Smart Coordinated Distribution System Control to Enable High Level Penetration of Rooftop PVs

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Thesis submitted in accordance with regulations of the Degree of Doctor of Philosophy in the Faculty of Science and Engineering, Queensland University of Technology, 2015.

January 2015

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Associate Supervisor: Prof. Gerard Ledwich
Faith gives life a motion and suspicion makes life intolerable.

Milton
Key words

Smart grid, Rooftop Photovoltaic (PV) system, Peak demand, Distribution network, Voltage profile, Voltage violation problem, Reactive capability of PV inverter, R/X ratio, Battery Energy Storage (BES) system, Constant droop control, Variable droop control, Coordinated control, Flow battery, BES sizing, BES utilisation, Discrete Time Markov Chain (DTMC), Customer participation, Communication protocol, Power Line Carrier (PLC), Probabilistic estimation, Probabilistic load flow (PLF), Latin Hypercube Sampling (LHS), Cholesky decomposition.
Abstract

Energy generation from green resources is a growing interest all over the world due to increasing awareness towards environment pollution. The technologies of renewable energy (such as solar photovoltaic, wind farms, hydro, etc.) are introduced in the electricity market with a view of harnessing energy from available natural resources. Renewable sources are having augmenting contribution in the present electricity generation mix. Most of the countries’ government have already set their specific renewable energy targets. This target demands widespread installation of renewables across the electricity grid. Small scale rooftop Photovoltaic (PV) generation are becoming more prominent in residential distribution network. Advancement in PV module fabrication technology with higher efficiency and decreasing trend of PV module price has overcome the initial barrier for PV system to be implemented into the distribution network. For this reason, substantial growth in rooftop PV installation is observed all over the world for last 5-7 years. With momentous contribution from PV in the generation mix, traditional monitoring and control concepts of electricity grid need to be redefined. It can be achieved by considering bidirectional power flow, two-way communications, smart control, etc. as a part of monitoring and control strategy. Especially bi-directional power flow has resulted in several technical issues in traditional distribution system. Among them, voltage rise is of the highest concern. Therefore, in the first part of this research, the effectiveness of reactive power capability of PV inverter is explored. It begins with the discussion of the pros and cons of all available techniques to address over voltage problem in distribution network. This technology can be incorporated with grid-tied PV system with small investment which makes it a trendy choice. However, resistive characteristic of distribution feeder, limits the effectiveness of reactive control. Simulation studies on a test network are performed to quantify the effectiveness in this phase of research.
This limited effectiveness has led to the development of a coordinated algorithm in the second phase of the research. Decentralised integration of storage system is considered in the developed algorithm. Due to discrepancy in PV generation and load demand, excess generation from PV can be stored and then supply back to support customers’ peak demand. This technology also gives more flexibility to utility companies in network investment. Usually utility companies consider the generation safety margin on top of peak demand to plan electricity generation. As peak demand lasts for a small period of time, a considerable amount of installed capacity remains unused. With increasing electricity demand, it becomes more and more challenging for utilities to maintain the safety margin of generation. If stored energy can support during the peak demand time, energy usage pattern from the grid becomes more flatten to effectively utilise the available resources. Coordinated control of storage and reactive capability give the provision of maximum and most efficient utilization of network resources. Therefore, second phase of the research includes development of coordinated algorithm and also verifies the algorithm with real network data.

Analysis with a worst case scenario helps to determine the required storage size for the coordinated algorithm. But utilization of installed storage capacity depends on seasonal variation as PV generation and load profile are strongly correlated with seasonal variation. Irregular generation pattern from PV system needs to incorporate probabilistic weather forecasting. For this reason, in the third phase of the research, probabilistic estimation of PV generation and load profile are performed. The proposed coordinated algorithm requires active participation of the customers, where the utilities do not have complete authority. Through several reward schemes customers can be motivated, but perfect participation may not be possible. So, the impacts of customer participation and network parameters (such as feeder distance, line resistivity) are analysed and quantified in this phase. There should be a common data representation and communication protocol in the network in order to smooth the coordination between the smart equipment. Therefore, a brief proposal on communication infrastructure is also included in this research phase.
The uncertainties of PV generation are incorporated using probabilistic load flow analysis. Latin Hypercube Sampling with Cholesky Decomposition (LHS-CD) with coordinated control algorithm to maintain voltage profile in distribution network is introduced in this thesis and is verified in a small test network as well as a real distribution network. Accuracy and computational burden of simulated results are compared with Monte Carlo simulations.
Dedication

I would like to dedicate my thesis work to loving parents, Humayun Kabir and Farida Yeasmin, my wife Israt Jahan Chowdhury and younger sister Nabila Kabir, whose love, moral support, motivation and encouragement helped me to overcome all the difficulties that I encountered during the course of PhD candidature.
Acknowledgements

I like to start the acknowledgement list by expressing my gratitude towards the Almighty, the Lord of everything.

My PhD journey in Queensland University of Technology (QUT) would never be possible without the immense support and guidance of various personalities. At first, I gratefully acknowledge the financial support provided by QUT (APA scholarship) during my whole candidature to make the carried research a success. My foremost gratitude goes towards my principle supervisor, Dr. Yateendra Mishra, for the continuous support, motivation and technical contribution throughout my candidature. I also like to express my gratitude towards associate supervisor, Professor Gerard Ledwich, for his constant guidance throughout my PhD journey. Without their indispensable assistance, the completion of this thesis would not have been possible. The time spent working with my supervisors has greatly shaped my professional identity and improved my research skills and I am grateful for this.

Further, I acknowledge QUT Research Student Centre staff members especially Ms. Chloe Finch, Ms Janelle Fenner, Ms. Judy Liu, Ms. Elaine Reyes and staff members from EEECS school especially Ms. Ellainne Steele, Ms. Jo Kelly, Ms. Joanne Reaves for their administrative support in managing travel applications and so on.

I also like to thank QUT for providing the opportunity to develop my teaching and learning skills in terms of several programs such as Sessional Career Academic Development program.

I am thankful for my fellow research mates from power engineering discipline for their support in creating a productive research environment. My special thanks to Ms. Cynthujah Vivekananthan for always giving valuable time to help me when I was in need.
Special gratitude goes to QUT High Performance Computing (HPC) team for their support. Finally, I like to thank all academic and non-academic staff for the support given to me in a countless number of ways.

I would like to thank Professional editor, Helen Whittle, provided copyediting and proofreading services to my thesis.

Last, but by no means the least, I would like to thank the government of People’s Republic of Bangladesh for providing me high quality education from primary school to university.
List of Accepted Publications

*Book Chapter:*


*Journal:*


*Conferences:*

Conference on Computational Methods (ICCM), November 25-28, 2012, Gold Coast, Australia.

Contributions

- **Effectiveness of Reactive Power Capability of PV Inverters (Chapter 3):**

  A novel control algorithm to utilize the reactive capability of PV inverter in residential distribution network to address the voltage violation problem is proposed in this chapter. Though using reactive power to regulate voltage can be found in some literatures, however these techniques are much effective in transmission network. High resistive characteristic (i.e. high resistance to reactance ratio) of distribution feeder put some limitation on the effectiveness of reactive power in regulating the voltage in distribution network. Apart from developing a control algorithm to utilize the reactive capability, research is also carried on to quantify the impact of reactive power in terms of line resistivity and feeder distance. Detail steps of all the algorithms are described in this chapter with simulation results for different type of networks (such as urban and rural network). Research outcomes of this chapter are published in Journal of Engineering Technology (JET).

- **Coordinated Control of Grid Connected Photovoltaic Reactive Power and Battery Energy Storage Systems (Chapter 4):**

  Reactive capability is an omnipresent feature from PV inverter and can be utilized to address the voltage violation problem in distribution network. However, this feature has some limitation as described in Chapter 3. A coordinated control to use reactive capability of PV inverter and integrated battery energy storage (BES) are proposed in this chapter. Using the sensitivity matrix, droop based control algorithm for storing the excessive generation from PV in BES during peak generation time (usually at midday) is proposed in this chapter. Algorithms to discharge the stored energy from BES are also proposed in this chapter. Simulation results on voltage profile improvement and combined profile of reactive power from PV inverter & charging-
discharging of BES to demonstrate the performance of coordinated algorithm are explained in this chapter. Performance comparisons with other control techniques such as using only droop based energy storage, constant and variable droop are also demonstrated. Battery selection criteria and economics of battery for different control techniques are also briefly covered. Simulation studies are conducted for both urban and rural scenarios. In this chapter, the proposed algorithms are also validated using network data from distribution network service provider. Outcomes from this segment of research are published in IEEE Transactions on Industrial Informatics.

➢ *Incorporating Variability in PV generation and Load Demand (Chapter 5):*

This chapter includes a probabilistic estimation of PV generation and load demand to analyse the utilization of installed BES capacity with seasonal variation. This chapter also includes simulation results demonstrating the variability of line characteristics of different networks (i.e. variable R/X ratio), the variability of end user’s participation in the overall voltage profile of network and installed BES utilization. Economics on system wide distributed BES is also briefly discussed in this chapter. Several command signals associated with control algorithm and the flow of signals are also included in this chapter. Communication realization of control signals using power line carrier with calculation on data throughput are also covered during the research. Overall research outputs are partially published in Elsevier Applied Energy journal and Handbook of Clear Energy systems (John Wiley and Sons) as a book chapter.

➢ *Probabilistic Load Flow Analysis to Prevent Over-Voltage Problem in Distribution Feeder with the Presence of Photovoltaic (Chapter 6):*

Intermittent characteristics of PV generation and load require incorporating probabilistic approach in load flow. Probabilistic load flow (PLF) is adopted in this chapter instead of traditional deterministic load flow to maintain the voltage profile in distribution feeder with developed coordinated control algorithm. Well established
method of PLF, Monte Carlo simulation is performed in this part of research. Another PLF method, such as Latin Hypercube Sampling (LHS) is then proposed to reduce the computational burden. Cholesky decomposition method is also combined with LHS to order the rankings of correlated input random variables. Performance evaluation of LHS is done for a test network. Simulations are also carried for a DNSP network to validate the proposed method.
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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

QUT Verified Signature

______________________________
Md Nayim Kabir

Date: 07 / 01 / 2015

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Nomenclature

*List of Abbreviations*

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AEMO</td>
<td>Australian Energy Market Operator</td>
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<tr>
<td>APC</td>
<td>Active Power Curtailment</td>
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<tr>
<td>APCI</td>
<td>Application Protocol Control Information</td>
</tr>
<tr>
<td>APDU</td>
<td>Application Protocol Data Unit</td>
</tr>
<tr>
<td>ARMS</td>
<td>Average Root mean Square</td>
</tr>
<tr>
<td>ASDU</td>
<td>Application Service Data Unit</td>
</tr>
<tr>
<td>BES</td>
<td>Battery Energy Storage</td>
</tr>
<tr>
<td>CAES</td>
<td>Compressed Air Energy Storage</td>
</tr>
<tr>
<td>CI</td>
<td>Clearness Index</td>
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<tr>
<td>CD</td>
<td>Cholesky Decomposition</td>
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<tr>
<td>CRC</td>
<td>Cyclic Redundancy Code</td>
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<tr>
<td>CT</td>
<td>Cloud Transients</td>
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<tr>
<td>DIF</td>
<td>Diffusion Irradiation</td>
</tr>
<tr>
<td>DLC</td>
<td>Double Layer Capacitor</td>
</tr>
<tr>
<td>DNI</td>
<td>Direct Normal Irradiation</td>
</tr>
<tr>
<td>DNP3</td>
<td>Distribution Network Protocol 3.0</td>
</tr>
<tr>
<td>DNSP</td>
<td>Distribution Network Service Provider</td>
</tr>
<tr>
<td>DoD</td>
<td>Depth of Discharge</td>
</tr>
<tr>
<td>DSTATCOM</td>
<td>Distributed STATic COMpensator</td>
</tr>
<tr>
<td>DTMC</td>
<td>Discrete Time Markov Chain</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>FCB</td>
<td>Frame Count Bit</td>
</tr>
<tr>
<td>FCV</td>
<td>Frame Count Valid Bit</td>
</tr>
<tr>
<td>GC</td>
<td>Gram-Charlier</td>
</tr>
<tr>
<td>GHI</td>
<td>Global Horizontal Irradiation</td>
</tr>
<tr>
<td>GW</td>
<td>Giga Watts</td>
</tr>
<tr>
<td>MW</td>
<td>Mega Watts</td>
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<tr>
<td>GWh</td>
<td>Giga Watt-hour</td>
</tr>
<tr>
<td>HAN</td>
<td>Home Area Network</td>
</tr>
<tr>
<td>HCI</td>
<td>Human Computer Interaction</td>
</tr>
<tr>
<td>HV</td>
<td>High Voltage</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electro-Technical Commission</td>
</tr>
<tr>
<td>iid</td>
<td>Independent and Identically Distributed</td>
</tr>
<tr>
<td>IPVBS</td>
<td>Integrated PV and Battery Storage system</td>
</tr>
<tr>
<td>IPVI</td>
<td>Integrated PV and Inverter system</td>
</tr>
<tr>
<td>kVAr</td>
<td>Kilo Volt Ampere Reactive</td>
</tr>
<tr>
<td>kW</td>
<td>Kilo Watt</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilo Watt-hour</td>
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<tr>
<td>LHS</td>
<td>Latin Hypercube Sampling</td>
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<td>LHS-CD</td>
<td>Latin Hypercube Sampling with Cholesky Decomposition</td>
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<tr>
<td>Li</td>
<td>Lithium</td>
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<tr>
<td>Li NMC</td>
<td>Lithium Nickel Manganese Cobalt</td>
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<tr>
<td>LiFePO₄</td>
<td>Lithium Iron Phosphate</td>
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<tr>
<td>LPDU</td>
<td>Link Protocol Data Unit</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>LSB</td>
<td>Least Significant Bit</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
</tr>
<tr>
<td>MC</td>
<td>Monte Carlo</td>
</tr>
<tr>
<td>MSB</td>
<td>Most Significant Bit</td>
</tr>
<tr>
<td>MV</td>
<td>Medium Voltage</td>
</tr>
<tr>
<td>MW</td>
<td>Mega Watts</td>
</tr>
<tr>
<td>MWh</td>
<td>Mega Watt-hour</td>
</tr>
<tr>
<td>NB</td>
<td>Narrow Band</td>
</tr>
<tr>
<td>NEM</td>
<td>National Electricity Market</td>
</tr>
<tr>
<td>Ni</td>
<td>Nickel</td>
</tr>
<tr>
<td>NiMH</td>
<td>Nickel Metal Hydride Cell</td>
</tr>
<tr>
<td>OLTC</td>
<td>On Load tap Changer</td>
</tr>
<tr>
<td>OSI</td>
<td>Open System Interconnection</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PF</td>
<td>Power Factor</td>
</tr>
<tr>
<td>PLC</td>
<td>Power Line Carrier</td>
</tr>
<tr>
<td>PLF</td>
<td>Probabilistic Load Flow</td>
</tr>
<tr>
<td>PV</td>
<td>Photo Voltaic</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>R/X ratio</td>
<td>Ratio of real (R) and reactive (X) component of Transmission/Distribution Line</td>
</tr>
<tr>
<td>SM</td>
<td>Smart Meters</td>
</tr>
<tr>
<td>SMat</td>
<td>Sensitivity Matrix</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------------</td>
</tr>
<tr>
<td>SMES</td>
<td>Superconducting Magnetic Energy Storage</td>
</tr>
<tr>
<td>SoC</td>
<td>State of Charge</td>
</tr>
<tr>
<td>SWER</td>
<td>Single Wire Earth Return</td>
</tr>
<tr>
<td>TSDU</td>
<td>Transport Service Data Unit</td>
</tr>
<tr>
<td>VI</td>
<td>Variability Index</td>
</tr>
<tr>
<td>Vn</td>
<td>Vanadium</td>
</tr>
<tr>
<td>ZnBr</td>
<td>Zinc Bromide</td>
</tr>
</tbody>
</table>
**List of Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$</td>
<td>Active power</td>
</tr>
<tr>
<td>$Q$</td>
<td>Reactive power</td>
</tr>
<tr>
<td>$S$</td>
<td>Apparent power</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Solar irradiation constant</td>
</tr>
<tr>
<td>$d$</td>
<td>Distance between backbone bus and respective house in the test network models</td>
</tr>
<tr>
<td>$F_d$</td>
<td>Distance between two consecutive buses in the backbone</td>
</tr>
<tr>
<td>$P_L$</td>
<td>Load power</td>
</tr>
<tr>
<td>$P_{L,\text{max}}$</td>
<td>Maximum load power</td>
</tr>
<tr>
<td>$P_G$</td>
<td>Active power generated from PV</td>
</tr>
<tr>
<td>$Q_G$</td>
<td>Reactive power generated from PV</td>
</tr>
<tr>
<td>$P_{G,\text{max}}$</td>
<td>Maximum PV generated active power from $n^{th}$ house of distribution feeder</td>
</tr>
<tr>
<td>$Q_{G,\text{max}}$</td>
<td>Maximum PV generated reactive power from $n^{th}$ house of distribution feeder</td>
</tr>
<tr>
<td>$Q_{\text{reqn}}$</td>
<td>Reactive power to minimise voltage violation from $n^{th}$ house of distribution feeder</td>
</tr>
<tr>
<td>$SMat$</td>
<td>Sensitivity Matrix</td>
</tr>
<tr>
<td>$\Delta \delta/\Delta P$</td>
<td>Variation in the bus angle with active power</td>
</tr>
<tr>
<td>$\Delta \delta/\Delta Q$</td>
<td>Variation in the bus angle with reactive power</td>
</tr>
<tr>
<td>$\Delta V/\Delta P$</td>
<td>Variation in the bus voltage with active power</td>
</tr>
<tr>
<td>$\Delta V/\Delta Q$</td>
<td>Variation in the bus voltage with reactive power</td>
</tr>
</tbody>
</table>
Δ$P_{\text{max}}$ Maximum difference in real power in the sensitivity matrix

