformer with connected high voltage winding and connected low voltage winding. The specification of this transformer is given in Table E.2.

Figure E.6. Photo of Power King single-phase load transformer

Table E.2. Power transformer nameplate data

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>K. V. A.</td>
<td>5</td>
<td>50</td>
<td>12700</td>
<td>0.394</td>
<td>250</td>
<td>20</td>
<td>3.5 %</td>
<td>C44-23</td>
</tr>
</tbody>
</table>
The high frequency power transformer model from the literature was extracted by putting the RLC values onto the Simulink for modeling the corresponding terminal a to ground with terminal b floating. The difference between the measured value and the simulated function value is most likely caused by the measurement error and the noise environment. It is expected that the admittance measurement of both ABB and Power King transformers and then the best fit values can be obtained from the vector fitting method. The results are then analysed by Matlab System Identification tool box. For the simplicity of this research project, the value of the RLC parameter of both ABB and Power King transformers was set at the measured value at 35 MHz of the high frequency power transformer model from the simulation model in the literature.
Appendix-F

Models for the hot withstand dielectric strength characteristics curves for SF$_6$ CBs and 12 kV vacuum CBs

An empirical dielectric strength model for SF6 CBs

SF$_6$ (Sulphur Hexafluoride) CBs have excellent interruption and dielectric recovery characteristics, and can interrupt the high frequency currents which result from arc instability or a free burning arc. For example, in a reactor current interruption, the interrupting current is so small that an interruption occurs in a short arcing-time range, causing a very high transient recovery voltage to be applied over the short distance between contacts, which could result in a re-ignition or a restrike. This appendix deals with the modeling of the SF$_6$ CB in ATP that replicates the original breaker’s dielectric recovery characteristics because it is essential to have a dielectric recovery characteristic for restrike breaker computations. Rather than using the measured parameters, the model is developed from theories and the findings of research published on simulation, in order to determine the overvoltages and re-ignitions/restrikes that may result for SF$_6$ switching. This research offers improved physical understanding of published experimental data and represents a real step toward the computer simulation of SF$_6$ switching performance. This is because the prediction of the SF$_6$ dielectric recovery characteristics for hot recovery will be significant for the SF$_6$ CBs research and developed for asset management.

Introduction

Switching transients are a contributory factor in the ATP-EMTP simulation in some SF$_6$ CBs failures, but without the SF$_6$ dielectric recovery curves. Insulation weakness may have also have been a factor. There was no information about the SF$_6$ hot dielectric recovery curves, as shown in Table F.1 below.
### Table F.1. Comparison amongst the failure data

<table>
<thead>
<tr>
<th>Item</th>
<th>Case 1 [22]</th>
<th>Case 2 [130]</th>
<th>Case 3 [131]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>25 MVA Transformer</td>
<td>Reactor bank 33 kV, 40 MVA</td>
<td>150 MVAR Shunt reactors</td>
</tr>
<tr>
<td>SF₆ CB rating</td>
<td>138 kV, 40 kA</td>
<td>33 kV</td>
<td>400 kV</td>
</tr>
<tr>
<td>Insulation weakness</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Chopping overvoltage</td>
<td>1.3 p.u.</td>
<td>1.5 p.u.</td>
<td>2.2 p.u.</td>
</tr>
<tr>
<td>Re-ignition</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Load side natural frequency</td>
<td>High</td>
<td>1 to 5 kHz</td>
<td>1 to 2 kHz</td>
</tr>
<tr>
<td>Arcing time</td>
<td>Short</td>
<td>Short</td>
<td>Short</td>
</tr>
<tr>
<td>Calculated chopping currents</td>
<td>2 A to 5 A</td>
<td>1 to 20 A</td>
<td>2 A to 18 A</td>
</tr>
<tr>
<td>Maximum rate of rise of the recovery voltage</td>
<td>160 kV/ms</td>
<td>unknown</td>
<td>1 to 2.2 MV/s</td>
</tr>
</tbody>
</table>

SF₆ CBs use SF₆ gas as the arc interrupting medium. SF₆ puffer CBs in which the arc is cooled by a “puff” of gas compressed by the opening mechanism of the CB are used in high voltage distribution and transmission systems. During the moment of CB opening, the ionization and deionization in the extinguishing medium are in strong interactions with the trapped energy. The conductivity and temperature is increased rapidly due to the collisions between ions. The event is the temperature drop (associated with the conductance reduction) and the recovery capability increases between the contacts that lead to the so-called ‘dielectric recovery’. When the CB has interrupted the small inductive current, the recovery voltage occurs with a fast rising rate. The proposed model takes into account hot recovery and the rate of transient re-ignition voltage, where the relation of the arc time versus dielectric strength.

Spiliopoulos [132] states three distinct recovery phases: thermal like phase, transition phase and Paschen phase. This may be identified according to a slow-fast-slow sequence of recovery rates. During the first slow phase ($\Delta t < 100\mu s$), the recovery rate is about $4V/\mu s$, in the second phase ($100< \Delta t < 300\mu s$) the recovery rate is $23 V/\mu s$ and, in the last phase ($300< \Delta t < 1000\mu s$), the rate diminishes to
about 6.5 V/μs. The result implies different physical phenomena which are responsible for the post-arc dielectric behaviour determining the gas recovery characteristics during gas recovery. The dielectric recovery characteristics of SF₆ are also affected by the influences of metal vapour contamination, gaseous flow modifications, the arc current value, the test gap geometrical parameters – namely, the gap spacing – the point radius which recovers faster, and arc roots stagnation on recovery performances.

The post-arc SF₆ dielectric recovery characteristic is also affected by the severe transient recovery voltages caused by the high-frequency oscillation between the inductance of the reactor and its equivalent terminal-to-ground capacitance. Because of the relatively small reactive currents involved, SF₆ CBs tend to interrupt the reactive load currents at very small contact gaps. Current chopping occurs when the current is prematurely forced to zero by the aggressive interrupting action of the CB. When the dielectric strength of the interrupting medium in the small contact gap is exceeded by the severe transient recovery voltage, the CB will re-ignite and interrupt at the next current zero, usually at a current-chopping level higher than at initial interruption. Thus, conditions are created that could result in insulation failure in the reactors, or a failure of the circuit to interrupt. This is the explanation for small current interruption.