Δ$P_{\text{reduced}}$ Required power reduction for droop based storage

$RX_{\text{cri}}$ Critical R/X ratio

$m_c$ Constant droop co-efficient

$m_v^n$ Variable droop co-efficient for $n^{th}$ house

$V_a$ Acceptable voltage

$V_n$ Bus voltage for $n^{th}$ house

$V_{\text{diff}}$ Difference between the acceptable voltage and $n^{th}$ house voltage

$V_{\text{cri}}$ Critical voltage above which droop based energy storage starts

$V_{\text{max}}$ Maximum allowable voltage (1.06 pu)

$V_{\text{expected}}$ Expected voltage level (1.0 pu)

$V_{\text{no}}^t$ Voltage at $n^{th}$ house without any energy supply from BES at a particular time $t$

$tvd$ Total time duration for voltage dip in a day

$\eta$ Round trip efficiency considering SoC and DoD

$m_{mf}$ Modification factor in droop equation for higher R/X ratio

$E_{\text{stored BES, total}}$ Total energy stored from each house using droop based storage

$E_{\text{stored BES, available}}$ Available energy to be delivered to each house at a particular time

$E_{n, \text{supplied}}$ Supplied energy from BES for $n^{th}$ house

$\{SPV_{t,n}\}$ Specific state (value) of solar PV generation process at $t^{th}$ time of $n^{th}$ day in a year
\[ NetGen_N \] Net Generation which is the difference between PV generation and Load demand at \( N^{th} \) time (where ‘\( N \)’ denotes the time for a specific set of values \( \{ n, t \} \) i. e. \( t^{th} \) time of \( n^{th} \) day in a year)

\[ Pr\{NetGen_N=a\} \] Probability of Net Generation having a specific value ‘\( a \)’ at \( N^{th} \) time

\[ Pr_{ab} \] The probability of having the value ‘\( b \)’ on next time (\( t+1 \)) of \( n^{th} \) day, provided that Net Generation gets a particular value ‘\( a \)’ at \( t^{th} \) hour of \( n^{th} \) day

\[ a_a \] Probability of being in the initial state ‘\( a \)’ at \( t^{th} \) time of \( n^{th} \) day for Net Generation

\( VI_{\text{max}} \) Maximum Variability Index

\( VI_{\text{normalised}} \) Normalised Variability Index

\( F(x) \) PDF of a Pearson distribution

\( C_0, C_1, C_2 \) Co-efficient in the PDF of Pearson distribution

\( \nu_1 \) Square of skewness

\( \nu_2 \) Kurtosis

\( \mu_{\text{NetGen}} \) Mean value of Net Generation

\( \sigma_{\text{NetGen}} \) Standard deviation of Net Generation

\( \sqrt{\nu_1_{\text{NetGen}}} \) Skewness of Net Generation

\( \nu_2_{\text{NetGen}} \) Kurtosis of Net Generation

\( \zeta \) Set of states where voltage remains within acceptable range

\( \lambda \) An event when voltage violation is occurred at \( N^{th} \) time

\( Data_{TP} \) Maximum data throughput (in kbps)

\( PS_{\text{bytes}} \) Total data packet size in bytes

\( t_{\text{round}} \) Total round trip time for message delivery
\( P_{tr} \) Transmitted Power

\( P_{re}(d) \) Received signal power at a distance \( d \) from the transmitter

\( ka \) Constant that expresses attenuation

\( \alpha \) Shape parameter of Pearson 5 distribution

\( \beta \) Scale parameter of Pearson 5 distribution

\( \gamma \) Location parameter to consider any shift in the Pearson 5 distribution

\( X_k \) \( k^{th} \) input random variable during LHS

\( S_{X1} \) Sampling vector for 1\(^{st}\) input random variable \( X_I \)

\( S_X \) Sampling matrix obtained from all the input random variables

\( L_k \) Rank of \( k^{th} \) input random variable

\( L \) Ordering matrix combining individual ranks of all the input random variables

\( \rho_L \) Correlation matrix of ordering matrix \( L \)

\( \mu \) Mean of corresponding input random variable

\( \sigma \) Standard deviation of corresponding input random variable

\( P \) Lower triangular matrix after Cholesky decomposition

\( err_\mu \) Error in “mean” value in sampling methods compared to MC

\( err_\sigma \) Error in “standard deviation” in sampling methods compared to MC
Chapter 1

Introduction

1.1 Background

All over the world the power industry is facing numerous challenges with the increasing need for electricity as well as changes in the demand patterns. Moreover, the focus on large-scale integration of diverse generation in terms of renewable energy, the smart management of all available resources and loss minimisation incorporates more challenges in the power industry. Clearly these types of critical issues cannot be resolved within the confines of the existing power grid. The existing power grid must be reformed with intelligent coordinated control and dissemination of smart technologies.

Traditional electricity grid is unidirectional in nature whereby electricity flows from generation to distribution network through transmission system. Significant losses occur during the flow of electricity through transmission lines. The top to bottom hierarchical structure of the present electricity grid can also lead to domino effect failure. As a consequence, majority of the electrical failures are observed on the distribution side. Therefore, increasing emphasis is placed on the distribution network in the roadmap of smart grid. On the other hand, traditional electricity grids are designed to meet the peak demand although it only exists for a short period of time (2-5% of the total load duration). To ensure uninterrupted electricity supply in the peak demand period, the
generation capacity may need to exceed up to 20% of its regular capacity. Supporting this short period of peak demand time with available alternative resources can save the immediate investment required to meet peak demand. Combining all the effects, the concept of placing the power generation closest to the end users is becoming more popular day by day. Placing the generation close to the distribution can reduce losses as well as ensure the smooth supply of electricity. Moreover, carbon emission footprint, optimum generation of green energy and the utilization of freely available natural resources (such as solar, wind, hydro and thermal energies) are having higher importance day by day. In a residential distribution network rooftop Photovoltaic (PV) has been emerged as an effective option to ensure the delivery of electricity from the closest point of generation. Looking into the growth rate of the worldwide PV market (Fig. 1.1), it is observed that PV market has experienced a significant boost since 2008. Even during the second wave of worldwide financial and economic crisis in mid-2011, the PV market continued to accelerate [1], [2]. With this increasing growth, the overall PV capacity passed the installed capacity level of 100 GW in 2013 [3]. An approximate future growth of global PV market is also demonstrated in [4].

While lagging behind European Union and North American countries, significant growth in installed capacity levels has also been observed in Australia. In fact, in the world solar insolation map, Australia is identified as one of the potential countries for large-scale PV installation [5]. In December 2013, Australia reached a total installed capacity level of 3 GW. Considering the history of PV power generation in Australia, this level of installed capacity is quite remarkable; for example, Australia’s capacity was only 180 MW in 2009. Public awareness of the option to harness green energy, a generous feed-in-tariff scheme from the Government and the increasing cost of grid-based electricity have resulted in this PV power generation growth in Australia. Most of the installed PVs are small scale rooftop residential PV systems. According to a research conducted by a solar consultant company, SunWiz, 14% of houses host a PV system in Australia [6]. Among all the states, South Australia (25%) and Queensland (22%) are leading the penetration level of residential PV systems. TABLE 1.1 shows the installed capacity level (in MW) and PV system penetration level in residential network for different states and territories:
TABLE 1.1. Installed capacity level and PV penetration level in Australia [6]

<table>
<thead>
<tr>
<th>State/Territory</th>
<th>Installed capacity (MW)</th>
<th>Percentage of houses with PV system</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>450</td>
<td>25%</td>
</tr>
<tr>
<td>QLD</td>
<td>986</td>
<td>22%</td>
</tr>
<tr>
<td>WA</td>
<td>334</td>
<td>18%</td>
</tr>
<tr>
<td>NSW</td>
<td>633</td>
<td>10%</td>
</tr>
<tr>
<td>VIC</td>
<td>532</td>
<td>10%</td>
</tr>
<tr>
<td>ACT</td>
<td>38</td>
<td>10%</td>
</tr>
<tr>
<td>TAS</td>
<td>55</td>
<td>9%</td>
</tr>
<tr>
<td>NT</td>
<td>11</td>
<td>4%</td>
</tr>
<tr>
<td><strong>Nationwide</strong></td>
<td><strong>3,039</strong></td>
<td><strong>14%</strong></td>
</tr>
</tbody>
</table>

However, such uptake in the grid integration of PV systems does not come without technical challenges for the Distribution Network Service Providers (DNSPs). According to a report by Australian Energy Market Operator (AEMO) [7], the penetration level of rooftop PV systems in the Australian National Electricity Market (NEM) was not significant enough to make any notable impact on the performance of electricity grid until the beginning of 2010. With the exponential increase over the
following two years, in 2013, PV generation has contributed up to 9.4% of NEM electricity demand and up to a maximum of 28% in South Australia [6]. Such significant contributions from PV generation have given rise to some constraints in distribution network which can limit the uptake volume. Among them, most prominent technical constraint is the voltage rise issue [8]. Unfortunately for a residential distribution network, the peak solar insolation time (usually at 12 noon) and peak demand time (usually in the evening at 6.00-8.00 PM) do not coincide. A rooftop PV system can feed the excess energy into the grid which results in higher voltage. Over voltage may damage the appliances and/or shut down the PV system (due to increase in temperature caused by over voltage) depriving the system owner from the expected revenue.

After considering the drastic growth in residential PV installation all over Australia and the severe technical issues arising for DNSPs, our research is primarily focused on the voltage violation problem associated with the residential distribution feeder. Studies that have addressed the voltage violation problem due to large-scale integration of PV systems are reviewed in details in Chapter 2. Some researchers have suggested on the use of reactive capability of PV inverter whereas others have suggested integrating a storage system. The review of these studies emphasises the search for a novel algorithm. To identify and develop the most appropriate algorithm, the present study investigates the effectiveness of reactive power support from the PV inverter, and quantifies the impact of network parameters (such as line resistivity, R/X ratio, feeder distance). Then to overcome the limitations identified in the research results, a coordinated algorithm is proposed using reactive power from the PV inverter as well as decentralised Battery Energy Storage (BES). All the factors associated with the coordinated algorithm such as variation in the network parameters, the probabilistic estimation of intermittently PV generation and load demand are also considered. As the proposed algorithm will require active participation from the end-users, the impact of the participation factor and end-users’ positions are also investigated as a part of this research. To ensure proper coordination between all the appliances and servers during the operation of proposed algorithm, an investigation of the necessary message signals and their communication medium is also included in this research. Finally, a suitable Probabilistic Load Flow (PLF) method is incorporated and comparison results are shown.
1.2 Framework and hypothesis of research

After determining the field of research, that is to address the challenges associated with solar PV in residential distribution feeder, research framework and relevant hypothesis are made. The research is mainly divided into three phases, starting with literature review. Among the available resources suitable and appropriate literatures are sampled using relevant keywords and stratified according to their research outcomes. From critical analysis of literatures, the research field is further narrowed down. Addressing the voltage violation problem has been considered as the research focus among all the challenges associated with high level penetration of PV in residential distribution networks. The severity of voltage violation and the need for a suitable algorithm to address it are the main reasons for such selection. Further literature review, critical thinking and study are performed based on more specific search with relevant keywords. Existing methods and their suitability are also analysed in this phase. Details of literature review are mentioned in Chapter 2. Study on different hypothesis/assumptions and regulations are done. Some traditional assumptions are such as unidirectional power flow in distribution networks, centralized generation rather than dispersed generation from renewable, having unity power factor injection from PV inverter to harness maximum real power, etc.

The next phase after the literature review is the “research planning phase”. Some factors are considered to identify the research gap and research questions. The research project is designed in a way to make it feasible with appropriate significance and innovation. One important segment of the research is to validate the simulated results. Access and availability of data are also considered while setting the research questions and research goals. These research questions and goals are mentioned in following sections.

Finally comes the “research contribution phase”. After setting the research questions and goals, analytical approach and comprehensive research studies are performed to achieve them. It should be noted that, critical analysis of literatures are carried even after the “literature review” phase to keep updated on existing research. Mathematical formulation, modelling and simulation studies are done in this phase. Observed results
are reflected to scholarly articles to recognize the significance and contribution of the research. Usually further analysis and observation on results are required during the recognition process. Then carried research can be added into the existing knowledge base. The overall research framework is shown in Fig. 1.2.

![Research framework diagram]

**Fig. 1.2. Research framework**

### 1.3 Research questions

This research is structured by the following research questions:

1. What are the available methods to address voltage violation problem in a residential distribution feeder with high level penetration of solar PV?

2. How the reactive capability of PV inverter can be utilized to improve voltage profile?

3. What are the limitations of using reactive capability and how to determine the effectiveness of it?
4. How to develop the coordinated algorithm using reactive capability of PV inverter and integrated storage system? What are the other factor (such as communication medium) needs to be considered for implementing the coordinated algorithm?

5. What would be the most appropriate technique for storage?

6. How to incorporate the probabilistic estimation of intermittent PV generation and load?

7. How to incorporate probabilistic load flow with the coordinated algorithm in a residential distribution feeder?

1.4 Research objectives and goals

This research is guided by the aim to achieve the following objectives: to analyse the impact of the PV inverter reactive capability on voltage improvement; to develop a control algorithm; to assess the impact of different factors on the effectiveness of the algorithm; to investigate the relevant communication media; and to identify a suitable PLF technique. Each of the objectives is discussed in detail as follows:

Analysis of the impact of PV inverter reactive capability on voltage improvement – At first the impact of reactive power compensation from PV inverter on voltage profile improvement is investigated in the research study. The factors limiting the effectiveness of using reactive capability are also analysed and quantified with necessary simulation studies.

Development of control algorithm – Two control algorithms are developed using only the reactive power compensation techniques and coordinated control of reactive compensation and energy storage. During peak generation time (with relatively less residential load demand period), in order to prevent the overvoltage problem, the excessive generation from rooftop PV systems is stored in integrated storage system in the proposed algorithm. The stored energy is fed back to meet the load demand partially during evening. In a residential distribution network, usually the load demand usually reaches the peak at evening when PV generation is completely absent. The scenario may
result in an unacceptable voltage profile with unwanted dips (i.e. voltages may go below the lower acceptable range). Otherwise, DNSP may need to invest more in electricity network reinforcement though peak demand rarely occurs in network. As a result, the coordinated control with PV and integrated BES is very effective to address these problems. The charging-discharging controls of integrated energy storage are also developed in this research.

*Assessment of the impacts of different factors on the effectiveness of the algorithm* – Enthusiastic participation from the end-users is required to make the algorithm effective. Unfortunately, it is a challenging task for the DNSPs to motivate all the end-users to take part. As a result random factors (different percentage of participation, different PV sizing) are included in the proposed algorithm, particularly during the simulation. Another important factor associated with the PV generation is its intermittent nature. Unlike conventional generation, PV modules do not provide continual generation. To consider this intermittency probabilistic estimation of PV generation will also be considered as a part of this research.

*Investigation of the relevant communication media* - For the smooth operation of the proposed coordinated algorithm, all the participating smart appliances must be smoothly correlated with each other. There should be a unique data representation model and well-defined communication protocol persistent throughout the network. Both the model and the protocol are studied and described in the research.

*Incorporating the PLF*–A probabilistic approach to integrate the variability in PV generation and load demand is also mentioned in this research. Probabilistic load flow is performed in distribution network with high penetration of PVs maintain the acceptable voltage profile. Latin Hypercube Sampling with Cholesky decomposition is implemented during the PLF simulations and its performance in terms of accuracy of result and computation time is compared with well-established Monte Carlo simulations.
1.5 Research significance

The significance of this research is established by the following points:

1. Quantification of the effectiveness of reactive capability of PV inverter on voltage control in a residential distribution feeder with a large penetration of PV generation.
2. Development of a novel coordinated algorithm to maintain an acceptable voltage profile in residential distribution feeder with high penetration of PVs.
3. Consideration of probable variations associated with generation, end-user participation and network parameters in order to make the developed algorithm robust.
4. Investigation of probabilistic estimation of PV generation with mathematical modelling in order to consider the intermittence of PV generation.
5. Development of a unified data model and well-defined communication protocol to ensure the smooth coordination between all the components during the operation of the algorithm.
6. Application of the PLF technique using Latin Hypercube Sampling with Cholesky decomposition considering the variability in PV generation and load demand. The PLF technique is implemented in a residential distribution network with high level penetration of PVs to address the voltage violation problem.

1.6 Thesis Outline

1.6.1 Outline of Chapter 2

Critical study and primary analysis on existing literatures are performed based on the research questions and goals. These studies are summarized in this chapter. Chapter 2 presents a review of the literature on the increasing focus on the renewable energies, especially; solution to the over-voltage problem; use of the reactive capability of PV inverter; use of energy storage; requirements of the communication network; requirements of probabilistic analysis and probabilistic load flow.
1.6.2 Outline of Chapter 3

After the initial literature review, the research questions and goals are addressed gradually. This chapter mainly focuses on the analysis of reactive power supply/absorption in residential distribution network. Reactive capability of the PV inverter can be a solution to address over voltage and voltage dip problems to some extent. This thesis proposes an algorithm to utilise reactive capability of PV inverters and investigate the effectiveness of the inverters for voltage improvement based on the R/X ratio of the feeder. The length and loading level of the feeder in order for a particular R/X ratio to have an acceptable voltage profile are also investigated. This can be useful for suburban design and residential distribution planning. Furthermore, coordination among different PV systems using residential smart meters via a substation based controller is also proposed.