The re-ignition of the interrupter may occur at a later time after the final current zero when the arc channel has lost all residual conductivity. And the magnitude of the TRV is greater than the dielectric withstand of the arc column. This mode of interrupter failure is known as a ‘dielectric failure’ [133]. The fact that re-ignitions were dielectric rather than thermal in nature is because the time constants of the SF₆ arc actually decrease as the current falls to a low value, as analysed from the mechanism causing re-ignition of the plain break interrupter. This understanding of the interruption process is a pre-requisite to analysing the dielectric recovery SF₆ characteristics.

The dielectric strength recovery after a current is interrupted by a SF₆ CB is a hot recovery action and is slightly different from a cold recovery, as shown in Figure F.1. Even after the current is interrupted at current zero and the plasma has disappeared, the insulating gas in the post-plasma space is rather hot, and its insulation characteristics differ considerably from those of a cold gas. The dielectric
strength of the post-plasma space is restored by means of the hot gas cooling. Therefore, the recovery is quick when the space-cooling is high, and the initial rate of rise of the dielectric strength recovery characteristics becomes slow as the breaking current or arc duration time increases. Computer modeling for SF$_6$ CBs is not complete because the dielectric hot recovery characteristics of SF$_6$ CB is not available and most of the published papers use a typical value of dielectric cold recovery characteristic of the SF$_6$ interrupter[22].

As stated previously, the dielectric recovery characteristics are affected by the local electric field concentration on the electrode, local gas density distribution in high-velocity gas flow between contacts, the history of the hot gas heated by a large current arc, and other factors. All these factors are analysed by computer modeling or experimental investigations. The first aim of this work is to study the published data for SF$_6$ post-arc recovery and to convert it into per unit value for generalising a statistical model. The second aim of this work is to study the last regimes in the published data, particularly in the re-ignition/restrikes condition of SF$_6$ CBs, as information in this field is still incomplete. Eventually, the author will adjust the dielectric characteristic curve with the results measured by physical SF$_6$ CBs for the re-ignition/restriking waveforms.

![A typical value of dielectric recovery characteristic of the SF6 interrupter](image)

Figure F.1. A typical curve of dielectric recovery characteristic of the SF$_6$ interrupter with conversion with per unit for overvoltage [22]
What follows is: a theoretical and empirical analysis of the dielectric recovery characteristic curve (in Subsection F); a synthesis of empirical data to formulate a hot dielectric strength curve (in Subsection F2); discussion (in Subsection F3); and conclusions (in Subsection F4).

**F1 A theoretical and empirical analysis SF6 dielectric recovery characteristic curve**

It was reported that many researchers concerned with predicting the current zero behaviour of SF$_6$ CBs in flow have found poor correlation between their determinations and measurements, and many have resorted to the use of values of thermal conductivity in determinations that were arbitrarily made several times greater than values available in the literature. The increased values of thermal conductivity are now considered to be necessary in accounting for the effect of turbulence.

Bachiller et al. [131] reported that field tests in Spain were carried out on a CB from Types A2, B1, B2 and C, which were provided with synchronous relays; the results are shown in Table F.1 and Table F.2, and in Figure F.3 and Figure F.4.

<table>
<thead>
<tr>
<th>Item</th>
<th>Spain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>Three-phase air-core reactor rated 400 kV, 150 Mvar</td>
</tr>
<tr>
<td>SF$_6$ CB rating</td>
<td>400 kV</td>
</tr>
<tr>
<td>Inductance directly grounded</td>
<td>unknown</td>
</tr>
<tr>
<td>Arcing time</td>
<td>1 to 14 ms</td>
</tr>
<tr>
<td>Chopping overvoltage</td>
<td>1.69 p.u. except B1 type with 2.2 p.u.</td>
</tr>
<tr>
<td>Re-ignition</td>
<td>13 re-ignitions in the same half cycle for B1 type CB</td>
</tr>
<tr>
<td>Load side natural frequency</td>
<td>1.2 kHz</td>
</tr>
<tr>
<td>Transient recovery voltage</td>
<td>1 and 2.2 MV/s</td>
</tr>
<tr>
<td>Switching overvoltages recorded</td>
<td>Figure F.3</td>
</tr>
<tr>
<td>Calculated chopping currents</td>
<td>2 A to 18 A</td>
</tr>
</tbody>
</table>
Table F.3. Results of the tests.

<table>
<thead>
<tr>
<th>Re-ignition Type</th>
<th>Max. $K_a$ after re-ignition</th>
<th>Time (ms)</th>
<th>Max. $U$ at re-ignition</th>
<th>TRV Slope</th>
<th>Max. $K_a$ without re-ignition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2 Unique</td>
<td>1.37</td>
<td>4</td>
<td>2.03</td>
<td>1/2.1</td>
<td>1.19</td>
</tr>
<tr>
<td>B1 Multiple</td>
<td>2.2</td>
<td>-</td>
<td>2.06</td>
<td>2/9.3</td>
<td>1.3</td>
</tr>
<tr>
<td>B2 Unique</td>
<td>1.69</td>
<td>2</td>
<td>1.31</td>
<td>2</td>
<td>1.43</td>
</tr>
<tr>
<td>C Unique</td>
<td>1.47</td>
<td>1.2</td>
<td>1.35</td>
<td>2.1/2.2</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Figure F.2. Overvoltage curves in regression lines of each CB type
There is a direct co-relation between the overvoltage curves between the chopping number in various CBs. Their regression lines are the same pattern.
In the tests, overvoltage values across the terminals which produced re-ignitions were obtained as a function of the arcing time. These values and their minimum regression line arc were represented for one of the CBs in Curve A of Figure F.4. The Curve A, together with the Curve B for the maximum overvoltages, recorded the same two terminals of the CB. The intersection of the two curves at about 5 ms is the value for the minimum arcing time which does not produce re-ignition with synchronised opening.