1.6.3 Outline of Chapter 4

Chapter 3 discussed and addressed couple of research questions and goals such as how to utilise the reactive capability of PV inverter and how to determine the effectiveness of it. After these analyses, Chapter 4 contains the research on coordinated algorithm. This research proposes the coordinated use of PV and BES to address voltage rise and/or dip problems. The reactive capability of the PV inverter combined with a droop based BES system is evaluated for rural and urban scenarios (having different R/X ratios). The results show that the reactive compensation from PV inverters alone is sufficient to maintain an acceptable voltage profile in an urban scenario (low resistive feeder), whereas, coordinated PV and BES support is required for the rural scenario (high resistive feeder). Constant as well as variable droop-based BES schemes are analysed. The required BES sizing and associated costs to maintain the acceptable voltage profile under both schemes are presented. Actual PV generation data and distribution system network data are used to verify the efficacy of the proposed method.
1.6.4 Outline of Chapter 5

Coordinated control of reactive capability from PV inverter and energy storage are discussed in Chapter 4. Different BES charging techniques such as constant and variable droops are analysed. However, due to the intermittent characteristic of solar irradiation, a probabilistic estimation is required. Mainly the research questions on communication realization to implement the coordinated algorithm and probabilistic estimation are discussed in this chapter. Chapter 5 considers the uncertainties in PV generation and load with the modelling of a probabilistic estimation of PV generation and randomness in the load in order to characterise the effective utilisation of BES. Disparity in participation is also considered. Moreover, a signal flow is discussed in this chapter to ensure smooth communication between all the equipment. A brief description of the data model, the communication protocol and their feasibility analysis in terms of data rate are also included here.

1.6.5 Outline of Chapter 6

Electricity generated from PV systems is based on intermittent solar radiation which is highly variable due to random cloud events and sudden weather changes. Weather change also has influence over the load demand. As a result, the variability incorporated with the input random variables (PV generation and load demand) of a distribution system show significant correlation between them. This scenario introduces new challenges to distribution network service providers. Traditional load-flow is deterministic by nature with single value from input parameters, which would not work well under randomly varying input variables. Therefore, this chapter considers the randomness in generation and load to perform PLF algorithms. The research questions for PLF are addressed in this chapter. PLF is performed in a residential distribution network with high level penetration of PVs to address the over-voltage problem using developed control algorithms. Two approaches of PLF, namely Monte Carlo and Latin Hypercube Sampling with Cholesky decomposition, are analysed and compared in this chapter.
1.6.6 Outline of Chapter 7

Chapter 7 summarises all the outcomes obtained from the research work in Chapters 3, 4, 5 and 6. The significant research findings and analysis are specified. The benefits and importance of the proposed techniques are summarised. Finally, recommendations for future research directions are suggested.
Chapter 2

Literature Review

2.1 Background

Driven by economical, technical, and environmental factors, the energy sector is moving into an era in which a large portion of the increased in electrical energy demands will be met through widespread installation of renewable energy systems [9]. The integration of renewable energy will increase the service reliability and reduces the need for future generation expansion or grid reinforcement up to some level. Moreover, it extends the possibility of making the renewable energy responsible for local power quality, voltage regulation and power factor correction, in a way that is not possible with conventional centralised generators [10]. Unlike large generators, which are almost exclusively 50/60-Hz synchronous machines, generation from renewable energy systems includes variable and/or fixed frequency (variable and/or fixed speed) sources (such as wind energy sources), high-frequency (high-speed) sources (such as micro turbines), and direct energy conversion sources producing dc voltages or currents (such as fuel cells and PV sources). Currently rooftop PV systems are being installed all over the world. The feasibility of small-scale solar-based neighbourhoods was demonstrated in [11] and [12]. Moreover, the environmental impact of petroleum-based transportation infrastructure along with the increase in oil prices can also be expected to lift the penetration level of PV systems. Increasing electricity price could be another potential reason for enhanced PV growth in commercial as well as residential areas [13].
increasing economy of scale, increasing efficiency of PV modules and decreasing pricing, PV system can become more widely available to customers [14], [15]. A decreasing trend of small scale residential PV module pricing is clearly observed, as illustrated in Fig. 2.1 [15].

![Small scale PV module pricing trend](chart.png)

**Fig. 2.1. Small scale PV module pricing trend [15]**

Integration of renewable energy (such as rooftop PV) with smart control mechanism is a significant cornerstone to transform the traditional grid into the smart grid. A schematic comparison of the existing and smart grid is shown in Fig. 2.2.

There are two types of PV systems, namely off-grid and grid-tied systems. Off-grid systems supply to some specific loads of customers and do not have any connection with a utility grid. On the other hand, grid-tied systems are connected to the local utility network with the provision of supporting load demand. The grid-tied PV system is usually connected to the grid through power electronic converters [16], [17]. In recent years, the use of grid-tied PV systems has increased more rapidly than that of off-grid PV systems [18]. Fig. 2.3 shows the trends in grid-tied and off-grid PV systems usage.
Fig. 2.2. Comparison of existing grid and smart grid

- Electromechanical → Digital
- Unidirectional Power Flow → Bi-directional Power Flow
- One Way Communication → Two Way Communication
- Centralized Generation → Distributed Generation
- Bottom Down Hierarchy → Connected Network

Fig. 2.3. Growth rate trends in off-grid and grid-tied PV system usage [18]

However, the use of PVs at the distribution level does not come without technical challenges. One of the main issues is the voltage violation problem [8]. This problem will pose new challenges to distribution planners and operators.
2.2 Voltage violation problem

Distribution systems have so far been designed and operated for unidirectional power flows from the distribution substation to the end-users, which only consume power. DNSPs are responsible for ensuring voltage according to regulation and utility requirements. A greater penetration level of PVs into existing systems will completely change the well-consolidated environment into a new environment in which distribution networks will no longer be passive. Hence, a gradual but ineluctable change toward a new kind of active networks is foreseen, with PV systems actively involved in management and operation [19]-[25]. However, with the addition of consumer-owned and intermittent PV units, current standard procedures for guaranteeing voltage profile may no longer be as effective.

With high level penetration of PVs, the usual peak production time and peak consumption time do not coincide. Thus, a typical PV system will inject most of the generated power into the grid during its peak production time. This reverse power flow causes a voltage rise along the power distribution line [26], [28]-[33]. The over-voltage problem becomes even prominent towards the end of the distribution line (Fig. 2.4).

Over-voltage in Low Voltage (LV) and Medium Voltage (MV) feeders with a high penetration of PV systems is usually prevented by limiting the generation capacity to very conservative values, even if the critical periods rarely occur. To allow high penetration of PVs and at the same time to avoid the over-voltage problem at the grid, the distribution system must have a control algorithm in addition to other protection algorithms which will regulate and/or storage the output power of the PV system if the voltage exceeds the acceptable range. New control algorithms for communication protocols for data exchange between generators and loads, and reliable communications systems are essential to ensure that such innovative practices can take place efficiently [21]-[25], [27]. The proposed research fills the existing gap in knowledge based on analysis and verification.
i) Reduce the secondary LV transformer voltage

An approach is proposed to control the secondary voltage by setting transformer tap in [8]. However, the main limiting factor in this approach is that the tap cannot be changed frequently. It needs to find an optimal setting that can be used for rated generation and minimum generation in order to maintain the voltage limits. For a fixed tap setting, there is a discrimination of very high voltage at the end of the transmission.

ii) Set an on-load-tap-changer

Particular focus was given to the real-time setting of the on-load-tap-changer (OLTC) of distribution substations in [34]. After demand estimation of the various feeders and measurements of power injection, it is possible to determine an OLTC setting that enables further power injections without exceeding voltage limits. In cases where curtailment schemes are in place (i.e., when PV modules curtail their power injections due to voltage or thermal constraints), these measurements can also assist in calculating the amount of power that those generators must trim off to keep the network within its operational limits [35], [36].
iii) Use reactive power control from the PV inverter

Grid-tied PV modules are connected to grid through power electronic inverters at the Point of Common Coupling (PCC). This inverter can operate on a power factor less than unity (either leading or lagging) to generate or absorb reactive power. The relation between real ($P$), reactive ($Q$) and apparent power ($S$) with power factor is described in section 2.3. Reactive power control may result in higher currents and losses in the feeder and also in lower power factors at the feeder, especially in LV systems where voltages are less sensitive to reactive power due to a “more resistive” ($R/X>1$) feeder characteristic. The impact of using reactive control from PV inverter is described in more details in the following section.

iv) Increase the conductor size and reduce the line impedance

Increasing the conductor size and/or reducing the line impedance can be another way to address the over-voltage problem. However, they are not a cost effective way to address the over-voltage problem compared with other methods such as using the reactive capability of PV inverter [8].

v) Apply active power curtailment from grid-tied PV systems

The capacity (active power) limitation of grid-tied PV systems to prevent the over-voltage issue has been investigated in [33]. Two Active Power Curtailment (APC) techniques for overvoltage prevention in radial LV feeders are discussed in [37]. In the first approach, all PV inverters have the same droop coefficients, while in the second one, different PV inverters have different droop coefficients to share the total active power curtailed and output power losses among them. The first option of APC seems very attractive as it has easily deployable control logic. However, after applying this method, the last house is curtailed few kilo-watts at noon whereas the curtailed amount is reduced for houses closer to the LV transformer. There may even no curtailment for initial houses of the distribution feeder. In principle, this would result in some PV systems (i.e. those located far from the LV transformer) being heavily penalised due to huge curtailment [37]. Thus, the choice of the most cost-effective solution(s) for voltage
management in a feeder with distributed generation is not straightforward. A number of more different approaches [38], [39] have been presented in the literature. Considering the existing state of development and the identified research gaps, new control algorithms are proposed in the present research.

The conducted research focuses on enabling the high-level penetration of renewable and increased energy delivery while maintaining an acceptable voltage profile by using the reactive power from PV inverter and integrated energy storage. A standard communication protocol is also described in the research. Narrations on few keywords related to this research are described below:

**Voltage violation** - Voltage violation (such as overvoltage or voltage dip) beyond the allowable limit is never desired by DNSPs. In a smart coordinated distribution system design with high-level penetration of residential rooftop PV systems, over-voltage is the main concern. However, an over-voltage scenario with a duration not exceeding one minute is categorised as a short time voltage violation, while those with time durations above one minute are categorised as long time voltage violations [40], [41]. Short term voltage violations which are mostly known as voltage swell or voltage sag, are not considered in the scope of this research. Voltage swell i.e. short duration increase in voltage level may happen due to reduction in load level. This research basically focussed on long term overvoltage problem caused by high penetration of solar PV in residential distribution feeder during noon at peak PV generation time. On the other hand, voltage sag or short term decrease in voltage level can be caused by overload or starting of motors. The voltage dip problem considered in this research is focused to defer the immediate need for network reinforcement.

**Reactive power and power factor** - As per the practice recommended by the Institute of Electrical and Electronics Engineers (IEEE), all grid-tied PV systems must inject power at a unity power factor [42]. This standard does not give the flexibility of regulating grid voltage using the reactive capability of PV inverter. Ideally, reactive
power should be generated at places close to the load in order to compensate line losses and free up more capacity of the conductors and transformers in the network [43].

**Communication protocol** - Some features of the recently developed (developed in March 2013 and published in October 2013) IEEE standard 1901.2-2013 for low frequency narrowband power line communication is incorporated in this research [44].

### 2.3 Reactive power control from PV inverter

Initially, the PV generation sources were integrated with the grid with a view to harness the maximum real power from it to ensure the highest possible generation. The focus was to maintain unity power factor at the PCC. Using the reactive support capability from the PV inverter to keep the acceptable voltage within the limit was not a previously held concern. More recently, utility companies have shown great interest in absorbing and supplying reactive power from PV inverters as substantial benefits can be obtained from such reactive support. Reactive power is a ubiquitous and critical feature of the modern electrical network. Most of the time, a PV inverter is operated below its rated output while converting solar irradiance to DC power and then to AC active power. The remaining capacity of the PV inverter can be utilised in terms of reactive power. The phasor relationship between the active ($P$), reactive ($Q$) and apparent ($S$) power is shown in Fig. 2.5. Clearly, the relationship shows that the required higher amount of reactive power can be provided even with a small sacrifice of real power. The great benefit of this implementation is that it comes at very little additional component cost.

As reactive power can directly modulate the grid voltage, there should be an appropriate control algorithm for reactive power support from the PV inverter. It is necessary to control the injection and absorption level of reactive power in order to accurately regulate the grid voltage level in a decentralised PV generation system throughout the distribution network. Localised management of the reactive power is the key to a smoothly-operating grid and maintenance of the voltage profile; mismanagement of reactive power control can lead to disaster such as higher line loss in distribution feeder. These decentralised PV generation systems will need to
communicate with a central substation/server. Therefore, the overall system can be a combination of smart meters, PV inverters with reactive capability and a centralised control system. Real-time control will allow the instant identification of voltage violation problems and corrective actions can be carried out accordingly before any significant damage can occur. Thus, significant insight can be obtained from the provision of reactive power which can create opportunities for a new market for reactive power generation from residential PV systems.

The low R/X ratio of the transmission line makes the reactive power support an effective solution. However, overloading of transmission line can happen as it is experiencing high apparent power even though only a fraction of that power is real power. This is the most significant challenge associated with reactive power support on the transmission side. Research has shown that, localised control of reactive power can achieve almost 80% savings in losses when compared to a centralised control [45], [46]. Those results were validated for a realistic distribution network. Therefore it is advised that reactive power control is produced and hence managed locally, closer to the load. While using reactive power from decentralised PV generation in distribution system, the effectiveness of the reactive power on regulating the grid voltage is limited by the resistive characteristics of distribution line.
2.4 Energy storage system

The increased contribution of intermittent renewable energy in the generation mix has led to an increased demand for storage devices into the grid. Particularly for a residential distribution network with a large penetration of PV systems, the peak generation and peak demand time never coincides. Usually maximum solar irradiation occurs at midday while the demand is not high for residential loads. On the hand, the peak demand occurs at evening when there is no generation from PV systems. The power demand pattern varies from season to season and electricity prices may also vary accordingly. Electricity consumption from the grid during peak demand time will definitely incur higher costs for the customer. Utility companies also need to ensure sufficient electricity supply to meet the peak demand with a generation safety margin. Utilities’ generation capacities and costs can be reduced by storing excessive energy during peak PV generation time and discharging it at peak demand time. The peak demand usually lasts for a small period of time which can be partially supported by storage system resulting in deferral of immediate grid reinforcement by the utility. With the “time shift” of electricity usage, customers can also be benefited in terms of cost effective electricity usage and tariffs. Using storage to decrease the gap between generation and demand may allow the load duration curve to become flatter, which indicates an efficient utilisation of available resources. As a result of all these cumulative impacts, energy storage may be an integral part of the future electricity grid. An overview of existing storage systems is presented in Fig. 2.6 and brief description is given below:

**Pumped hydro storage system** –The pumped hydro storage system has been used for more than 70 years. Its working principle is much simpler. Conventional pumped hydro storage systems use two water reservoirs at different elevations to pump water during off-peak hours from the lower to the upper reservoir (charging). The stored water is released during the times of high electrical demand (discharging). Such storage systems usually work on powering a turbine and also require a specific geographic location. High cost and time involvement in planning and building such a storage system make it an unpopular choice [47]. It is not at all suitable for a decentralised storage system in the residential distribution feeder.
**Compressed Air Energy Storage (CAES) system** - This technology has been used since the 19th Century for different industrial applications. Air is used as the storage medium due to its abundances. During the off-peak period, electricity is used to compress air into an underground reservoir or surface vessel/piping system. When there is demand for electricity the air is released, mixed with a fuel source, burned and supplied to a gas turbine. This technology is more suitable for centralised bulk storage. Requirement of specific geographic location with air tight facilities is one of the main disadvantages [48], [49].

**Flywheel energy storage system** - Energy is stored in this technology in the form of kinetic energy in a spinning rotor. The amount of stored energy is calculated based on the angular momentum of the rotor. The key features of the flywheel storage system include:

i) Low maintenance cost (the mechanical bearings may require servicing in 3-5 years) [50].

ii) Long life-cycle [51].

iii) Suitable for deep discharge application [52].

iv) Able to supply 15s of power for engine or turbine generator starts [50].
Flywheel storage is typically used in transportation and power quality applications that require a frequent charging/discharging cycle [53], [54]. In the algorithm proposed in the present study, the charging and discharging process will “trigger in” after certain conditions are fulfilled. Therefore, charging/discharging may not be too frequent. However, the “state of charge” of flywheel storage system needs to be maintained all the time using its inertia and speed [55]. The mechanical characteristic of the rotor makes it suitable for large scale centralised storage and hence, an unfavourable solution for residential PV energy storage.

Super capacitor/ultra-capacitor/ Double Layer Capacitors (DLC): This technology has been known for more than 60 years. Energy is stored in an electric field between a pair of the conductors. Frequently reversible characteristic allows the DLC to charge/discharge numerous times. With an extremely high capacitance value (order of thousands of farads) and low internal resistance make the charging/discharging process very fast. Its other advantages include a long life-cycle, less maintenance and the capacity for operation over a wide temperature range [56]. With these attributes the DLC is the most appropriate storage system for applications with a large number of short charge/discharge cycles. It is not suitable for the storage of energy over longer periods of time as a result of its high self-discharge rate, low energy density and high investment cost [57].

Superconducting Magnetic Energy Storage (SMES) system –The electro-dynamic principle is the core of this technology. The main component of this storage system is a coil. Magnets of conducting coil are cooled down (below the superconducting critical temperature) to create a magnetic field to store the energy. Its main advantage is high round trip efficiency (90%) and high dynamic response that permits a response time within milliseconds. However, the overall efficiency depends on the refrigeration system which may require approximately 1.5 kW continuously per MWh of storage capacity [58]. Considering the additional requirement for the refrigeration system this technology is mainly suitable for large-scale storage rather than decentralised residential storage.

Hydrogen storage system - A typical hydrogen storage system consists of an electrolyser, a hydrogen storage tank and a fuel cell. The main working principle is to
convert the chemical energy in an electrical current in this hydrogen fuel cell. Hydrogen storage is relatively immature technology with efficiency between 50 to 60% and a high cost of fuel cells [48].

**Battery Energy Storage (BES) system** - BES plays the perfect role in residential distribution network by providing the “time shift” of electricity usage support while maintaining an acceptable voltage profile. The main advantage of the BES system is its wide range of batteries (such as lead acid, nickel cadmium, nickel metal hydride, Lithium-ion, flow batteries) in terms of the different electro-chemical mechanism. From this variety of mechanism it is possible to identify a suitable BES technology considering all the factors such as energy/ power density, life-cycle, round trip efficiency, self-discharge and cost. A detailed analysis of the BES selection is presented in Chapter 4 (section 4.7).

**2.5 Communication requirement of the smart electricity grid**

Essentially, the smart grid should incorporate the provision of effective communication between all the smart equipment as well as widespread control over the resources and services. As maximum utilisation of available resources and their widespread control requires active participation of the end-users, utility companies need to find out innovative ways to enable all the stakeholders to interact with each other. Most of the emerging concepts and algorithms to maintain an acceptable voltage profile in the distribution feeder will fail to function as a viable solution without the active participation of the end-users.

With the objective of enabling widespread control and communication between smart equipment throughout the network, the smart grid is appearing as a mixture of IT, communications and power engineering [59]. In future, communication infrastructure will become an indispensable part of the electricity grid. Incorporation of such additional technology will act as an additional layer or interface for the electricity grid. For the
smooth operation of all the technologies and interfaces, development of new algorithms will be required.

The roadmap of the future smart grid is likely to be an evolutionary uptake rather than any radical overhaul. Massive change in the existing grid will incur a huge financial investment which is not a feasible solution. Therefore, any new algorithms should have the provision to integrate smart control alongside the traditional grid. These new control algorithms will ensure the co-existence of smart as well as traditional technologies.

Fig. 2.7. Simple schematic diagram of bottom down hierarchy in the traditional grid

Fig. 2.7 shows the basic structure of an existing hierarchical electricity grid. The hierarchy is a bottom down structure with generation plants are at the top and the customer load at the bottom of the hierarchy. During the planning phase of the traditional grid, power flow is considered to be only one way; that is, the power flows from the top to the bottom of the hierarchy. There is no provision for the consideration
of any real-time network information to dynamically allocate the available resources. Therefore, the traditional grid is usually designed to cater for the peak demand considering losses and reliability which is an infrequent occurrence. As a result, installed capacity of huge generation remains unutilised during most of the time. This scenario was well accepted and practised when the generation was abundant in compared to the demand.

The diminishing availability of fossil fuel, its impact on environmental pollution, and the exponentially increasing demand for electricity, have given rise to the concern about maximum utilisation of available resources. It has become too challenging to keep pace with accelerating demand in terms of the generation safe margin. In such a situation any unprecedented demand spike may lead to a disaster or blackout due to a diminishing generation safe margin. Utility companies have already started to integrate of diverse generation sources (both centralised and decentralised) in order to ensure uninterrupted generation. However, the unscheduled characteristic of some generation sources needs special consideration in the operation algorithms. The emerging control algorithms should consider these diverse generations from the available natural resources as a complement to the existing electricity grid, not as a replacement. To enable the control algorithm in the future grid, a pervasive communication network needs to be incorporated. More detailed literature review is given in following chapters.

### 2.6 Probabilistic analysis

Generation from renewable energy sources (e.g. solar PV) depends on regional, seasonal and daily variations. To incorporate the variability and intermittency of PV generation and load demand, probabilistic estimation is highly recommended. The estimation can be done by defining the generation as a process and determining the probability of future values based on present values. The Markov chain has been used for weather forecasting by several researchers [60]-[62] and hence it can be used for PV generation as well [63], [64]. Apart from that, another growing interest among the
researchers is PLF techniques. It is an emerging approach to calculate the line flows under different uncertainties.

PLF was first introduced back in 1974 [65]. Since then a variety of PLF methods including numerical and analytical approaches have been proposed [65]-[71]. The numerical approach includes the Monte Carlo (MC) simulation with random selection which was one of the most popular choices [72]. However, the MC simulation involves a high computational cost for a larger and complicated network. The theory of conventional convolution is used in some of the PLF techniques but, again the requirement of high computation time is a major drawback. Recently, the point estimation method [73], Gram-Charlier & Cumulant expansion series [67], and Latin hypercube sampling methods have been developed for PLF [71], [74]. Most of the proposed PLF techniques are having some drawbacks such as computational burden (Monte Carlo, conventional convolution), sensitive accuracy with the complexity of system (point estimation method), requirement of necessary linearization (multi-linear simulation) and convergence problem (Gram-Charlier expansion, Cornish Fisher expansion). These techniques have some limitations in addressing over voltage problem in distribution network that requires complex control. In this research, Latin Hypercube Sampling with Cholesky Decomposition (LHS-CD) is introduced with coordinated control algorithm to maintain voltage profile in distribution network. A comparison between the Monte Carlo simulation and LHS-CD are performed in terms of accuracy and computation time.

2.7 Summary

Based on the literatures, the present research focuses on the large integration of rooftop PV systems in the residential distribution feeder with the aim to create the roadmap of the smart grid.
The growing concerns associated with the smart grid are illustrated in Fig. 2.8. The rapidly increasing pattern of PV penetration in the distribution grid is described from the available literatures. Such rapid integration of PV systems creates bi-directional power flow in the electricity grid which results in several technical challenges. The scope of this research is mainly limited to the most prominent problem, namely, voltage violation. To address the voltage violation problem, the impact of reactive capability of PV inverter is investigated in this research. Based on the research findings, a coordinated control to use the reactive capability of the inverter and integrated BES is proposed. Furthermore, increasing energy demand requires significant grid reinforcement from utility companies which is based on the peak demand. Limited duration of the peak demand leaves a noteworthy amount of generated electricity unutilised. Energy stored in the BES system can be supplied back to customers during the peak demand period, which can defer the need for immediate investment from utility companies. As a result, a beneficiary scheme can be established to encourage customers to participate. A coordinated and intelligent control technique is demonstrated in this research using reactive capability as well as integrated BES. Suitable communication technology with a data management server is also analysed to ensure the smooth operation of the coordinated algorithm. Moreover, as discussed, the intermittent characteristic of PV generation introduces uncertainties in the generation pattern. Probabilistic estimation of
PV generation and demand is included in this research for that reason. Finally the research concludes with an analysis of the PLF technique in power distribution network. In summary, the scope of this research includes the blue coloured boxes associated with smart grid in Fig. 2.8.
Chapter 3

Effectiveness of Reactive Power Capability of PV Inverters

3.1 Background

There is significant contribution of electricity generation from rooftop Photovoltaic (PV) in recent years. Small-scale PV integration is suitable for urban and rural areas which have been thoroughly demonstrated in [11], [12]. Government incentives combined with public awareness for green technology has resulted in unprecedented growth of rooftop PV modules in residential premises. The penetration of PVs increases the service reliability and defers the need for immediate investment in grid reinforcement. However, high level penetration of PV systems brings several technical challenges in transmission and distribution network [75]-[78]. Among these challenges associated with distribution network, voltage rise is considered to be the most prominent. An approach is proposed to control the voltage using transformer tap settings in [79]. The main limiting factor of this approach is the inability of frequent tap changing and finding an optimal setting. Particular focus has been given to the real-time setting of the OLTC of distribution substations [80], [81]. After instant demand forecasting and measurements of power injected by PVs, it is possible to determine OLTC settings to keep the voltage within limits. This requires reliable communication
link between PV customers and system operators [25], [81], [82]. Another way of keeping the acceptable feeder voltage is to limit the PV injection [8]. Such capacity limitation hinders the effective utilization of green energy.

Though not permitted under existing standards of PV interconnection, feeder voltage control using the reactive capability of PV inverters can be a useful method to avoid voltage violations. Usually PV inverters have the capability to supply or absorb reactive power which can be easily utilised for voltage regulation [83]. The provision of reactive power may involve a trade-off with active power supply which needs to be thoroughly investigated. Different methods to utilise the reactive power have been demonstrated in [84], [85] as following:

i) Fixed power factor mode of inverter
ii) Fixed reactive power mode of inverter
iii) Reactive power control as a function of voltage at the PCC

Fixed power factor and fixed reactive power modes operate in fixed settings and do not consider the dynamic allocation of reactive power. As addressing the voltage violation problem is the key focus of this research, reactive power from PV inverter is controlled as a function of voltage at the PCC. In the present research, an algorithm for maintaining voltage profile by reactive power control is shown for two scenarios, urban case (low R/X ratio) and rural case (considering Single Wire Earth Return-SWER line with comparatively higher R/X ratio). References [86]-[89] give some insight on the reactive power control but they are developed mainly for Medium Voltage (MV) and High Voltage (HV) networks. Also, line characteristics such as feeder length and line resistivity are not considered.

Voltage control capability of rooftop PV inverters can be affected by feeder length and its R/X ratio. The focus of this research is to quantify the reactive power capability of PV inverters to maintain the acceptable voltage limit in the residential distribution feeder. An algorithm to use the reactive capability of PV inverter is also developed. Feasibility of incorporating the developed control algorithm in a distribution network is briefly discussed. This chapter is organised as follows: Section 3.2 introduces an algorithm for utilising reactive power capability of PV inverters. It also mentions about
how the developed algorithm can be incorporated in distribution system with Smart Meters (SM) and Home Area Network (HAN). Section 3.3 describes the residential system, PV generation and load profile used in this study. Section 3.5 describes effectiveness of reactive power capability of PV inverters for urban and rural Cases. The impact of line resistivity and feeder distances are discussed and quantified with results in Section 3.6 and 3.7 respectively followed by discussions in Section 3.8.

3.2 Reactive power capability of PV inverters and Home Area Network

The reactive power capability of PV inverter can be utilised for voltage control. If the apparent power capability and instantaneous real power generated from an inverter are $S$ and $P_G$ (where $S>P_G$) respectively, then the reactive capability range of PV inverter is given by $|Q_G| < \sqrt{S^2 - P_G^2}$. Thus, for a 6 kVA inverter, at 0.8 PF, maximum allowable real power ($P_G$) is 4.8 kW. Reactive power ($Q_G$) generation capability is 3.6 kVAr and 6 kVAr with maximum and minimum $P_G$ generation respectively. In this research, reactive power control algorithm is developed in such a manner that PV inverters absorb reactive power during solar radiation time and supplies reactive power during peak load demand time to address the voltage violation problem. This can be achieved by controllers communicating with smart meters.

Each residential premise can be equipped with advanced metering system such as HAN interfaced with PV inverter controlled by SMs. HAN is an in-house network and have inter-operation among all the connected devices. It ensures bi-directional secured communication among the devices to automate the proposed control algorithm. Appropriate authentication mechanism is an integrated part of HAN which allows only the recognised devices to connect the network [90]. HAN is configured within an individual residential premise with the functionality of i) in-house energy management; ii) use the reactive capability of PV inverter using the developed control algorithm.
Successful operation of the proposed algorithm requires coordination and communication between HAN systems of all the houses as well as with the substation controller. Several HAN system can communicate with each other through SMs. The communication medium of HAN as well as SMs can be wired (power line cable) or wireless network (cellular networks). Use of existing power line cable as communication medium, known as Power Line Carrier (PLC) communication [91], is a promising technique for inter-substation communications. An extensive and pervasive network is already developed for all the end users; and therefore the deployment cost in networking infrastructure, like dedicated cables or antennas can be omitted. In fact, the communication requirement for HAN and/or SMs is protocol dependant. For example, in case of fault management, the objective is to instantly and accurately identify the fault feeders and trigger the protection action [92], [93]. One of the key qualities of service for such protective actions is “Message Delivery Delay”, which makes PLC not favourable for applications where instant response is required. In the proposed algorithm, whereas, the response time of 2s-30s is acceptable and hence PLC can be used in HAN application and in sending/receiving information between substation controller and individual SMs.

The centralised controller at the substation level communicates with the SM of each house to determine the necessary reactive power to be absorbed/ supplied from the PV inverter. SM of each house carries this message signal to corresponding PV inverter through HAN system. In this way, the proposed reactive support algorithm can be easily deployed in the distribution system.

### 3.3 System description

A particular test network is considered for simulating the impact of feeder length and R/X ratio of line impedances on reactive control (Fig. 3.1). The test network consists of an 11 kV/240 V transformer supplying electricity to 12 houses in a 120 metre long overhead residential feeder. Different set of line parameters are used to investigate the impact of feeder length and R/X ratio of line impedances. In an urban scenario, distance
between backbone buses, $F_d$, and that between backbone bus with corresponding houses, $d$, are 20 metres each. R/X ratio is considered unity for the overall urban network. Whereas, in a rural scenario (Single Wire Earth Return (SWER)) $F_d$ and $d$, are 20 metres and 100 metres respectively. R/X ratio is considered to be around 5.6. These parameter values are tabulated in Appendix.

Fig. 3.1. Model of the test system

Fig. 3.2. PV generation and load profile for a peak day [116]

A typical summer peak load profile for a particular house is taken from one of the
Australian Distribution Company’s Annual Report which reaches maximum load of 3 kW at 8 pm. The PV generation profile is assumed to have a normal distribution and starts from 6 am and reaches peak of 6 kW at 12 noon and then gradually dies out at 6 pm. Identical PV generation and load profile (a lagging Power Factor (PF) of 0.8) is assumed for all the houses as shown in Fig. 3.2.

3.4 Proposed Algorithm

The proposed is summarised in Fig. 3.3. All the steps of the algorithm are as follows:

- 1st step: At substation controller, voltage at each house is calculated from a load flow without any reactive power injection or absorption. Necessary information (PV generation, load demand, etc.) to run the load flow is collected from the individual SMs at each house. These voltages identify whether any house violates the voltage profile in normal situation at that particular time. For the initial checking it only considers the voltage of last house. For a radial line, all other houses do not have any violation if voltage at last house is within limit.

- 2nd step: If voltage violation exists, difference voltage \( V_{\text{diff}} \) is calculated using (3.1) and then required reactive power \( Q_{\text{req}} \) to minimise this voltage difference is calculated using (3.3) for each of the houses at substation controller.

- 3rd step: For each house the substation controller checks whether \( Q_{\text{req}} \) exceeds the maximum inverter capacity \( Q_{\text{Gmax}} \) of a particular house. If \( Q_{\text{req}} \) exceeds \( Q_{\text{Gmax}} \) then \( Q_{\text{req}} \) is set to the maximum inverter capacity i. e. \( Q_{\text{Gmax}} \). Same steps are followed for all the 12 houses.

- 4th step: After determining \( Q_{\text{req}} \) for all the houses a load flow is run to check the voltages of all houses again by the controller.

- 5th step: If still the voltages are not within the limit, critical house nodes (houses with violated voltage profile) are identified. \( Q_{\text{req}} \) is set to \( Q_{\text{Gmax}} \) for these particular houses. And for other houses new \( Q_{\text{req}} \) is calculated using (3.3). Again the load flow is run and voltage is checked for all the houses by substation controller.
6th step: This iterative process runs until all the house voltages fall within acceptable range or reach the maximum inverter capacity though acceptable voltage profile is not yet achieved for all (this is the situation in rural case). Determined $Q_{req}$ is sent to corresponding SMs by the substation controller. SMs of each house communicate with PV inverters using HAN system to perform the reactive support. Equations for determining $V_{diff}$ and $Q_{req}$ are as follows:

$$V_{diff} = V_o - V_n \quad (3.1)$$

![Flow-chart](image)

Fig. 3.3. Reactive power control flow-chart
Where, $V_n$ is the house bus voltage for $n^{th}$ house and $V_a$ is acceptable bus voltage as in (3.2).

$$V_a = \begin{cases} 
1.06\,pu, & \text{if } V_n \geq 1.06\, pu \\
0.94\,pu, & \text{if } V_n \leq 0.94\, pu \\
V_n, & \text{otherwise} 
\end{cases}$$

(3.2)

$$Q_{reqn} = k.V_{diffn}$$

(3.3)

Where, $k$ is a constant. Constant ‘$k$’ is determined using an iterative approach. The value of ‘$k$’ is initially set as zero so is the $Q_{reqn}$. So, there will be no reactive power supply or absorption. In case of the voltage violation problem, the value of ‘$k$’ is increased ($k=k + \Delta k$) to get the required amount of reactive power to keep the voltages within limit. On the other hand the value of $V_{diffn}$ is in the range of $10^{-2}$ due to use of per unit calculations. In a loop, the value of $k$ is increased by a small amount to have a $Q_{reqn}$ value. Then the acceptable voltage level is checked and new $V_{diffn}$ is calculated if still voltage profile is violating. The value of ‘$k$’ is further increased and same steps are followed until the voltages fall into the acceptable range or reach the maximum reactive power capability of PV inverter ($Q_{G,maxn}$). In these cases the loop terminates and final value of $Q_{reqn}$ is considered. The value of ‘$k$’ is always positive. The sign of $V_{diffn}$ will decide whether reactive power will be supplied or absorbed. Based on the sign of difference voltage $V_{diff}$ (positive or negative), decision on reactive power injection or absorption from PV inverter is made for each bus. Negative value indicates the situation when house voltage $V_{hn} \geq 1.06$ pu, so reactive power is absorbed. Reactive power is supplied when the house voltage $V_{hn} \leq 0.94$ pu. The value of $k$, $V_{diffn}$ and hence $Q_{reqn}$ will be different for different houses. These values depend on the location of houses across the feeder and hence the severity of voltage violation for different houses. It may not need to reach the maximum available capability for the houses at the beginning of the feeder.
3.5 Effectiveness of reactive power capability of PV inverters for urban and rural cases

MATLAB is used for all the simulation results presented in this research. For a system shown in Fig. 3.1 and the assumed PV generation and load profile as in Fig. 3.2, voltage profile across the feeder is investigated. As two houses are connected with same backbone bus and have the same characteristics, only 6 houses are plotted for 24 hours.