Song et al. [41, 134] used two methods to predict the dielectric recovery strength of the model SF₆ CBs. One method (solid line) is the empirical formula as shown below:

$$V_{bd}(t) = \frac{a \rho^b}{E_0}$$  \hspace{1cm} (G.1)

where a,b are constants determined from the breakdown tests, and E₀ is the local stress when the potential difference is 100 V between both contacts. This equation
was based on the concept that the breakdown voltage can be described in the static SF6 gas with the local gas density $\rho$ and the local electric stress $E_o$. The other method is the theoretical approach based on the streamer theory proposed by Raether and Meek. Figure F.8 is the summation of results of Figure F.5, Figure F.6, Figure F.7 and Table F.4.

Figure F.5. Dielectric recovery data for Model A GCB
[126]

Figure F.6. Dielectric recovery data for Model B GCB
[126]
Figure F.7. Dielectric recovery data for Model C GCB

[126]

Figure F.8. Combined dielectric recovery data for Model A, B and C GCB
Table F.4. Comparison amongst Model A, B and C calculated results

<table>
<thead>
<tr>
<th>Item</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re-ignition</td>
<td>6 out of 15</td>
<td>2 out of 28</td>
<td>Zero</td>
</tr>
<tr>
<td>Arcing time</td>
<td>1 to 3 ms</td>
<td>1 ms</td>
<td>1 to 9 ms</td>
</tr>
<tr>
<td>Breakdown voltage</td>
<td>520 to 631 kV</td>
<td>572.4 to 595.4 kV</td>
<td>362 kV</td>
</tr>
<tr>
<td>Dielectric Recovery Data</td>
<td>Figure F.5</td>
<td>Figure F.6</td>
<td>Figure F.7</td>
</tr>
</tbody>
</table>

**Data interpretation**

In terms of precision, it can be said that the application of the empirical equation is more accurate in the prediction of the dielectric recovery characteristics. Also, the empirical equation seems to have fewer predicted errors than the theoretical approach based on the streamer theory.

It was found that the difference between the calculated results from the streamer theory and the empirical equation in the fast regime is referenced from Mitchell data due to the effect of turbulence. There is a flow accompanied with a shock wave, causing a great effect to the dielectric recovery performance when a small current is interrupted. This may be due to the different pressure ratio distributions in the downstream region of the nozzle throat.

From the test results in Figure F.6 for the dielectric recovery characteristics of the Model A CB, it was found that the restrikes occurred 5.46-6.54 ms after contact separation; these were outside the calculated results based on the empirical equation and the streamer theory. It seems that it is not reliable to use both equations to predict the dielectric characteristic, but the data outside the equations can be used for the prediction.

**F2 Analysis of dielectric recovery characteristic data**

Mitchell [135] developed a method of estimating the dielectric recovery that was based on a two-dimensional model of the arc, and used the model to calculate arc temperature by solution of equations for mass, momentum and energy. The computed temperature profiles of decaying arcs were then used to predict the dielectric recovery of the arc.
The dielectric recovery of SF$_6$ arcs were established in laboratory-scale CBs having two different nozzles, which were called “reference” and “enlarged” geometries. The breakdown voltages were computed at the stagnation point as a function of time after current zero. The results are plotted on Figure F.10 for the reference geometry. The figure shows the experimental breakdown voltages as points. Two recovery curves for the enlarged geometry, corresponding to two quite different initial conditions, are given in Figure F.11.

The theoretical curve (solid line) for the reference geometry begins at 50 μs after current zero, being at an average rate of over 1 kV/μs and continuing at this rate until the cold-gas breakdown limit is reached. The predicted recovery curve agrees well with the low end of the experimental scatter until about 200 μs. After 200 μs, the theory predicts recovery at a rate of about half the observed value of 1.5 kV/μs. Full recovery is predicted to take about 400 μs, or about 100-150 μs longer than the experimental value.

The experimental recovery curve for the enlarged geometry (see Figure F.10) has very little scatter, particularly the first 300 μs after current zero. After 400 μs, the simulation predicts an increased recovery rate of about 0.6 kV/μs. Recovery to the experimentally available voltage level of 300 kV is predicted to occur at about 500 μs.
Dielectric Recovery curves for enlarged geometry

![Graph: Time vs Breakdown Voltage]

Figure F.10. Dielectric recovery for enlarged geometry

[22]

Table F.5. Comparison between the reference geometry and enlarged geometry of the nozzles

<table>
<thead>
<tr>
<th>Regimes</th>
<th>Reference Geometry</th>
<th>Enlarged Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial fast condition</td>
<td>Begins at 50 μs after current zero</td>
<td>First 300 μs with very little scatter after current zero</td>
</tr>
<tr>
<td>low</td>
<td>An average rate of over 1 kV/μs</td>
<td>Increased recovery rate of about 0.6 kV/μs after 400 μs</td>
</tr>
<tr>
<td>fast</td>
<td>Full recovery about 400 μs</td>
<td>Full recovery about 500 μs</td>
</tr>
<tr>
<td>Dielectric recovery</td>
<td>Figure F.10</td>
<td>Figure F.11</td>
</tr>
</tbody>
</table>

Mitchell’s criterion for dielectric breakdown is calculated as

\[ U_b = (E/N)^*(U / E) pN_0(T_o / T) \]  \hspace{1cm} (G.2)

Critical value of \((E/N)^*\) for SF6 is \(3.6 \times 10^{-15}\)

where \(p\) is pressure in bars and \(N_0 = 2.45 \times 10^{19} \text{ cm}^{-3}\) is the gas number density at \(T_o = 300\ \text{K}\) and 1 bar. This technique obtains good agreement between the minimum measured breakdown voltage and theoretical predictions for situations where the temperature of the stagnation point is below about 2000 K.

It was found that the theoretical curve (solid line) of both the reference geometry and enlarged geometry were offset from the actual breakdown data due to the effect of turbulence.
F.2.1 Synthesis of data to combine a hot dielectric strength curve for the SF₆ CBs

In order to develop a hot dielectric strength curve for the SF₆ CBs, field test data and laboratory test data are interpreted and combined below:

F.2.2.1 Field tests data for small current inductive interruption

Field Tests in Germany in 1992, as shown in Figure F.11:

![Graph showing field test data in Germany](image)

**Figure F.11. Field tests in Germany [136]**

**Data interpretation**

There were only three isolated break-downs. This may have been due to a particle fixed to an insulator, free moving particles or multiple faults [137]. Other data could be approximately represented by a straight line with scatters on the breakdown overvoltage time characteristics. The overvoltage (p.u.) is maintained between 0.9 and 1.4 due to the controlled switching operation.