3.5.1 Without using reactive capability of PV inverters

In normal situation (without using the reactive capability of PV inverter), voltage profile of all houses are shown in Fig. 3.4 (urban case) and Fig. 3.5 (rural case). Grid connected PVs are considered to operate at unity PF with Maximum Power Point Tracking (MPPT) algorithm.

![Fig. 3.4. 24 Hour Voltage Profile for urban case in normal situation](image-url)
From Fig. 3.4 and Fig. 3.5, it is evident that the voltage at the end of the feeder is extremely high when PV generation is peak. House No# 11 and 12, (H-11/12) has 1.11 pu and 1.13 pu voltages at 12 noon for urban and rural case respectively (LV feeder voltage allowable range is ± 6% [22]). All the houses (except first 2 houses for both the cases) exceed their voltages from the highest allowable range 1.06 pu when load (1.875 kW) is much lower than the peak generation (6 kW). On the other hand, due to absence of PV generation at peak demand or evening time, voltage profile gets a dip and all the houses (except first 6 houses for urban case and first 4 houses for rural case) cross the lower limit. Fig. 3.5 shows even worse voltage profile (higher overvoltage and higher voltage dip) for rural case which has longer feeder and higher R/X value in line impedances. In other way it can be said that networks with longer feeder and/or higher R/X value in line impedances have worse voltage profile.

3.5.2 With using reactive capability of PV inverters

The reactive power capability of PV inverter is utilised for the voltage control of all the houses as described in Section 3.2. Fig. 3.6 shows the voltage profile of all houses.
and corresponding PV inverter reactive power injection/absorption for urban case. Voltage of House No# 11 and 12 (H-11/12) during peak PV generation has been reduced below 1.06 pu (Fig. 3.6, plot 1) using the reactive capability of the PV inverter. H-11/12 voltage was 1.11 pu (Fig. 3.4) without reactive absorption. Similarly, during evening where there is no PV generation and loading level reaches the peak, the voltage dip is improved by the reactive power injection from PV inverters. Therefore, using PV inverter reactive capability, the house voltages can be kept within acceptable limits in the urban case after applying the developed algorithm. Corresponding reactive power profile is shown in the same figure (Fig. 3.6, plot 2). Reactive power on the negative axis indicates the absorption of reactive power by PV inverter and its presence in the positive axis indicates the reactive power supply from PV inverter. PV inverters operate with a power factor of 0.8. At this time, real power is slightly sacrificed maintaining the relation between real power ($P$), reactive power ($Q$) and apparent power ($S$) shown in Fig. 2.5. This relationship is elaborately described in section 2.3.

![Fig. 3.6. Voltage profile and PV inverter reactive power compensation (urban case)](image-url)
Voltage profile of all the houses across SWER lines and their PV inverter reactive power injection/absorption for the rural case is shown in Fig. 3.7. Voltage profile shows violation for the houses particularly in voltage dip (during peak loading and no PV generation), even after using the maximum capability of PV inverter. Therefore, the conclusion can be made that using the reactive capability of individual PV inverter may not be effective due to higher R/X ratio of line in rural scenario. In the following sections the impact of R/X ratio and feeder distance will be quantified.

### 3.6 Impact of line resistivity

The key focus of this section is to determine a limit of R/X ratio for which PV inverter reactive power capability is not sufficient to improve the voltage dip during peak loading. R/X ratio of the line between feeder bus and adjacent house (shown as $d$ in Fig. 3.1) is varied from 1 to 8. Peak loading is simulated keeping the injection of reactive power maximum i.e. -3.6 kVAR considering the real power is not sacrificed at any time. R/X ratio of backbone feeder is kept unity. Simulation is performed at 0.8 PF.
and 100% loading in each house. Fig. 3.8 shows that when R/X ratio is higher than 4.5, voltage goes below lower acceptable range (0.94 pu).

Fig. 3.8. Voltage level Vs R/X ratio with full loading

A trade off in loading level is required to keep the voltages within acceptable range (0.94 pu) for a feeder whose R/X ratio is higher than 4.5. Fig. 3.9 shows the percentage of feeder loading level with increase in R/X ratio for maximum reactive power injection and zero reactive power injection. Steps for determining the permitted loading curve with maximum reactive power injection are shown in Fig. 3.10. Similar steps are followed for determining the same curve with zero reactive injection from PV inverter. From Fig. 3.9, it is observed that with higher R/X ratio (higher than 4.5~5), loading should be reduced to 70% of peak value to keep the voltages in acceptable range. Moreover, same reactive injection incurs higher losses in higher resistive lines. Plotting incremental loss (increase in loss with respect to unity R/X) with R/X ratio variation is also shown in Fig. 3.9. After certain R/X ratio (above 4.5~5) losses are too high (50% increase). Therefore it can be concluded that, the effectiveness of PV inverters for voltage control is limited if the R/X ratio of the feeder is higher than 4.5~5. This R/X value is termed as the critical R/X ratio ($RX_{cri}$). Whenever the R/X ratio of the feeder goes beyond $RX_{cri}$, using only the reactive capability of PV inverter cannot keep the voltages within limits.
3.7 Impact of feeder distance

Impact of backbone feeder distance ($F_d$ in Fig. 3.1) on the effectiveness of PV inverter reactive power capability to maintain the acceptable voltage profile is investigated in this section. In previous section, only distance between feeder bus and adjacent house ($d$ in Fig. 3.1) is increased and $F_d$ is kept constant. Here, $F_d$ is varied to
find a relationship between $F_d$ and R/X ratio to maintain an acceptable voltage profile. PV inverter reactive capability is kept maximum i.e. 3.6 kVAR, assuming that the real power generation from PV is not sacrificed/curtailed at any time.

For a particular $F_d$, load flow is performed to observe feeder voltages and R/X ratio is reduced if voltage is not acceptable and resolve the load flow. This is continued until acceptable feeder voltages are achieved. This procedure of finding R/X ratio for a particular $F_d$ is repeated for all $F_d$’s ranging from 7 to 56 meters. R/X ratio is kept within the range 1~11, which is acceptable for a rural distribution network.

TABLE 3.1. Relation between $F_d$ and R/X ratio of the feeder backbone for an acceptable feeder voltage profile

<table>
<thead>
<tr>
<th>$F_d$ (meters)</th>
<th>R/X ratio</th>
<th>$(F_d) \times (R/X\ ratio)$ (meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>11</td>
<td>77</td>
</tr>
<tr>
<td>14</td>
<td>5.57</td>
<td>77.97</td>
</tr>
<tr>
<td>16</td>
<td>4.89</td>
<td>78.24</td>
</tr>
<tr>
<td>17</td>
<td>4.55</td>
<td>77.35</td>
</tr>
<tr>
<td>18</td>
<td>4.52</td>
<td>81.38</td>
</tr>
<tr>
<td>19</td>
<td>4.4</td>
<td>83.6</td>
</tr>
<tr>
<td>22</td>
<td>3.7</td>
<td>81.4</td>
</tr>
<tr>
<td>28</td>
<td>2.78</td>
<td>77.81</td>
</tr>
<tr>
<td>56</td>
<td>1.39</td>
<td>77.97</td>
</tr>
</tbody>
</table>

TABLE 3.1 shows the relationship between $F_d$ and R/X ratio for acceptable voltage profile. It is interesting to observe that $(F_d) \times (R/X\ ratio)$ is more or less same for all simulations except for R/X ratio of 3.7 to 4.5. $(F_d) \times (R/X\ ratio)$ value is slightly higher (81~83) in this range but within 5% of the other values of $(F_d) \times (R/X\ ratio)$. Fig. 3.11 shows the value of $(F_d) \times (R/X\ ratio)$ and its variation with R/X ratio of the feeder.
From the analysis a significant conclusion can be made that when distance between adjacent buses in the backbone feeder ($F_d$) is increased, the R/X ratio of the backbone feeder should be reduced so that their multiplication is kept nearly constant for acceptable voltage profile. This can be relevant for rural network distribution planning.

### 3.8 Discussion

This research introduces an algorithm to utilise the reactive power capability of PV inverters. The reactive power is controlled based on the voltage at PCC. Other available techniques to control the reactive power such as fixed PF or fixed reactive power are not capable of regulating reactive power dynamically. As a result, the research only focused on controlling reactive power with PCC voltage. Moreover, the research also investigates effectiveness of reactive capability under different scenarios. Urban scenario has unity R/X ratio whereas rural case considers SWER line with R/X ratio of 5.6. Simulation results show that reactive power capability of PV inverter can be sufficient for urban case to maintain acceptable voltage profile but rural case would require additional support such as capacitor banks, storage or load curtailment.
Furthermore, the research is focused in determining the limit on the effectiveness of reactive capability of PV inverters; hence, comparison between different techniques of using reactive power is limited on the scope.

For feeders having R/X ratio less than 4.5, reactive power capability of PV inverter is sufficient for voltage control. Also, it is observed that the product of the distance between adjacent buses in the backbone feeder ($F_d$) and R/X ratio should be maintained nearly constant for acceptable voltage profile. This is relevant for newer suburban design and rural network distribution planning. The solution to maintain acceptable voltage profile for longer feeders and highly resistive lines can be a coordinated control of reactive power and BES. The energy can be stored in BES during peak PV generation time and supplied back during peak demand time at evening and can be considered as a part of ongoing work.
Chapter 4

Coordinated Control of Grid Connected Photovoltaic Reactive Power and Battery Energy Storage Systems

4.1 Background

The energy sector has jumped into an era where increased energy demand is partly met through widespread installation of PV systems due to favourable economic, technical, and environmental factors. Fig. 4.1 shows the predicted growth of PV generation in Australia [7], which is expected to grow from 320 MW/year to 1130 MW/year under different uptake scenarios. This trend would result in 16%-20% of total electricity produced from rooftop PVs by 2031. Residential rooftop PVs contribute around 43% of total rooftop PV generation in Australia as shown in Fig.4.2. PVs can increase service reliability and hence defer the need for immediate investment in grid reinforcement. This would extend the possibility of utilising PVs for local voltage regulation in a way that is not possible with conventional centralised generators [94], [95].

Nevertheless, high level penetration of PVs in a distribution network requires addressing technical challenges such as voltage violation problem. In the previous chapter, particular focus has been given in utilising the reactive capability of PV inverter after discussing the suitability of other methods. Several research studies are performed on different centralised and decentralised reactive control strategies in [96]-[98]. The
authors in [99] propose autonomous inverters for voltage improvement using their reactive capability, by limiting the active power feed-in, which would result in the loss of customer revenue. Besides, reactive control strategies become less effective in Low Voltage (LV) distribution network compared to Medium Voltage (MV) and High Voltage (HV) networks [80]. Hence, in sub-urban and/or rural areas, where the distribution network is more resistive, a more suitable approach to maintain voltage profile is required.

![Graph 1](image1)

**Fig. 4.1.** Predicted PV growth in Australia under rapid and moderate uptake scenarios [7]

![Graph 2](image2)

**Fig.4.2** Composition of rooftop PV generation in Australia at Feb 2012[7]
Integration of energy storage systems to store excessive energy instead of curtailing can be another solution to alleviate the over-voltage problem [100]-[102]. Battery Energy Storage (BES) systems are compact and can play vital role in maintaining residential voltage profile in terms of “time shift” which is encouraged by storage charging at off-peak time and discharging at the peak time. Addressing voltage fluctuations caused by PVs using customer side energy storage systems has been introduced recently in [103]-[109]. Low energy density and deep discharging of non-battery type energy storage systems, such as Electro-chemical capacitors, are ideal for high power, short duration applications. One the other hand, battery storage has shown good performance in some specific applications such as delivery of energy for longer time period which will be an admirable feature to maintain voltage profile with “time-shift” strategy in residential distribution network [109]. The inverter control of PV and BES system is reconfigured to work as current source in phase with grid voltage under grid connected mode and as voltage source using droop scheme under islanded mode [103]. Authors in [104], [105] and [106] have proposed coordinated controller for medium and large scale commercial customers and uses lumped grid scale storage with complex control modes. Considering high line losses in LV systems due to complex control modes, lumped grid scale storage is not a good option for residential networks.

Authors in [107] also performed analysis on integrating decentralized storage devices in residential feeder almost in the same time with this research. However, the voltage equation used for calculation is based on the assumption of negligible cable loss and hence the impacts of R/X ration are neglected. In our research, a coordinated algorithm is proposed considering variability with PV generation, load and some network parameters such as feeder distance, R/X ratio.

PV module topology with battery equaliser can be used to raise the active power output from partially shaded PV modules [110]. Considering cloud transient and seasonal variation to quantify the solar resource potential for planning purposes is reported in [111]-[113]. However, the model to account the variability in PV generation and randomness in loads is not yet explored in detail.

The present research proposes a coordinated control of PV and BES system for
voltage control of residential distribution systems. Unlike [105] and [108], a local droop based control of BES placed at each house is proposed and does not require advance metering infrastructures. In this research, integration of PV and BES in each house is similar to [103], except that BES charging and discharging is based on the house voltage. Coordinated inverter control is different compared to [110], as the primary aim is not to increase the active power injection from PV modules and make over-voltage problem worst.

Another major contribution of present research is the quantification of the impact of line characteristics on the effectiveness of reactive control, which has not been reported in the past. Although, authors in [80] have shown that the reactive control is effective for wide range of load and generation condition, its quantification with respect to R/X ratio of the line is missing. This quantification will determine the optimum BES sizing by utilising the reactive capability of PV in combination with BES.

In section 4.2 and 4.3, the coordinated control algorithm of PV and BES for voltage improvement is introduced. A sample LV system and extensive simulation results are presented in section 4.4. The economics of the PV and BES systems is discussed in section 4.7 highlighting the choices for battery selection and cost comparison. Finally in section 4.8 validation of the efficacy of proposed scheme with real network data is demonstrated.

4.2 Coordinated control of PV and BES for voltage improvement

Existing regulations require grid connected PV inverters to operate at unity power factor for maximum real power injection. However, power injection at unity power factor causes over-voltage issues in a radial distribution feeder. Although different regions in the world will have different feeder voltage level as well as power ratings of the distribution transformer, voltage violations are observed in most of the grids across the world irrespective of the voltage levels. Fig. 4.3 is a setup found in typical Australian
distribution systems which is more sensitive due to the prevalence of overhead lines. Over-voltage problem across the feeder is simulated and shown in Fig. 4.4.

The voltage rise is usually more prominent towards the end of the feeder and rural voltage profile is worse than that of urban due to the higher resistive characteristic of rural feeders.

![Typical radial residential distribution feeder](image)

**Fig. 4.3. Typical radial residential distribution feeder**

![Over-voltage problem with PV (at 12 midday)](image)

**Fig. 4.4. Over-voltage problem with PV (at 12 midday)**

The reactive power capability of PV inverter can be utilised to reduce the over-voltage problem with very little loss of real power. For a given apparent power ($S$) and instantaneous real power generated ($P_G$) from an inverter, the range of allowable reactive power generation is given by $|Q_G| \leq \sqrt{S^2 - P_G^2}$. The operation of PV inverters
in non-unity power factor mode will reduce real power injection and allow reactive power absorption. Real power grid injection from PV inverter can be further limited (if required) by using a BES system, thereby reducing over-voltage problem.

Control of power storage in batteries can be achieved using either constant droop based or variable droop based methods. The constant droop method utilises same droop co-efficient ($m_c$) for all houses to store energy. $m_c$ is a function of maximum load ($P_{L,\text{max}}$) and generation ($P_{G,\text{max}}$) and is defined as in (4.1). In the overall calculations, per unitised values of all the entities (such as maximum allowable voltage, $V_{\text{max}}=1.06$ pu) are used to make the dimension consistent. It eliminates the complexities associated with unit conversion. The droop co-efficient ($m_c$) has become a unit less entity after using the per unit values of voltage and power. As a result, droop co-efficient and other entities can be used in the mathematical formulation keeping the dimension consistent.