F.3. Field tests in Spain

Field Tests in Spain in 1994, as shown in Figure F.12:
Data interpretation

This is an enlarged geometry of the nozzle on the basis of the data being approximately represented by a straight line, with little scatter on the breakdown overvoltage time characteristics. The overvoltage (p.u.) is maintained between 1 and 1.6 due to the controlled switching operation.

Data interpretation

The test results in principle indicate the same behaviour of the CB both in Spain and Germany, which is almost independent of the network configuration. Comparison of the results, as shown in Table F.6, can be used to determine a SF$_6$ CB’s behaviour such as dielectric recovery characteristics, number of re-ignitions and overvoltages when switching small inductive currents for reactor switching. On
the basis of normal distribution of statistics, the prospective behaviour of the SF₆ CB can be predicted.

Table F.6. Comparison between the field data in Spain and Germany

<table>
<thead>
<tr>
<th>Item</th>
<th>Spain</th>
<th>Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor</strong></td>
<td>Five-legged gapped iron-core reactor rated 420 kV, 150 Mvar, 200 A</td>
<td>Five-legged gapped iron-core reactor 110 Mvar, 150 A</td>
</tr>
<tr>
<td><strong>SF₆ CB rating</strong></td>
<td>420 kV, 50 kA, 50/60 Hz, 3150 A</td>
<td>420 kV, 50 kA, 50/60 Hz, 3150 A</td>
</tr>
<tr>
<td><strong>Inductance directly grounded</strong></td>
<td>3.7 H</td>
<td>5.1 H</td>
</tr>
<tr>
<td><strong>Arcing time</strong></td>
<td>10.5 ms</td>
<td>8 ms to 13 ms</td>
</tr>
<tr>
<td><strong>M Chopping overvoltage</strong></td>
<td>1.3 p.u.</td>
<td>1.08 p.u. up to 1.89 p.u.</td>
</tr>
<tr>
<td><strong>Re-ignition</strong></td>
<td>6 out of 26</td>
<td>25% of 68 i.e. 17</td>
</tr>
<tr>
<td><strong>Load side natural frequency</strong></td>
<td>1310 Hz</td>
<td>1280 Hz</td>
</tr>
<tr>
<td><strong>Load side capacitance</strong></td>
<td>3.9 nF</td>
<td>3 nF</td>
</tr>
<tr>
<td><strong>Switching overvoltages recorded</strong></td>
<td>Figure F.12</td>
<td>Figure F.13</td>
</tr>
<tr>
<td><strong>Calculated chopping currents</strong></td>
<td>2 A to 14 A</td>
<td>2 A to 14 A</td>
</tr>
<tr>
<td><strong>Maximum rate of rise of the recovery voltage</strong></td>
<td>2.2 MV/ms</td>
<td></td>
</tr>
</tbody>
</table>

**Laboratory test data**

**Data interpretation**

The dielectric recovery data from Japan, as shown in Table F.7, has three clusters: 0 to 3.2 ms with overvoltages up to 0.3 p.u., 4 to 7 ms from 0.5 to 0.9 p.u. and 7 to 9 ms from 1.2 to 1.85 p.u. Figure F.13 is the derived results from Table F.6 and Figure F.14.
Table F.7. Laboratory test data in Japan

<table>
<thead>
<tr>
<th>Item</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>Single-phase air-core reactor rated 500 kV, 150 Mvar, 347 to 381 A</td>
</tr>
<tr>
<td>SF₆ CB rating</td>
<td>550 kV</td>
</tr>
<tr>
<td>Inductance directly grounded</td>
<td>2.65 Henry(H)</td>
</tr>
<tr>
<td>Arcing time</td>
<td>9 to 18 ms</td>
</tr>
<tr>
<td>Chopping overvoltage</td>
<td>1.5 p.u</td>
</tr>
<tr>
<td>Re-ignition</td>
<td>Up to 9 ms between CB contact separation point and first reactor current zero point and to be determined by controlled switching with phase angle</td>
</tr>
<tr>
<td>Load side natural frequency</td>
<td>1.8 to 2.5 kHz</td>
</tr>
<tr>
<td>Load side capacitance</td>
<td>0.1 source side capacitance</td>
</tr>
<tr>
<td>Switching overvoltages recorded</td>
<td>Figure F.13</td>
</tr>
<tr>
<td>Calculated chopping currents</td>
<td>2 A to 18 A</td>
</tr>
<tr>
<td>Maximum rate of rise of the recovery voltage</td>
<td>2.2 MV/ms</td>
</tr>
</tbody>
</table>
Figure F.13. Laboratory dielectric recovery data from Japan [138]
<table>
<thead>
<tr>
<th>Item</th>
<th>Spain</th>
<th>Germany</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reactor</strong></td>
<td>Five-legged gapped iron-core reactor rated 420 kV, 150 Mvar, 200 A</td>
<td>Five-legged gapped iron-core reactor 110 Mvar, 150A</td>
<td>Single-phase air-core reactor rated 500 kV, 150 Mvar, 347 to 381A</td>
</tr>
<tr>
<td><strong>SF₆ CB rating</strong></td>
<td>420 kV, 50 kA, 50/60 Hz, 3150 A</td>
<td>420 kV, 50 kA, 50/60 Hz, 3150 A</td>
<td>550 kV</td>
</tr>
<tr>
<td><strong>Inductance directly</strong></td>
<td>3.7 H</td>
<td>5.1 H</td>
<td>2.65 Henry(H)</td>
</tr>
<tr>
<td><strong>grounded</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Arcing time</strong></td>
<td>10.5 ms</td>
<td>8 ms to 13 ms</td>
<td>9 to 18 ms</td>
</tr>
<tr>
<td><strong>Chopping overvoltage</strong></td>
<td>1.3 p.u.</td>
<td>1.08 p.u. up to 1.89 p.u.</td>
<td>1.5 p.u.</td>
</tr>
<tr>
<td><strong>Re-ignition</strong></td>
<td>6 out of 26</td>
<td>25% of 68 i.e. 17</td>
<td>Up to 9 ms between CB contact separation point and first reactor</td>
</tr>
<tr>
<td>Current zero point and</td>
<td></td>
<td></td>
<td>current zero point and to be determined by controlled switching</td>
</tr>
<tr>
<td><strong>Load side natural</strong></td>
<td>1310 Hz</td>
<td>1280 Hz</td>
<td>with phase angle</td>
</tr>
<tr>
<td><strong>frequency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Load side capacitance</strong></td>
<td>3.9 nF</td>
<td>3 nF</td>
<td>0.1 source side capacitance</td>
</tr>
<tr>
<td><strong>Switching overvoltages</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>recorded</strong></td>
<td>Figure F.12</td>
<td>Figure F.13</td>
<td>Figure F.14</td>
</tr>
<tr>
<td><strong>Calculated chopping</strong></td>
<td>2 A to 14 A</td>
<td>2 A to 14 A</td>
<td>2 A to 18 A</td>
</tr>
<tr>
<td><strong>currents</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Maximum rate of rise of</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>the recovery voltage</strong></td>
<td>2.2 MV/ms</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparison for field data in Germany & Spain and Japan laboratory data