Using $m_c$, the amount of reduced power, $\Delta P_{n,\text{reduced}}$, from $n^{th}$ PV is calculated as in (4.2). With constant droop method, BES starts charging when the voltage of the house goes above a critical voltage ($V_{\text{cri}}$). With droop based energy storage, the injection from PV inverters into the grid are gradually decreased, hence, the voltage rise also decreases gradually. If the droop based storage kicks in at maximum allowable voltage limit ($V_{\text{max}}$), the voltage will still be going up due to injection from PV. For this reason, the droop based storage starts at a voltage level lower than the $V_{\text{max}}$. This voltage level is named as critical voltage ($V_{\text{cri}}$) as defined in (4.3).

\[
m_c = \frac{P_{G,\text{max}} - P_{L,\text{max}}}{V_{\text{max}} - V_{\text{expected}}} \quad (4.1)
\]

\[
\Delta P_{n,\text{reduced}} = m_c (V_n - V_{\text{expected}}) \quad (4.2)
\]

\[
V_{\text{cri}} = V_{\text{max}} - (m_c \times \Delta P_{\text{reduced},\text{max}}) \quad (4.3)
\]

Where, $\Delta P_{\text{reduced},\text{max}}$ is the maximum amount of reduced power among all the ‘$n$’ houses and $V_{\text{expected}}$ is the per unitised nominal voltage which is 1 pu.
On the other hand, the variable droop based BES uses different droop co-efficient \((m_v^n)\) for different houses to ensure uniform energy storage. The calculation of \((m_v^n)\) is based on Sensitivity Matrix \((SMat)\), which in turn is defined using Jacobian of the load flow as in (4.4).

\[
SMat = \begin{bmatrix} 1 & 0 \\ 0 & |V| \end{bmatrix} \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix}^{-1} \begin{bmatrix} \Delta \delta \\ \Delta \delta \end{bmatrix} \begin{bmatrix} \frac{\Delta P}{\Delta P} & \frac{\Delta Q}{\Delta P} \\ \frac{\Delta V}{\Delta P} & \frac{\Delta V}{\Delta Q} \end{bmatrix}
\]

(4.4)

Each element of voltage sensitivity sub-matrix \((AV_i/\Delta P_j)\) represents the expected variation in voltage of any house \((i)\) with respect to a unit injection of active power \((P)\) in another house \((j)\). Positive signs in all the elements of \(AV_i/\Delta P_j)\) indicate that any injection of active power at any house \((j)\) will increase other house \((i)\) voltage and vice versa. The droop coefficients \((m_v^n)\) are designed to keep the house voltages between 1 pu and \(V_{max}\) (1.06 pu as per Australian standards). The droop co-efficient of \(n^{th}\) house \((m_v^n)\) is defined in (4.6). The amount of power stored in the \(n^{th}\) BES systems, \(\Delta P_{n, reduced}\), is calculated in (4.7). With variable droop based methods, BES starts charging when voltage of the house goes above a critical voltage \((V_{cri})\) as defined in (4.8). Per unit calculations are used for determining all the values.

\[
\Delta P_{\text{max}} = \frac{V_{n,max} - V_{cri}}{\sum_{j=1,N}^{i=N} \frac{\Delta V_i}{\Delta P_j}}_{\text{max}}
\]

(4.5)

\[
m_v^n = \frac{\Delta P_n}{V_n - \frac{\Delta P_n (V_n - V_{cri})}{\sum_{j=1,N}^{i=N} \frac{\Delta V_i}{\Delta P_j}}}
\]

(4.6)

\[
\Delta P_{n,\text{reduced}} = m_v^n (V_n - V_{\text{expected}})
\]

(4.7)

\[
V_{cri} = V_{\text{max}} - (m_v^{\text{max}} \times (\Delta V / \Delta P)_{\text{max}} \times \Delta P_{\text{reduced,\text{max}}})
\]

(4.8)
BES sizing will be determined by using either the constant or the variable droop based methods. The coordinated control of PV inverters and BES is required to alleviate the over-voltage problem. The overall algorithm for determining the appropriate BES sizing can be summarised below:

Step 1: House voltages are observed every hour without any reactive compensation of PV inverters or droop based BES systems.

Step 2: At a particular time step, if all the house voltages are within limit as well as below the critical voltage ($V_{cri}$), no action is taken and all voltages are measured during next hour.

Step 3: If the voltage of a particular house goes above $V_{cri}$, PV supply power to BES systems instead of supplying power to grid. House voltages are updated by running the load flow.

Step 4: If the voltage still exceeds the upper acceptable range (1.06 pu), reactive power is absorbed using the PV inverters. PV inverters absorb reactive power during peak solar radiation time, the amount of which can be proportional to excess voltage i.e. the amount of voltage exceeding the upper acceptable range (1.06 pu) of the respective house at that time.

Step 5: Finally, the load flow is performed again. If all house voltages are within the limit and then wait for the next hour and start again from Step 1. Otherwise repeat Step 4.

Newton-Raphson technique is used to perform the load flow in the simulations. For radial distribution systems, some specially designed methods, such as the well-known backward-forward sweep technique, can be more efficient to compute the power flow than the conventional Newton-Raphson method [114], [115] and hence can be used here. Similar coordination of PV inverters and BES can be utilised for improving the low voltage problem during peak demand as shown in Fig.4.5. During evening time, when solar resource becomes unavailable ($P_G=0$), the full capacity of PV inverter ($S$) can be used for reactive compensation. PV inverters inject reactive power when voltage goes below the lower acceptable value (0.94 pu as per Australian standards). Real power is also supplied from the BES during the peak demand period.
The energy is supplied when the voltage, $V_{no,t}$, of $n$th house at time step $t$ is below the lower acceptable limit (0.94 pu). $Tvd$ is defined as the total time duration when voltage dips are observed and is calculated based on past data (typically 4-5 hours/day). Using previous data of generation and load, voltage level is determined from load flow calculations. The time periods when the voltage remains below the lower acceptable range (0.94 pu) are then calculated and denoted by $tvd$. Then the available stored energy in $n$th BES system ($E_{n,stored\ BES,\ available}$) is calculated from the total stored energy in $n$th BES system ($E_{n,stored\ BES,\ total}$) by multiplying it with round trip efficiency factor ($\eta$) considering State of Charge ($SoC$) and Depth of Discharge ($DoD$) of the battery as in (4.9).

$$E_{n,\text{stored \ BES, available}} = \eta * E_{n,\text{stored \ BES, total}}$$  \hspace{1cm} (4.9)

Supplied energy from the BES for the $n$th house is then determined as in (4.10).

$$E_{n,\text{supplied}} = \frac{E_{n,\text{stored \ BES, available}}}{tvd}$$  \hspace{1cm} (4.10)

Fig. 4.5. BES energy supply during peak demand to eliminate voltage-dip
For constant droop based BES, stored energy, $E_{n,\text{stored BES, available}}$, and hence $E_{n,\text{supplied}}$ will be different for all the houses. Whereas, in case of variable droop based BES, $E_{n,\text{stored BES, available}}$, $E_{n,\text{stored BES, available}}$ and $E_{n,\text{supplied}}$ are same for all the houses, assuming identical BES systems are used. After supplying energy from the respective BES, house voltages ($V_n$) are again checked by running the load flow. If $V_n$ is still below 0.94 pu, reactive injection from PV inverter is performed for the $n^{th}$ house. The overall procedure continues until all the house voltages are above 0.94 pu.

Probable improvement in the voltage profile after applying proposed algorithm is shown in Fig. 4.6. Fig. 4.6 shows gradual decrease in voltage rise to keep the voltage level between critical voltage and upper limit. It also shows the expected improvement during peak demand as well. Simulation results will validate the algorithm in following sections.
4.3 Flow chart for coordinated control

A well-defined operation steps are developed to keep the voltage within acceptable limit. Feeder characteristics such as R/X ratio and feeder length have significant impact on determining the appropriate voltage control algorithm. The impact of feeder characteristics on the voltage violation level in a distribution feeder is investigated in Chapter 3. Depending on the feeder characteristics, voltage violation problem can be addressed using Reactive Capability of PV Inverter (RCPVI) only or coordinated RCPVI & BES technology. Choice of the appropriate and most effective algorithm is made considering the feeder characteristics and network parameter. The controller located at substation level collects the network data, PV generation and load data on hourly basis and analyse the need for required support to keep the voltages within limit if voltage profile is violated. After the analysis, the substation controller sends appropriate control signals. There are also controllers at each house integrated with the PV system. This combined system is termed as Integrated PV and Inverter (IPVI). Depending on the feeder characteristics some houses will require BES combined with the IPVI system. This combined system is termed as Integrated PV and BES system (IPVBS). Overall voltage control operation to keep the voltages within acceptable range for all the houses in the community can be summarised in Fig. 4.7.

4.3.1 Control operation if only RCPVI were to be required (as shown by Blue lines in Fig. 4.7):

Substation controller collects the network data, PV generation and Load data on an hourly basis for all the houses in that community. Load flow is performed at the substation level to determine the voltage at each house ($V_n$, for all ‘$n$’ houses) connected to the feeder. The controller checks whether any $V_n$ is beyond the acceptable limits. Controller sends RCPVI command signals to the respective IPVI to use the reactive capability of PV inverter whenever voltage profile is violated. If no voltage violations are reported for that hour, controller waits for another hour and collects the PV generation and load data and repeats the steps.
Take the scenario where voltage violation exists

Start

Is RCPVI alone sufficient for voltage control?

Time, t=0

Is PVgen=0?

Is \(V_n > V_{cri}\) for any \(n\) house?

Send ‘Droop’ signal

Send ‘Droop’ and ‘RCPVI’ signals

Time, t=t+1

Is t=24?

End

Yes

No

Substation collects the PVgen data, load data and SoC of BES for all ‘n’ houses in every hour

Run the load flow to determine all house voltages \(V_n\).

Is \(V_n < 0.94\) for any \(n\) house?

Yes

No

Calculate \(E_{n,\text{supplied}}\) for all ‘n’ houses

Set \(E_{n,\text{supplied}} = E_{n,\text{remaining}}\) and Send ‘\(E_{n,\text{supplied}}\)’ and ‘RCPVI’ signals

Yes

No

Is SoC of BES < 10%?

Send only ‘\(E_{n,\text{supplied}}\)’ signal

No

Yes

No

Send ‘Droop’ signal

Send ‘Droop’ and ‘RCPVI’ signals

Time, t=t+1

Is t=24?

Yes

No

Substation collects the PVgen data, load data for all ‘n’ houses in that community every hour

Run the load flow to determine all house voltages \(V_n\).

Is \(V_n > 1.06\) pu or \(V_n < 0.94\) pu for any \(n\) houses?

Yes

No

Send ‘RCPVI’ signal

Yes

No

No

Yes

Yes

Yes

No

No

No

Yes

No

Fig. 4.7. Operation flow chart

4.3.2 Control operation if coordinated RCPVI & BES support were to be required (marked in Green lines in Fig. 4.7):

Substation controller collects the network data, PV generation data, load data and State of Charge (SoC) of BES for all the houses connected to a distribution feeder. Load flow is performed at the substation level to determine the voltage of all houses. Now, if PV generation is present i.e. during day time, controller checks whether any house voltage exceeds the critical voltage \((V_{cri})\). If yes, then the “Droop” coefficient is calculated as per equation (4.5). Controller sends only the ‘Droop’ command signal to all the PV inverters if the voltage is below 1.06 pu but above \(V_{cri}\). However, if the voltage is still above 1.06 pu despite using “droop” based storage, then controller sends both the ‘Droop’ and ‘RCPVI’ command signals to all PV inverters to perform parallel operation of using reactive capability and energy storage. However, if PV generation is not there i.e. during evening time, the controller checks if the voltage of any house is
below the acceptable range (0.94 pu). If yes, energy supplied for each \( n \)th house \((E_{n,\text{supplied}})\) is calculated by substation controller using equation(4.9). If the SoC of the batteries is below the threshold level (10% of capacity), then \( E_{n,\text{supplied}} \) is set to energy remaining in BES for the \( n \)th house \((E_{n,\text{remaining}})\) and both RCPVI and \( E_{n,\text{supplied}} \) command signals to the IPVBS. If the SoC level is above 10%, the controller sends only supplied energy \((E_{n,\text{supplied}})\) signal to IPVBS. If the voltage of any house is above the acceptable range (0.94 pu) and/or below \( V_{cri} \), the controller waits for another hour and collects the network data and repeats the above steps.

### 4.4 Test System description and simulation results

An overhead residential feeder supplying electricity to 12 houses by an 11kV/240V transformer is considered as a test network (Fig. 4.3). All the houses are equipped with rooftop PVs rated at 6kVA each. In the urban scenario, the distance between backbone bus and each house \((d)\) is 20 m and R/X ratio is considered unity. Whereas in the rural scenario, \( d \) is 100 m, R/X ratio is 2.8 for the backbone and 5.6 for the SWER line (from the backbone bus to the respective house). Distribution networks in rural areas have weak characteristics (in terms of line resistance and inductance) and are reflected in the test system.

A typical summer load profile (shown for 24 hours in Fig. 4.8) is taken from an Australian Distribution Company [116]. A maximum load of 3 kW is considered for each house. Variation in the residential load profile distribution of different houses is modelled using white Gaussian Noise. The random load of H11/12 is shown in Fig. 4.8. Real-time data (15 minutes and 60 minutes interval) for PV generation from The University of Queensland (UQ) solar system is used in this study [117]. Fluctuations in PV generation due to clouds are more prominent in short interval data. In current research, hourly data profile is considered for the coordinated control of PV and integrated BES.
Fig. 4.8. PV generation profile and load profile of each house [116]

A summer day is chosen to simulate the worst case scenario (extreme PV generation will create worst over voltage and summer peak load demand will have worst voltage dip). Fig. 4.8 shows PV generation profile for a typical Australian summer day (6\textsuperscript{th} December, 2012) with moderate cloud transient.

4.5 Voltage profile during high PV generation and peak loading time

In normal situation (without considering any kind of reactive power control or Battery Storage), the hourly voltage profile of the residential distribution feeder is plotted and is shown for urban and rural scenario in Fig.4.9 for H11/H12.
The voltages of last two houses in the feeder, H11/H12, exceed the allowable limit of 1.06 pu at 12 noon. The H11 and H12 loads are 1.875 kW compared to the PV generation of 6 kW at 12 noon. Similarly, during the peak loading time i.e. at evening (around 8 pm) when there is no generation from PV modules, the voltage goes well below the lower limit of 0.94 pu. The voltage profile of H11/H12 is the worst for the rural case.

The reactive capability of PV inverters (if operated at non-unity power factor) can be used to improve the voltage profile. For a 6 kVA PV inverter, 3.6 kVAr of reactive power ($Q_G$) is available at 0.8 power factor. During the night, when $P_G=0$, the full capacity of PV inverter can be used for reactive compensation. So, the maximum reactive capability of a PV inverter during day and night time is considered to be 3.6 kVAr and 6 kVAr respectively.

The effectiveness of PV inverters for voltage control is limited for higher R/X ratio cases. Therefore, the effectiveness is thoroughly analysed and discussed in section 3.6. For the urban case (R/X ratio=1), the reactive capability of PV inverters is sufficient for the voltage improvement. Whereas, for the rural case (R/X > 5), the reactive
compensation alone is not sufficient and additional technology needs to be incorporated to achieve improved voltage profile. Coordinated control with integrated energy storage is proposed in this research.

4.6 Coordinated control of PV inverters and BES for improvement in voltage profile in the rural case

Coordinated control of PV inverters and constant/variable droop based BES to improve the voltage profile for the rural scenario is investigated. All the houses connected to the rural distribution feeder are proposed to have BES for improved voltage profile. Whereas, for the urban scenario, there is no need of BES since the reactive compensation from the PV inverter is sufficient to maintain an acceptable voltage profile.

The hourly voltage profile, reactive support from PV inverters, and accumulated stored energy in each BES is shown in Fig. 4.10 and Fig. 4.12 for constant and variable droop based methods respectively. Two houses connected to a single bus possess the same characteristics and therefore, for plotting purposes, only 6 houses are shown. The BES is charged during the day time and discharges during the evening when the house voltage goes below 0.94 pu. Supply of stored energy usually starts at late afternoon (5 pm-6 pm). So, a gradual decrease in the stored energy profile is observed. With the application of coordinated control algorithm, the voltage profile is improved for the rural network for both the cases- constant and variable droop. Constant droop based BES requires different sizes of BES for different houses and the last two houses H11/H12 require 5 kWh BES. Houses at the end of the feeder require larger BES capacity and hence higher investment, which may not be seem as a fair solution in the community. Whereas, the variable droop based method requires 2 kWh of battery for all houses as shown in 3rd and 4th subplot of Fig. 4.12. Moreover, with variable droop based BES, the total storage capacity required to achieve the same improvement in the voltage profile is significantly reduced. All the houses require total of 40.5 kWh of BES for the constant
droop based method compared to only 24 kWh if the variable droop based method is chosen.

![Voltage profile, PV inverter reactive support, stored energy and supplied energy during coordinated control of PV inverter and constant droop based BES](image1)

**Fig. 4.10.** Voltage profile, PV inverter reactive support, stored energy and supplied energy during coordinated control of PV inverter and constant droop based BES

![Accumulated Stored kWh and Supplied kVAR profile](image2)

![Hourly Stored Energy and Supplied Energy profile](image3)

**Fig. 4.11.** Hourly stored energy and supplied energy profile for the coordinated control algorithm of PV inverter and constant droop based BES
Fig. 4.12. Voltage profile, PV inverter reactive support, stored energy and supplied energy during coordinated control of PV inverter and variable droop based BES

Fig. 4.13. Hourly stored energy and supplied energy profile for the coordinated control algorithm of PV inverter and variable droop based BES
Fig. 4.14. Voltage profile, stored energy in BES and supplied energy from BES when constant droop based BES is used alone for voltage improvement

Fig. 4.15. Hourly stored energy and supplied energy profile of BES when constant droop based BES is used alone for voltage improvement
Fig. 4.16. Voltage profile, stored energy in BES and supplied energy from BES when variable droop based BES is used alone for voltage improvement.

Fig. 4.17. Hourly stored energy and supplied energy profile of BES when constant droop based BES is used alone for voltage improvement.
Fig. 4.11 and Fig. 4.13 show the hourly stored energy and supplied energy from each BES for coordinated control with constant droop and variable droop respectively. From these profiles it is clear that the coordinated control is developed to supply all the stored energy in a particular day. Accumulated excessive storage for the next days will result in the requirement of high capacity storage. High capacity storage will incur higher investment from the customers. Different houses have different amount of stored and supply energy for each hour for constant droop based coordinated control (Fig. 4.11). Whereas, for variable droop based coordinated control algorithm all the houses store and supply same amount of energy for each house (Fig. 4.13). As a result, equal BES sizing is observed for all the houses.

If BES alone were to be considered for voltage improvement, all the houses will need much higher capacity of batteries. For H11/H12 alone, the constant droop based method will require a 20 kWh BES system (Fig.4.14) and the variable droop needs 17 kWh (Fig. 4.16). Fig. 4.15 and Fig. 4.17 also show the hourly stored and supplied energy for constant and variable droop when only BES is used to address the voltage violation problem. It requires higher amount of storage and supply for each hour. This is excessively large and economically infeasible. Hence, the coordinated approach is preferred compared to using BES alone for voltage improvement.

4.7 Economics of coordinated PV inverters and BES systems

The section compares the cost of constant and variable droop based BES systems versus a utility feeder reinforcement such as DSTATCOM. An appropriate battery has been selected for the cost comparison.

4.7.1 Battery selection

There are wide range of existing batteries systems available for storage including lead-Acid, Li-Ion, Alkaline, NiMH and flow batteries (ZnBr, Vn redox). The following criteria are used for selecting the appropriate BES for residential purposes:
The first criterion is recharging ability. Alkaline batteries are good for only 25-30 cycles when operating with higher DoD. Therefore, these batteries are not considered due to lack of recharging ability.