Figure F.14. Combined data from fields and laboratory dielectric recovery results
Figure F.15. A hot dielectric recovery model derived from the laboratory dielectric recovery data from Japan and the measured data from Korean experimental results

F.4 Discussion

The temperature decay after current interruption at zero current, as well as the gas density, determines the SF$_6$ dielectric recovery characteristics of the arc region. According to the experiments and the determinations, three different regimes can be distinguished in the first few hundred microseconds after current interruption: the thermal, the transition and the Paschen regime. The fast regime during the Paschen phase can be adjusted to give different re-ignitions.

SF$_6$ dielectric recovery characteristics are summarised as follows:

1. Effect of Arcing time

Arcing time of the SF$_6$ CBs is the time between the contact separation and the following current zero. The higher the arcing time, the more sufficient the capacity provided for the breaker to develop its dielectric strength. This leads to the successful interruption of the arc. Prevention of re-ignition overvoltages and re-ignition can be achieved by phased-angle-controlled switching [139].

289
2. Overvoltage level
Each SF₆ CB has different overvoltage (p.u.) against time. The higher the overvoltage, the higher probability of the re-ignition/restriking.

3. Scattering due to the magnitude of the turbulent effects
There are different scatters for breakdown voltage (p.u.) which can be represented by confidence intervals.

4. Imperfection of gas
This may be due to a particle fixed to an insulator, free moving particles or multiple faults.

5. Standard or enlarged geometry for nozzle
The enlarged geometry has very little scatter, while the standard geometry has a wide scatter for breakdown voltage level.

In order to develop a statistical model for the SF₆ CB, laboratory test, data from Japan is used as a reference. Types of characteristics to be used in computer modeling are:

(i) The recovery curves exhibit distinct phases with time as well as different recovery rates according to a fast -slow-fast sequence. Re-ignition/restriking occurs at the final slow regime.

(ii) The final fast regime exhibits scatter dielectric recovery characteristic due to turbulence effect. This can be represented by standard deviation.

(iii) Breakdown arcing time is between 2 to 8 ms for reactor switching. The average breakdown voltage curve V50 and deduce curves, V50(1-σ (sigma)), V50(1-2 σ) and V50(1-3 σ) are shown in the above figure. The sigma denotes statistical standard deviation 8% and is assumed to be based on the insulation testing under uniform fields.

F.5 Conclusion
The dielectric characteristics of SF₆ CBs have been studied using fields in Germany and Spain, laboratory tests and determinations. A complete set of experimental and field data are presented as well as the physical characteristics. The main conclusions are as follows:

1. The use of field/experimental hot recovery data in per unit value is more accurate than a typical value of dielectric cold recovery characteristic of the SF₆ interrupter, taking into account the final fast regime, the arcing time, imperfection of the gas,
standard or enlarged geometry of the nozzle, and scattering due to the magnitude of turbulence effect.

2. The scatter variation can produce different re-ignitions/restrikes.

3. The health condition of SF$_6$ can be represented by cluster analysis of the dielectric recovery characteristic.

**F.2 A generalised dielectric strength model for 12 kV vacuum CBs**

This subsection generalises the modeling of vacuum CB dielectric strength. It also presents a novel way to model the curve, combining a straight line, Equation $V_{BD} = \alpha d^n$ and experimental results. The model takes into account the vacuum breakdown voltage and electrode separation, and its connection to the vacuum breakdown mechanism. The resulting model produces restrike waveforms for analyzing vacuum CB dielectric strength degradation data. This model is then compared with the manufacturer’s model to identify which is better for the simulated waveforms of restrikes/re-ignition phenomenon for 12 kV vacuum CB equipment data. Experiments also prove how adequate this model is for restrike waveform signatures in Chapter 5.

**F.2.1 Introduction**

Modeling of vacuum CB’s dielectric strength characteristic curve is one of the most important problems of computer simulations of transients in power systems [34]. Restrikes are initiated when the transient recovery voltage exceeds the dielectric strength. One of the possible effects is the vacuum dielectric strength degradation. Current practice in studying CB degradation due to restrikes is shown in Ref.[83].

A statistical vacuum CB dielectric strength model with ATP is proposed by several authors [8],[53] and [140]. However, there were several common shortcomings in all these papers. Firstly, with the exception of [149], many authors only took the time axis into account for computer simulations, without taking the contact opening velocity into account. Secondly, no statistical breakdown probability has been considered in the literature. Accordingly, no standard formula has been derived for vacuum CB dielectric curve characteristics. Thirdly, a standard form for computer simulations, which can be incorporated as a model for any setup, has not been given.
In this subsection, modeling methodologies are proposed. In order to apply the derived Equation $V_{BD} = a d^n$ and the straight line equation from the literature [141], theory and experimental results related to the vacuum breakdown mechanism are used. A generalised statistical vacuum CB dielectric strength model is proposed, which takes into account the contact opening velocity and different prestressing until the complete arc is quenched, and which provides more accurate modeling of vacuum CB dielectric strength behaviour and its connection to the vacuum breakdown mechanism. In Subsection F.2.3, laboratory layout and typical results are presented. In Subsection F.2.4, developed ATP models and matched waveforms of re-ignitions/restrikes are produced. In Subsection F.2.5, predicted results and discussion are presented, and conclusions and future work are given in Subsection F.2.6.

In this subsection, a generalised statistical vacuum CB dielectric strength model for the restriking/re-ignition phenomenon is proposed. This model incorporates Ref. [142] because it improves the accuracy of the simulated results, and the simulated results of restriking/re-ignition phenomenon in a 12 kV vacuum CB are presented against the manufacturer’s model. The current manufacturer’s statistical model is defined as dielectric strength variation on the basis of Weibull distribution for the summation of each breakdown voltage probability. The main goal of this contribution is to develop a generalised statistical vacuum CB dielectric strength model as a tool for the production of simulated waveforms with restrikes/re-ignition, using a 12 kV vacuum CB experimentally and findings from a literature search.

F.2.2 Proposed modeling methodologies

A power system is formed by different kinds of components and equipment and the simulation adopted. The following describes a general modeling methodology for the components under study. For this reason, the components that are analysed include high frequency response, supply source, auto-transformer, vacuum CB, cable and the damped inductive dividers.
Supply Source

Supply source is represented by the ATP-EMTP software with supports for an AC voltage source and a series source inductance.

Auto-transformer Model

A standard ATP model, the Saturable Component, was used [89].

Vacuum CB

A statistical vacuum CB model, as per [143], and the statistical vacuum CB is revised with the following three features:

1. Current chopping = 3 A, as recommended by [53]
2. Contact opening velocity = 1 m/s

Arc quenching capability, as measured by Glinkowski [31], are referred to Table F.9.

<table>
<thead>
<tr>
<th>di/dt</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>-3.4E11</td>
<td>255.0E6</td>
</tr>
<tr>
<td>Medium</td>
<td>0.32E12</td>
<td>155.0E6</td>
</tr>
<tr>
<td>Low</td>
<td>1.00E12</td>
<td>190.0E6</td>
</tr>
</tbody>
</table>

The low di/dt is selected for the ATP simulation.

It is relatively easy to measure a dielectric characteristic of a vacuum CB dynamically, i.e., under actual opening (or closing) condition. Typically, an R-C circuit with high resistance (some MOhms) and relatively modest capacitance is used. The capacitor is charged to some DC voltage (somewhere around the maximum peak of the TRV) and when the gap is opened and current interrupted, the capacitor charges the stray capacitance of the vacuum gap through the resistor. In this way, the charging time constant is very short (some pF of vacuum gap x MOhms of the resistor) and the gap quickly breaks down. Since the resistor limits the discharge current to a very small value (mA), the gap immediately interrupts this current and recovers again. The cycle repeats and the resistor charges the gap from the capacitor, which can be obtained from the manufacturer or the literature. Also,
the statistical properties of a dielectric strength rise are expressed by a Weibull distribution as follows:

A continuous random variable V has a Weibull distribution if its density function is given:

\[ F(V) = \alpha \beta V^{\beta-1} e^{-\alpha V^\beta}, \quad V > 0, \text{ elsewhere}, \]

where the scale parameter is \( \alpha \) and shape parameter is \( \beta. \)

Data has been extracted from the literature for Type A 12 kV vacuum CB 50 kV/ms for rise of dielectric strength regarding breakdown voltage and gap length relationship [144].

Using the equation

\[ V_{BD} = \alpha d \quad (G.3) \]

\[ V_{BD} = 43.889d \text{ for } d < 2\text{mm due to field emission} \]

\[ V_{BD} = \alpha d^n \text{ from [141] for } d > 3\text{mm due to micro-particle and Matlab curve fitting tool:} \]

\[ V_{BD} = 43.889d^{0.876} \quad (G.4) \]

for 50% breakdown

Minimum  \( V_{BD} = 33.902d^{0.9141} \)

Maximum  \( V_{BD} = 55.984d^{0.8046} \)

Assume the vacuum CB opening velocity if 1 m/s.:

Figure F.16 is more accurate than the straight line equation for ATP simulations compared with a straight line equation.

![Figure F.16](image)

Figure F.16. A general dielectric strength model for 12 kV vacuum CBs taking vacuum breakdown mechanism into account
The curves in different colours (green, red, blue and purple) in Figure F.17 represent the different dielectric strength characteristics for different prestressing until the complete arc quenching. Ref. [145] has shown that the dielectric strength depends on the rate of rise of the recovery voltage, which occurs to the opening contact-system.

![Figure F.17. A novel statistical dielectric strength curve taking consideration of transitional process, chopping current and rate of current rise after current interruption [146]](image)

Modeling of the vacuum dielectric strength and chopping current make use of a random generator in ATP, where numbers in the interval [0,1] were defined. Alternatively, we can simulate and model the statistical vacuum CB for the probability $P(EV)$ as per the following manufacturer model [147], as shown in figure 3.31 and get the probability from experimental results [148].

$$P(EV) = 1 - \exp\left( - \left( 1.125 \left( \frac{EV}{\overline{EV}} - 0.2 \right) \right)^n \right) \quad (G.5)$$

when $\overline{EV}$ is the average dielectric strength and $EV$ is the instantaneous dielectric strength value where $n=6.96$ for type A 12 kV vacuum CB.

Welbull distribution breakdown probability =

$$P(EV) = 1 - \exp\left( - \left( 1.125 \left( \frac{EV}{50} - 0.2 \right) \right)^{6.96} \right) = 0.5$$

295
P(EV) = 52.16 kV (50% breakdown probability) 
P(EV) = 55.3 kV (68.27% breakdown probability) 
P(EV) = 62.2 kV (95.45% breakdown probability) 
P(EV) = 67.26 kV (99.7% breakdown probability) 

Each re-ignition as it occurs during a simulation is recorded as to instantaneous voltage and time of occurrence.