The Second concern is safety. By-products of the battery charging process such as hydrogen gas, sulphuric acid can cause explosion, corrosion or burning. If overheated, some Li-Ion batteries may suffer thermal runaway which can lead to combustion in extreme cases. Deep discharge may short circuit the cell, making them unfavourable for residential premises.

The Third criterion is the space and weight characteristics. Too heavy and spacious battery equipment may require additional structural support and may not be an attractive option.

The Fourth factor is the round trip efficiency during charging-discharging process, which will affect battery size and cost. Therefore, high round trip efficiency is desirable. Lower self-discharge rate is another measure of the efficiency. Life cycle of the BES is highly correlated with frequency of charging-discharging and DoD. Residential BES system needs at least one charging-discharging cycle every day.

The Fifth factor is the cost. This is given a least priority as the cost is constantly changing due to technological advancement. TABLE I compares Lead-Acid, Li-ion, NiMH and flow batteries (Vn Redox, ZnBr) [118], [119].

Traditionally, lead-acid batteries were the prime choice for off-grid PV applications. Despite their long history and widespread usage, lead-acid batteries are one of the lowest energy-to-weight and energy-to-volume battery designs making it big and heavy for residential applications. Nevertheless, they are far cheaper than any other BES system available in the market. Also, lead-acid batteries work optimally with 40%-50% DoD only. In recent years, flow batteries are becoming popular for small scale storage (range of 5-10 kWh) due to its efficient performance in frequent deep discharging (up to 100%). Unlike other battery technologies, flow batteries are not fatigued by frequent deep discharging as the electrolytes are kept in separate chamber. They are also resistant from self-discharging [118]. Among all flow batteries available, ZnBr is selected to be the most suitable for this study, as it is cheaper than Vn redox.
TABLE 4.1. Battery characteristics comparison

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Lead Acid</th>
<th>Li NMC/Graphite</th>
<th>Li FePO4/Graphite</th>
<th>Ni MH</th>
<th>Vn Redox</th>
<th>Zn Br</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density (Wh/kg)</td>
<td>40</td>
<td>160</td>
<td>110</td>
<td>75</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>Power density (W/kg)</td>
<td>350</td>
<td>1300</td>
<td>4000</td>
<td>600</td>
<td>120</td>
<td>110</td>
</tr>
<tr>
<td>Lifetime (Cycles)</td>
<td>600</td>
<td>2500</td>
<td>5000</td>
<td>900</td>
<td>12000</td>
<td>7000</td>
</tr>
<tr>
<td>Round trip efficiency (%)</td>
<td>85</td>
<td>93</td>
<td>94</td>
<td>75</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Self-discharge (%/month)</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td>20</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Energy Storage System cost (USD/kWh)</td>
<td>330</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>600</td>
<td>400</td>
</tr>
</tbody>
</table>

4.7.2 Cost comparison

The authors in [120] perform an economic comparison of PV integrated systems with and without PV production limitation. However, the research is conducted in Belgium market following European standards and regulations. Cost comparison analysis is performed in this thesis in Australian context.

The cost of constant and variable droop based ZnBr battery system is shown in TABLE 4.2. Constant droop based BES systems costs $2,100 for the last two houses which is ten times higher than the first two houses. Whereas, variable droop based BES system costs $800 for each house. Overall, the cost of variable droop based BES storage system is 40% of constant droop based storage for the given network.

The cost of storage for voltage improvement is compared with the utility based reactive power control devices such as D-STATCOM. The capacity of a D-STATCOM is determined iteratively using load flow studies by placing a D-STATCOM at the 5th bus in the network shown in Fig. 4.3 (two third the distance i.e. nearly 75% of feeder [121]). For the given network, 65 kVAR of D-STATCOM is required, which will cost
around $3500 (assuming $50-55/kVAr [122]). Although one time investment in a D-STATCOM is less when compared to the total investment in BES ($9,600), BES provides long term technical benefits in terms of peak shaving. D-STATCOM can only regulate voltage with reactive compensation but cannot supply real power during peak demand. On the other hand, new technological innovation in the batteries may bring down the cost significantly, making the proposed scheme economically attractive.

**TABLE 4.2. Cost comparison between constant and variable droop based BES systems for voltage improvement**

<table>
<thead>
<tr>
<th>Houses</th>
<th>Constant droop based BES system</th>
<th>Variable droop based BES system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacity (kWh)</td>
<td>Cost (USD)</td>
</tr>
<tr>
<td>H1-H2</td>
<td>0.5</td>
<td>200</td>
</tr>
<tr>
<td>H3-H4</td>
<td>2</td>
<td>800</td>
</tr>
<tr>
<td>H5-H6</td>
<td>3.25</td>
<td>1300</td>
</tr>
<tr>
<td>H7-H8</td>
<td>4.25</td>
<td>1700</td>
</tr>
<tr>
<td>H9-H10</td>
<td>5</td>
<td>2000</td>
</tr>
<tr>
<td>H11-H12</td>
<td>5.25</td>
<td>2100</td>
</tr>
<tr>
<td>Total</td>
<td>16,200</td>
<td></td>
</tr>
</tbody>
</table>

**4.8 Validation of proposed method with real network data**

The proposed method is applied in a distribution system in Australia. For urban case, a North Brisbane city location is chosen (Fig.4.18). Houses are close to each other (distance varies from 10m-35m) and R/X ratio is close to unity (varies from 0.9~1.2). The cumulative load data is also taken from an Australian distribution company [116]. The peak load for each house is the average value, calculated by dividing the cumulative peak load with the number of customers/houses. The average value of the house peak load is around 3kW. Installed PV generation in each house is considered twice the peak load to simulate severe over-voltage conditions. For the rural case, network data is taken
from rural areas in North Queensland (Fig.4.19). In this scenario, houses are located much farther from each other (80m-200m) and R/X ratio is much higher (~6).

The house located towards the end of the distribution transformer has the worst voltage profile. The voltage profiles of all houses are monitored, but for plotting purposes, only the house towards the end of the feeder i.e. P5883-I (urban case) and P17 (rural case) is shown in Fig.4.20. Voltage profile is much worse for rural case.
The voltage profile after reactive compensation from PV inverter is shown in Fig.4.20. Voltage improves after the PV reactive support in urban case; however voltage violation still exists in rural case. Reactive compensation from PV inverter alone for rural and urban cases is shown in 2\textsuperscript{nd} plot of Fig.4.20. The maximum capability of PV
inverter is used (3.6 kVAr absorption during the presence of sunlight and 6 kVAr supply during the evening) for the rural case, but acceptable voltage profile is yet to be achieved. Coordinated control of PV inverters and variable droop based BES is applied to the rural case. Fig.4.21 shows improvement in the voltage profile of the last house in the feeder.

4.9 Discussion

This chapter introduces the use of coordinated control of PV inverters and droop based BES to keep voltage in the acceptable range with high penetration of rooftop PVs in residential distribution systems. There may be over-voltage issues in the feeder due to the unity power factor real power injection from PV inverters in some residential feeders. Utilising the reactive power capability of PV inverter is proposed to overcome this issue. However, it is also found that when the line resistivity exceeds a certain critical value (this critical R/X ratio is 4.5~5 for the given network), reactive compensation alone becomes less effective.

Therefore, the reactive capability of PV inverters alone is sufficient to improve the voltage profile in urban case, where R/X ratio is close is unity. Whereas, droop based BES combined with PV inverters are required in the rural case which has higher R/X ratio. If BES system were to be used alone for the voltage improvement, larger BES capacity is required.

Constant as well as variable droop based BES schemes are investigated. Although both schemes show good performance, constant droop based BES requires larger battery size and unequal investment in BES for the customers depending on their location in the feeder. Variable droop based BES, however, requires smaller battery size and equal investment in BES from all the customers in distribution feeder. The proposed coordinated control algorithm alleviates both the over-voltage and the voltage dip problem in the residential feeders.
Advantage of variable droop based energy storage is discussed in terms of financial investment from customers and brief comparison of financial and technical advantages between BES and D-STATCOM (reactive power compensation device) is presented. Although one time investment in D-STATCOM is lower when compared with total investment in BES, BES provides long term technical benefits in terms of peak shaving.

Considering the intermittent characteristics of PV generation, probabilistic estimation is also performed. The probabilistic estimation of PV generation and randomness in load profiles are considered over a year (2012) to analyse the utilization of BES. Two distinct seasonal profiles (summer and winter) are considered. It is found that BES capacity is well utilised for the voltage control purposes for more than 50% of time in the year (185 days/year).

The proposed method is applied in the actual urban and rural distribution network in Australia and similar improvement is observed.
Chapter 5

Incorporating Variability in PV generation and Load Demand

5.1 Background

In the previous chapter, a novel coordinated operation algorithm was proposed to regulate the distribution feeder voltage. A control algorithm to regulate voltage was demonstrated using either the Reactive Capability of PV Inverter (RCPVI) alone or the coordinated RCPVI with droop-based storage in BES systems. Extensive research was carried out to develop the algorithm to use the RCPVI, energy storage and supply from BES system and finally the coordinated operation of both. Modelling the effect of cloud transient using variability of PV as well as load is considered in this segment of research. This chapter discusses a detailed probabilistic modelling to find the effective utilisation of BES under variable PV generation.

For the smooth coordinated operation, all the inverters and the storage system should have a synchronised communication system between them. Several intensive studies have been undertaken across diversified perspectives. For example, [123]-[127] investigated communication requirements and corresponding system architectures, while [128] surveyed the feasible communication technologies and applicable standards for communications in the future power system.
In the present research, the existing power line cable is proposed as the communication medium which is known as Power Line Communication (PLC). Use of the PLC as a communication solution dates back to 1920 [91]. High attenuation and low data rates made PLC an unpopular choice as a communication medium. The concept became popular again at the beginning of this century in its application to make an automated distribution network by sending control signals between several automated servers. The pragmatic features of the PLC in distribution network automation led to the recent development of the IEEE standardisation of PLC [130]. The foremost advantage of PLC over other communication mediums is the existence of a pervasive power line. DNSPs simply need to retrofit the existing power line network for communication purposes. Feasibility of the communication infrastructure is also briefly analysed in this section.

5.2 Probabilistic estimation of PV generation

The need for additional voltage support (whether using the RCPVI alone or using the coordinated control of RCPVI and BES) depends on the PV generation and load characteristics of the particular distribution network. Solar irradiance and cloud transients are sporadic in nature and therefore PV generation is intermittent. As a result, probabilistic analysis is necessary to anticipate the severity of the voltage violation problem. DNSPs can use hourly data from consecutive days of a specific season to perform the probabilistic analysis. PV generation can be defined as an independent and identically distributed (iid) random process if an infinite number of samples can be taken, and this is not possible in practice. Rather the process is considered as a Discrete Time Markov Chain (DTMC) process. The weather forecasting process is usually considered as a Markov chain which is a “memory less” stochastic process [131]-[133]. DTMC assumes that the “future state” depends only on the “present state” and is independent of the “past states”. Each state is dependent on the immediate past state, so all the “past states” are considered for the “future state” in terms of the conditional probability. Moreover, only discrete data (hourly generation) are considered in this
research which makes the DTMC suitable for present analysis. For example, a yearly profile of PV generation can be considered as a process by \{SPV_{t,n} \text{ where } t=0, 1,\ldots, 24; n=1, 2,\ldots, 365\}, where \(SPV_{t,n}\) denotes a specific state of solar PV generation at time ‘\(t\)’ on a particular day ‘\(n\)’ in a year. In this research, the term “state” is used to indicate a specific hourly value of PV generation output. Future “state” will be estimated based on the immediate past “state” which is stationary in nature. The past “states” are not time-varying in nature.

The probability of transferring into another state at time ‘\(t+1\)’ entirely depends on the state at present time ‘\(t\)’ and is independent of the past states at \(t-1, t-2,\ldots, 1, 0\). To include the load variation, in this research “Net Generation” is considered as a DTMC process, which is defined as the difference between PV generation and load demand at a particular hour (\(t\)) of a particular day (\(n\)). For each particular hour, the load demand is subtracted from the PV generation to get the “Net Generation”. \(NetGen_N\) (where ‘\(N\)’ denotes the time for a specific set of values \{\(n, t\}\}) is a state of the “Net Generation” process and can have a finite number of values. In this portion of research, the finite number of values of “Net Generation” process is termed as the “states” of \(NetGen_N\).

The probability of the initial state \(NetGen_N\) can be defined as in (5.1)

\[
\alpha_a = \Pr\{NetGen_N = a\} \quad (5.1)
\]

where \(N=0, 1, 2,\ldots, 24*365\). The conditional probability of state \(NetGen_{N+1}\), having a specific value, say ‘\(b\)’ at \(N+1\)th time, given that the state \(NetGen_N\) has a particular value ‘\(a\)’ at \(N\)th time, is defined as \(Pr_{ab}\) in (5.2)

\[
\Pr\{NetGen_{N+1} = b \mid NetGen_N = a\} = Pr_{ab} \quad (5.2)
\]

The unconditional probability of state \(NetGen_{N+m}\), at say \(N+m\)th time is defined as
\[
\Pr\{NetGen_{N+m}\} = \sum_{i=N+1}^{N+m} \Pr\{NetGen_i \mid NetGen_N = a\} \ast \Pr\{NetGen_N = a\}
\]

\[
= \sum_{i=N+1}^{N+m} \Pr_{i,m} \ast \alpha_i
\]

(5.3)

Where, \(m=1,\ldots, 24\times 365-N\) and is based on present state at \(N^{th}\) time.

The range of \(NetGen_N\) can vary from \{-max load, i.e. when the PV generation is zero\} to \{max PV generation, i.e. when the load is zero\}. Solar irradiation and Cloud Transient (CT) affect the PV generation and hence affect the range of \(NetGen_N\).

Solar irradiance can be classified as Direct Normal Irradiation (DNI), Global Horizontal Irradiation (GHI) and DIFfusion (DIF) [134]. DNI dominates in concentrated solar power plants and PV tracking systems are designed to keep their surfaces perpendicular to the sun’s direct rays. In addition, the impact of DIF is negligible if the residential PV panels are widely spaced (typical suburban or rural scenario). In the residential PV systems, fixed panels are used and therefore the generation depends primarily on GHI. In this study, the variation of PV generation only due to GHI is considered.

The effect of CT on the solar generation can be quantified using the Clearness Index (CI) and Variability Index (VI). The daily CI is the ratio of solar energy measured on a given surface to the theoretical maximum energy on that same surface during a clear sky day. The maximum value of CI should ideally be 1. Clear sky solar insolation is measured as the normal distribution of the solar data for a particular season. The peak of the distribution is taken from the mean of solar data. CI can be expressed in (5.4)

\[
\text{Clearness Index} = \frac{\text{Measured Solar Insolation}}{\text{Calculated Clear Sky Solar Insolation}}
\]

(5.4)

On the other hand, VI is the ratio between the length of measured irradiance plot (obtained from real-time data) and the clear sky irradiance plot (ideal normal distribution
of solar irradiance) as in (5.5). The curve length between two consecutive points is measured using a line segment. The VI can vary from 1 to 25. VI can be expressed by the following equation:

\[
\text{Variability Index} = \frac{\text{Length of Measured Irradiance Plot}}{\text{Length of Clear Sky Irradiance Plot}}
\] (5.5)

VI is then normalised by the maximum VI for the season (\(VI_{\text{max}}\)) as in (5.6)

\[
VI_{\text{normalized}} = \frac{VI}{VI_{\text{max}}}
\] (5.6)

The CT effect is inversely proportionate to CI and proportionate to \(VI_{\text{normalized}}\) and simply can be represented as a linear combination of CI inverse and \(VI_{\text{normalized}}\) as shown in (5.7).

\[
CT = 0.5\left(\frac{1}{CI}\right) + 0.5*VI_{\text{normalized}}
\] (5.7)

Finally the \(\text{NetGen}_N\) value after considering the solar radiation and CT effect comes in the form of (5.8)

\[
\text{NetGen}_N = \frac{GHI}{CT}
\] (5.8)

Considering the CT and solar radiation effect on PV generation, Probability Density Function (PDF) is determined for the “Net Generation” process using various \(\text{NetGen}_N\) states for all \(N\). Although PV generation is considered as a normal distribution, “Net Generation” process has a different characteristic. As peak solar irradiation is available only for few hours in a day and load demand is consistent throughout the day, the overall distribution of “Net Generation” shows positive skewness and hence belongs to the family of Pearson distribution [135]. Depending on the higher order moments (e.g.
skewness, kurtosis), Pearson distribution can be of different types as shown in TABLE 5.1. The PDF of a given Pearson distribution can be considered as \( F(x) = C_0 + C_1 x + C_2 x^2 \), with coefficients \( C_0 = 4v_2^2 - 3v_1 \); \( C_1 = \sqrt{v_1} (v_2 + 3) \) and \( C_2 = 2v_2 - 3v_1 - 6 \), where \( v_1 \) is the square of the skewness and \( v_2 \) is the kurtosis. Using \( v_1, v_2 \) and \( \omega \) (another variable defined as \( C_1^2 / 4C_0C_2 \)), the appropriate type of Pearson distribution can be determined. After determining the mean (\( \mu_{\text{NetGen}} \)), standard deviation (\( \sigma_{\text{NetGen}} \)), skewness (\( \sqrt{\nu_1_{\text{NetGen}}} \)) and kurtosis (\( \nu_2_{\text{NetGen}} \)) of the “Net Generation” process, the appropriate distribution and hence the PDF is determined from the Pearson family.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Distribution Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_2 = 3 )</td>
<td>Standard normal distribution (Type 0)</td>
</tr>
<tr>
<td>0&lt;( \omega &lt;1 )</td>
<td>Four parameter beta distribution (Type 1)</td>
</tr>
<tr>
<td>( v_2 &lt; 3 )</td>
<td>Symmetric four parameter beta distribution (Type 2)</td>
</tr>
<tr>
<td>( \omega &lt; 0 )</td>
<td>Inverse gamma distribution with location scale (Type 5)</td>
</tr>
<tr>
<td>( v_2 &gt; 3 )</td>
<td>t-distribution (Type 7)</td>
</tr>
<tr>
<td>else</td>
<td>Pearson IV distribution (Type 4) or F-distribution (Type 6)</td>
</tr>
</tbody>
</table>

Using the net power generation from each bus, the mismatch vector \( [\Delta P; \Delta Q] \), which is used to calculate the voltage changes at each bus using (5.9).

\[
\begin{bmatrix}
\Delta |V| \\
\Delta \delta
\end{bmatrix} =
\begin{bmatrix}
J_1 & J_2 \\
J_3 & J_4
\end{bmatrix}
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
\] (5.9)

Considering \( \zeta \) to be the set of states where the voltages remain within acceptable limit (\( \pm 6\% \) of the base value), whenever the voltages are violated, it enters into a different
state, say $\bar{\xi}$. An additional voltage control approach is required to take the voltages back into the set $\xi$. If the voltage is violated at $K^{th}$ time, then

$$K=\min\{N: \text{NetGen}_N \in \bar{\xi}\} \quad (5.10)$$

The probability of recurrence in state $\bar{\xi}$ is calculated; where again the voltage control approach is required. Let $\lambda$ be defined as an event when voltage is violated at a particular time $N$. The total occurrences of voltage violation (i.e. total occurrences of voltages enter into state $\bar{\xi}$) is determined and then the probability of $\lambda$ is calculated as:

$$Pr(\lambda)=Pr\{\text{NetGen}_N \in \bar{\xi} \mid \text{NetGen}_K \in \bar{\xi}\} \text{ for all } K \quad (5.11)$$

$Pr(\lambda)$ indicates the percentage of times when the voltage violation is occurred and when additional voltage control is required. Finally, if $Pr(\lambda)$ is greater than 0.5 (i.e. voltage violation occurs more than 50% of the time), the integration of additional voltage control methods such as RCPVI or the combination of RCPVI and droop-based BES is essential to keep the voltages within the acceptable range. Even if $Pr(\lambda)$ is less than 0.5, voltage violation still occurs; however the frequency is not too high to integrate additional voltage control methods.