![Figure F.18. Dielectric strength characteristic derived from Ref.[143] and Ref.[147]](image)

**The Cable**

The cable has been modeled using the cable model available in ATPDRAW. During a literature search, it was found that there are two ATP cable models that have been published with similar cases [4]. The significance of this is to apply the cable model against the experimental results.

The two ATP cable models are: a simplified cable model that makes use of [-] sections with a capacitance and a resistance and inductance, and the JMarti
frequency-dependent cable model. Only \( \Pi \)-sections with a capacitance and a resistance and inductance are used in the simulations.

When the experiments were performed it was observed that the used voltage dividers do not have the same characteristics and did not provide the same exact result. In order to obtain a better match between simulations and measurements, a damped inductive model has been proposed. The values are given by [149].

Each re-ignition/restrike as it occurs during each simulation is recorded as to instantaneous voltage and time of occurrence. With more simulations, we can calculate the statistical probability of re-ignition/restrike for that vacuum CB.

F.2.3 Laboratory layout and typical results

The laboratory experiment should trial several different arrangements and operating conditions for calibration with condition monitoring method of restriking medium voltage CBs.

Figure F.19 shows the circuit arrangement. A set-up transformer is used to raise the test voltage 5 kV as the network source voltage. A 11 kV rated vacuum CB is used to switch the reactor.

For the load side, the rated inductance \( L_a \) is 20 H and the total load side equipment capacitance \( C_L \) is 5.0 nF.

The natural frequency of the LC oscillation on the load side is:
\[ f_0 = \frac{1}{2\pi \sqrt{L_B C_L}} = 500 \text{Hz} \quad (G.6) \]

**Cable**

Cable has a length of 5 m and its data is reported in Table F.10 as follows:

<table>
<thead>
<tr>
<th>Rated voltage [kV]</th>
<th>24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section of the conductor [mm²]</td>
<td>95</td>
</tr>
<tr>
<td>Conductor material</td>
<td>Al</td>
</tr>
<tr>
<td>Insulation thickness [mm]</td>
<td>5.5</td>
</tr>
<tr>
<td>Insulation material</td>
<td>XLPE</td>
</tr>
<tr>
<td>Inner/outer semiconductor thickness [mm]</td>
<td>0.8/0.7</td>
</tr>
</tbody>
</table>

Inductance= 0.00345 mH  
Capacitance= 0.00085 μF

**Autotransformer**

A step-up transformer (15 kVA, 0.24/11 kV) is used to raise the low voltage of the mains supply to a suitable high voltage 5 kV, simulating the network source voltage.

**Coaxial cable**

The coaxial cable is of double shielded RG88 Cellfoil with low loss characteristics. The cable capacitance per meter is 100 pF. Each cable length for the passive antenna is set to 20 metres in order to ensure similar capacitance from each antenna to the oscilloscope.

Figure F.19 shows a single core XLPE cable connected from the vacuum CB to the 20 H reactor, which is not visible in the photograph. The passive antenna can be
seen to be located next to the reactor. The active antenna and oscilloscopes are located inside the laboratory room. A series of tests were carried out at varying test voltages and varying antennas location for both passive and active antenna.

In the test, the passive antenna was located close to the supply transformer and the active antenna was located in the control room. Prior to the opening test being carried out, measurement was carried out to calibrate the passive antenna using the supply voltage. The calibration was carried out with the vacuum breaker in closed position.

Figure F.19 shows the results similar to Ref. [150] for the voltage escalation and multiple re-ignition. This is one of the possible vacuum CB degradation features and will be analysed with signal processing techniques such as Wavelet Transforms.

F.2.4 Developed ATP models for restrike waveforms

The models, as shown in Figure F.20, are used to represent the components in the laboratory experiment with ATP-EMTP for comparison. From these results, it needs to be also pointed out that the application of POW switching of supply angle, and the dielectric strength breakdown behaviour must be adjusted in order for the restriking/re-ignition to be modeled correctly.

Figure F.20. ATPDRAW Model to duplicate for the experimental measurements for simulated waveforms production

F.2.5 Predicted results and discussion

Below are the legend for the results, as shown in Figure F.21.
EL=Generalised Model Minimum Limit
EM= Generalised Model Median Limit
EU= Generalised Model Maximum Limit
M1=Manufacturer Model breakdown probability 50%
M2=Manufacturer Model breakdown probability 68.27%
M3=Manufacturer Model breakdown probability 95.45%
M4=Manufacturer Model breakdown probability 99.7%

From Table F.11 the number of strikes happening for the generalised model was closer than Table F.11, the manufacturer’s model, which is closer to the number of restrikes for actual waveforms using the same set of data.

Table F.11. Results for different dielectric strength curves

<table>
<thead>
<tr>
<th>Dielectric Strength Curve</th>
<th>Number of restrikes</th>
<th>% Difference from the measured switch</th>
</tr>
</thead>
<tbody>
<tr>
<td>EL</td>
<td>24</td>
<td>4</td>
</tr>
<tr>
<td>EM</td>
<td>18</td>
<td>28</td>
</tr>
<tr>
<td>EU</td>
<td>13</td>
<td>48</td>
</tr>
<tr>
<td>M1</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>M2</td>
<td>11</td>
<td>56</td>
</tr>
<tr>
<td>M3</td>
<td>12</td>
<td>52</td>
</tr>
<tr>
<td>M4</td>
<td>13</td>
<td>48</td>
</tr>
</tbody>
</table>
F.2.5 Conclusions

A novel vacuum statistical restrike switch model was set up with all parameters as an input for ATP simulations to produce simulated waveforms of re-ignitions/restrikes related to the vacuum breakdown mechanism. There is a noticeable difference in the statistical vacuum dielectric strength model from the manufacturer equation and the generalised model derived from literature. It has been stated that a more accurate number of restrikes is indicated in the generalised model than in the manufacturer’s model. The generalised model can give median, maximum and minimum breakdown value. The manufacturer’s model can give results for 50%, 68.27%, 95.45% and 99.7% breakdown probability in the simulations.

The results of matching the equation with the experimental work are more accurate than the corresponding manufacturer’s data using the experimental results. Appropriate confidence intervals will be developed as a parametric determination (sensitivity analysis) model on the basis of experimental work.
Appendix-G
A predictive interpretation technique for CB diagnostics

The basic circuit:

Figure G.1. A laboratory test setup with inductive load
The Transformers are represented by the high frequency power transformer model in Appendix E. Dielectric strength characteristic is the actual dielectric envelope from measurements.

G.1 A predictive interpretation technique for different parameters

In accordance with IEEE Guidelines for the Application of Shunt Reactor Switching IEEE Standard. C37.015TM-2009, a typical waveform signature is as below:

![Waveform Diagram]

\[ V_o \] is the power frequency crest voltage across the shunt reactor at the instant of current interruption
\[ V_o' \] is the supply-side capacitance voltage after charge redistribution at reignition
\[ k_s \] is the suppression peak overvoltage in pu of \( V_o \)
\[ k_P \] is the reignition overvoltage peak to ground in pu of \( V_o \)
\[ k_1 \] is the reignition overvoltage excursion in pu of \( V_o \)

\[
\frac{V_o'}{V_o} = \frac{C_1}{C_s + C_L} \left( 1 - k_2 \frac{C_L}{C_s} \right)
\]

Figure G.2. Re-ignition at recovery voltage peak for a circuit with low supply-side capacitance

[151]
In order to distinguish the waveform degradation features for different parameters, the predictive interpretation technique used two interrupter degradation factors to characterize the CB’s behaviour:

1. Recovery slope

   The recovery curve can be approximately taken as a straight line with slope $S$ due to the combined effects of contact material with breaker contact separation velocity:
   
   \[ U_b(t) = S \cdot t + U_{bo} \]

   where $U_b$ is the breakdown voltage
   
   $U_{bo}$ is in the order of 0.5 – 1 kV from measurement [152]
   
   the value of the constant $S$ same as $A$ is measured or calculated to be between 2 V/µS and 50 V/µS when B is set to zero in Ref. [6], which is quite normal when determining the dielectric withstand of the breaker.

2. Breakdown reduction factor

   The HF interruption ability is usually expressed as the maximum value of $\frac{dI}{dt}$ that can be interrupted; however, it was found that interrupted $\frac{dI}{dt}$ is far from a constant for a very small gap length (less than 1 mm) from experiments. Therefore, another parameter to character HF interruption ability during current zero has been defined as follows.

   The UHF-TRV is caused by parasitic ($C_{hf}$, $L_{hf}$) near or inside the vacuum CB, as shown in Figure G.2. The maximum value of this UHF-TRV depends on the residual voltage ($U_{co}$) – at HF current zero – on the equivalent capacitance ($C_{hf}$) that Dr.ives the HF current. Dielectric process is assumed to be responsible for continuation of the HF arcing period, it can be stated that an alternative criterion is stated for HF current interruption as below:

   \[ U_{in} < \alpha U_b \]

   where $\alpha$ is the breakdown reduction parameter ( in theory $0 \leq \alpha \leq 1$) that incorporates the reduction of the (cold) breakdown voltage by previous HF arcing. From simple circuit-theory, both parameters can be linked by the following equation:

   \[ \frac{dI}{dt} \text{ max} \]

   From the above Equation H.1 it can be seen that $\frac{dI}{dt} \text{ max}$ is dependent on both circuit and recovery slope, where $\alpha$ is a candidate for a truly independent interruption parameter [152].
Parameter variation studies determination methods:

ATPDRAW program was applied to calculate waveforms of currents and voltages associated with multiple re-ignitions. It completely took into account the HF phenomenon. In this method, relevant parts of the waveforms can be treated in an analytical way.

G.2 Simulation of parameter – contact opening velocity for a transformer load

The slow contact opening velocity results in slow rise in the withstand dielectric strength which is less than the TRV; therefore, it is anticipated that more resrikes will occur and with a longer restrike duration. The way we expect the slow contact opening velocity to impact on the response is as follows in Figure G.4 and Figure G.5. The frequency is in the range of a few MHz, the recovery slope as shown in Figure G.4, and the breakdown reduction factor, as shown in Figure G.5.
The left hand figure (a) is for the breaker at 1 m/s, which has 10 restrikes and the recovery slope 16.3 V/μs and a restrike duration of 0.8 ms. The right hand figure (b) is for the breaker at 0.8 m/s, which has 18 restrikes and the recovery slope 27.7 V/μs and a restrike duration of 3.25 ms.

The left hand figure (a) is for the breaker at 1 m/s, which has 40 kV with rise-time 180 μs. The right hand figure (b) is for the breaker at 0.8 m/s, which has 56 kV with rise-time 280 μs.
Figure G.6. Zoomed values of the re-ignition voltage (upper) and current (lower) across the breaker at $\frac{d}{dt} |_{\text{max}}$ at 1 m/s and 0.8 m/s to calculate the breakdown reduction factor.

Both the left hand figures (a) and (c) give the breakdown factor 0.62 for the breaker at 1 m/s, and right hand figures (b) and (d) give the breakdown factor 0.75 for the breaker at 0.8 m/s; this takes the same time period at $\frac{d}{dt} |_{\text{max}}$. i.e. 11.76 to 11.84 ms for the breaker at 1 m/s, and 12.549 to 12.592 ms for the breaker at 0.8 m/s.
Table G.1. Summary of contact opening velocity simulation results

<table>
<thead>
<tr>
<th>Contact opening velocity</th>
<th>1 m/s</th>
<th>0.8 m/s</th>
<th>Δ = 0.2 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>V (kV)</td>
<td>40</td>
<td>56</td>
<td>+16</td>
</tr>
<tr>
<td>I (A)</td>
<td>100</td>
<td>460</td>
<td>+360</td>
</tr>
<tr>
<td>Number of restrikes</td>
<td>21</td>
<td>38</td>
<td>+17</td>
</tr>
</tbody>
</table>

Voltage Signature

Current Signature

Recovery curve (S) v/μs

Breakdown reduction factor(α)

Slope (di/dt) A/s²

It is found that slow opening velocity breaker can be detected by longer duration of restrike, a larger number of restrikes and decrease of the recovery slope, but an increase in the breakdown reduction factor.