5.3 Simulation results

To simulate the worst case scenario, summer PV generation and load profiles are considered for the test network described in Chapter 4 (Section 4.4). To consider the impact of CT on PV generation, real data are taken from the University of Queensland (UQ) [117]. CI and VI are determined for the whole year 2012 using (5.4) and (5.5).

Using both the indices, four types of days are classified as i) high variability (with $VI>12$), ii) moderate variability ($3 \leq VI \leq 12$), iii) overcast ($VI<3$ and $CI<0.4$) and iv) clear ($VI<3$ and $CI>0.4$). CI and VI are calculated for 1 minute, 15 minute and 1 hour data and are shown in Fig. 5.1. It is seen that the variability due to CT is negligible while
taking the hourly data. For the determination of BES sizing, the hourly data are considered as BES does not need to charge/discharge every 15 minutes or so.

Using the hourly data, the probability distribution analysis is performed as discussed above. It is found that the “Net Generation” process satisfies the conditions for Pearson type 5 distribution (inverse gamma distribution with location parameter) with skewness and kurtosis values of 0.833 and 2.81 respectively. The actual hourly data are also plotted as a histogram to verify the accuracy of the probability analysis. Fig. 5.2 shows the histogram and the corresponding Pearson 5 distribution ($\alpha = 6.866$, $\beta = 28.763$, $\gamma = -5.28$, the detailed equation for the Pearson 5 distribution is provided in the appendix). Using EasyFit software [136] the “goodness of fit” for the distribution is found 0.07215 using the Kolmogorov-Smirnov test, which reassures that the Pearson 5 PDF is a good representation of the actual solar generation and load profile. The Pearson 5 PDF is used for the DTMC “Net Generation” process and a finite set of states $\xi$ is obtained. Using these data, the probability of the occurrence of voltage violations, $Pr(\lambda)$, is found to be 0.7. Therefore, additional voltage control methods such as RCPVI alone or the combination of RCPVI and BES are required to improve the voltage profile.

Fig. 5.1. Percentage of different types of days using CI and VI using 1 minute, 15 minute and 1 hour solar data
5.4 BES utilisation with seasonal variation

Using the estimated solar PV generation of each hour over a year (2012), the percentage utilisation of the BES capacity is determined. BES capacity is the size determined from the worst case analysis in previous chapter (Section 4.6). During the simulation, random load profiles with two distinct seasonal variations, namely winter (April-September) and summer (October-March) are considered for every house in the network. Using the estimated PV generation values and random load profiles, the load flow is run for each hour of the year (total 24*366 times) to determine the daily BES utilisation percentages for the year 2012 for all the houses. The coordinated control algorithm with the PV inverter and variable droop-based BES is considered for all the simulations.

The results of the BES utilisation are summarised in Fig. 5.3. The BES system is underutilised (<10% of BES capacity) for only 16.2% of the time (59 days/year). The BES sizing determined from the developed algorithm is well utilised for 50.5% of the time (185 days/year).
5.5 Impact of R/X ratio variation and end users’ participation on battery sizing:

The BES capacity varies for different networks having different R/X ratios. The required BES sizing is shown for several R/X ratios higher than $RX_{cri}$ in Fig. 5.4 (considering the BES round trip efficiency of 0.9). $RX_{cri}$ is defined in section 3.6. A tremendous increase in the BES sizing is observed for feeders with an R/X ratio beyond extremely high value such as 10. Highly resistive lines have higher losses and hence worse voltage profiles. A modification factor ($m_{mf}$) needs to be multiplied with the droop coefficient ($m_{vd}$) in order to calculate the required BES sizing. Due to multiplication with $m_{mf}$, a step rise in the BES sizing is observed for R/X ratio over 10. $m_{mf}$ is defined as (5.12).

$$m_{mf} = \frac{(\Delta V / \Delta P)_{\text{max}}}{RX - RX_{cri}} \quad (5.13)$$

Where, $RX$ is the R/X ratio value between each house and corresponding bus. The $m_{mf}$ values for different R/X ratios (11~15) are shown in TABLE 5.2.
TABLE 5.2. Modification factor values for different R/X ratios

<table>
<thead>
<tr>
<th>R/X ratio</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{nf}$</td>
<td>1.56</td>
<td>2.12</td>
<td>2.75</td>
<td>3.46</td>
<td>4.25</td>
</tr>
</tbody>
</table>

Fig. 5.4. BES sizing with R/X ratio

The required BES sizing also depends on the participation of the community members. If some of the community members do not wish to participate in the grid reinforcement process, other members may need to install higher capacity BES. The capacity of BES increases with the decreased participation of the members (shown in Fig. 5.5). BES capacity also varies with the position of the non-participating houses. Fig. 5.6 shows the required BES capacity in the network if the position of two non-participating houses changes from bus 1 to bus 6 (end of the feeder, referring to Fig. 4.3). With the increase in distance along the feeder, the BES capacity from other houses increases proportionately. If the houses towards the end of the feeder choose not to participate in the coordinated algorithm, the network would require higher BES capacity from rest of the houses in order to maintain the acceptable voltage profile. These end-users’ will also definitely benefit more. The R/X ratio beyond 10 requires $m_{nf}$ resulting in higher BES capacity.
So far, in all the simulations, the capacity of PV inverters is considered to be the same. TABLE 5.3 shows the effect of differently sized PV inverters in the feeder on the required BES capacity for each house.

### TABLE 5.3. BES capacity with different set of PV generations for all the houses

<table>
<thead>
<tr>
<th>House</th>
<th>H 1/2</th>
<th>H 3/4</th>
<th>H 5/6</th>
<th>H 7/8</th>
<th>H 9/10</th>
<th>H 11/12</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV gen (kW)</td>
<td>5.48</td>
<td>0.91</td>
<td>4.95</td>
<td>3.23</td>
<td>5.98</td>
<td>0.47</td>
<td><strong>42.05</strong></td>
</tr>
<tr>
<td>BES (kWh)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td><strong>12</strong></td>
</tr>
<tr>
<td>PV gen (kW)</td>
<td>5.21</td>
<td>2.51</td>
<td>2.4</td>
<td>1.56</td>
<td>4.8</td>
<td>2.59</td>
<td><strong>38.13</strong></td>
</tr>
<tr>
<td>BES (kWh)</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td><strong>10.8</strong></td>
</tr>
<tr>
<td>PV gen (kW)</td>
<td>2.66</td>
<td>0.64</td>
<td>5.77</td>
<td>0.03</td>
<td>4.65</td>
<td>4.9</td>
<td><strong>37.3</strong></td>
</tr>
<tr>
<td>BES (kWh)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td><strong>9.6</strong></td>
</tr>
<tr>
<td>PV gen (kW)</td>
<td>0.09</td>
<td>0.26</td>
<td>1.01</td>
<td>3.89</td>
<td>4.39</td>
<td>3.89</td>
<td><strong>27.07</strong></td>
</tr>
<tr>
<td>BES (kWh)</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td><strong>4.8</strong></td>
</tr>
<tr>
<td>PV gen (kW)</td>
<td>2.34</td>
<td>1.45</td>
<td>2.42</td>
<td>0.58</td>
<td>0.79</td>
<td>5.65</td>
<td><strong>26.47</strong></td>
</tr>
<tr>
<td>BES (kWh)</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td><strong>3.6</strong></td>
</tr>
</tbody>
</table>

Fig. 5.5. BES capacity with percentage of non-participating members
Fig. 5.6. BES capacity with the position of non-participating houses

With the decrease in the total generation, the BES capacity also decreases. In the simulated results, the total generation of 72 kW from the residential PV (6 kW*12 houses) requires a total BES capacity of 22.4 kWh (1.87 kWh*12 houses). After incorporating a random factor in the PV generation, all the houses now have a different generation. The total BES capacity reduced to 12 kWh with the decrease in the total generation to 42.05 kW. Gradually the total BES capacity reduces even further with decreased PV generation.

5.6 Economics of a system wide distributed BES

System wide storage can support the increased growth in peak demand by deferring the immediate network reinforcement. Several communities can participate together in a similar program to eliminate over-voltage and support during peak demand from stored energy to defer the investment from DNSP up to a certain time period. Peak demand lasts for a very short duration, which can be illustrated from the load duration curve of the utility. Fig. 5.7 shows the 2009-10 load duration curve for an Australian utility.
company. System peak demand increases from 4,200 MW to 5,040 MW for only 2% of the time in a year [116]. Localised distributed BES systems can provide support during these short periods.

Assuming that during peak demand, the average market clearing price is increased by $100/MWh. Hence, delivering the peak demand of 840MW for 2% of the time (147 GWh of energy) the electricity market cost would increase by $14.7 million annually. In contrast, a total of $67.4 million would be required if this energy was to be supplied by distributed BES systems (assuming $670 for 2 kWh battery, using one charging-discharging cycle/day for 365 days in a year). These are only indicative figures and the active power losses in the systems are neglected. It also assumes that BES systems will be available at every house or community. Nevertheless, this cost comparison does indicate that the cost of a BES system would pay for itself in almost 4.5 years.
5.7 Various command signals required for the operation of coordinated control

Successful operation of the substation voltage controller largely depends on smooth communication between all the servers. Three basic types of signals are identified for the communication infrastructure along with the “request” and “acknowledgement” signals. This section provides a brief description of these control signals. Flow of the associated control signals are shown in Fig. 5.8.
5.7.1 RCPVI command signal

Substation controller determines the required amount of RCPVI in conjunction with operating Power factor (PF) of PV inverter and sends this signal to each IPVI or IPVBS. A sketch of this signal is shown in Fig. 5.9. The equations used for determining $V_{diffn}$ and $Q_{reqn}$ were set out in Chapter 3 (Section 3.2).

5.7.2 Droop command signal

The algorithm of the droop command signal was mainly developed on Chapter 4 and described with all necessary equations in section 4.2.
5.7.3 \( E_{n,\text{supplied}} \) command signal

Stored energy is supplied back to respective houses during the peak demand time (usually around 8 pm). It gives benefits to both the customers and the DNSPs.

The substation controller calculates \( E_{n,\text{supplied}} \) for a particular hour and passes this information through \( E_{n,\text{supplied}} \) signal. A sketch of this signal is shown in Fig. 5.10. The necessary equation to calculate \( E_{n,\text{supplied}} \) was shown in (4.10).
5.8 Low cost solution for realising coordinated control using PLC

A unified data model and communication network is required to ensure the smooth communication of control signals for the coordinated operation. Using PLC to ensure the data communication between the servers is an ancient approach. Main advantage of using PLC is to use the pre-existing power line network. Existence of a widespread and omnipresent power network for all the end users can omit the deployment cost in networking infrastructure, like dedicated cables or antennas. Communication requirement in PLC is completely protocol dependent. For example, in case of fault management, the objective is to instantly and accurately identify the fault feeders and trigger the protection action [92], [93]. One of the key Quality of Service (QoS) measures for such protective actions is “Message Deliver Delay”. PLC may not be a suitable medium for such actions. Ultra narrow band, Narrow Band (NB) and broadband are three main classes of PLC. Broadband PLC technique can support higher data rate, but it comes with an expense of higher operational frequency spectrum (1.8-250 MHz) [137]. In fact, power lines are not specially designed for data communication, so higher frequency spectrum will result signal attenuation. NB PLC has been proposed in this research considering moderate operational frequency spectrum (3-500 kHz), moderate operational range and less attenuation. Moderate response time (2s-30s) is acceptable for proposed operation algorithm and hence NB PLC appears to be a suitable medium for such communication. To ensure the coordinated system control in a complex system with lot of servers, there should be a unified data model to communicate between the servers. Distribution Network Protocol 3.0 (DNP3) can be used for the communication purpose with binary representation of the data set [138].

The overall data communication system consists of a centralised server located at the substation transformer and decentralised servers of IPVI/IPVBS at each house. The centralised server is considered as the “Master Server”. The decentralised servers at each house level are considered as “Slave Servers”. Mainly three types of signal are communicated between “Master Server” and “Slave Servers” namely RCPVI, droop and
Each of these signal messages is carried out to the “Slave Servers” after making the decisions at the substation level. Acknowledgement of all the messages is also required. For the smooth coordinated operation all the equipment should interpret all the parameters in the same way. Bit-wise binary representation of all the parameter values in a specific byte at different communication layer are considered in this research. Similar binary representation is also considered to represent any deciding event such as exceeding the critical or acceptable voltage. DNP3 is used as the data communication model in this research. DNP3 is the enhanced performance architecture (EPA) model of the 7-layer Open System Interconnection (OSI) model. The DNP3 model which is the 3-layer subset of 7-layer OSI model is developed by International Electro-Technical Commission (IEC). The three layers used in this model are the two hardware layers at the bottom (physical and data link layer) and the top software layer (application layer). In addition to these layers, DNP3 adds another pseudo-transport layer to add some transport functions. This pseudo-transport layer corresponds to the transport layer and network layer of the OSI model with limited functionality. Fig. 5.11 shows the relation between the DNP3 model and OSI reference model. The original message arising from the application layer can also generate from the “User application” depending on the situation. “User application” layer can be visualised as a layer above the application layer and the input in this layer may come from the servers directly with/without processing or from Human Computer Interaction (HCI). All the associated messages are described in below section.

Fig. 5.11. Relationship of DNP3 model to OSI model
DNP3 model works in “Multi drop from one master” topology (Fig. 5.12). In the overall operation algorithm “Master Server” needs to communicate with all the “Slave Servers” individually (RCPVI is sent to the specific IPVI/IPVBS) or may need to broadcast the signal (in the case of energy supply from all the BES at the same time). To incorporate both the communication type (either one to one communication or broadcast) from the “Master Server”, among the four available network topologies “multi-drop from one master” is the most suitable. Other available topologies are “master-slave”, “hierarchical with intermediate data concentrators” and “multiple masters”. In the proposed DNP3 model “Full Duplex” procedure is considered in the physical layer. Direct link with Full Duplex procedure is the most appropriate one in case “Multi drop from one master” topology. Probable collisions can be avoided as all the “Slave Servers” have dedicated channel with the “Master Server”. In the “multi-drop from one master” topology, DNP3 model performs in “balanced” mode. At the data link layer, the term “balanced” and “unbalanced” are used to describe whether all stations may initiate communications or not. In the proposed operation algorithm, it is required to initiate the communication from the “Slave Servers” when critical or acceptable voltage is exceeded, whereas the “Master Server” needs to send the associated RCPVI, droop and $E_{n,\text{supplied}}$ signals.

![Fig. 5.12. Multi-drop from one master topology](image)

### 5.9 Message formation in the coordinated operation

Organization of different layers in the DNP3 model is shown in Fig.5.11. Data request or acknowledgement message signals (for both “Master Server” and “Slave Server”) are generated at first in the application layer in bytes using the binary logic. Then the message goes down to subsequent lower levels and adds header information
byte/bytes. Finally in the physical layer the message is transmitted to the peer. Physical layer ensures the connectivity among the “Master Server” with the “Slave Servers”. In the message formation process in different communication layers, the message becomes larger in size even with zero size messages. When sending the acknowledgement signal, though original message is significantly small (only one significant bit setting the acknowledgement bit to 1), it becomes much larger after assembling the additional header in the subsequent lower layers. In the receiving end, the complete message is received at the physical layer. Necessary action or responses are obtained from the application layer. So, the message goes in the subsequent upper level this time, disassembles into the smaller units of data and finally the original message is revealed in the application layer. Message formation in DNP3 is shown in Fig.5.13.

![Fig.5.13. Build-up of DNP3 message](image)

While sending or receiving the acknowledgement of any associated signal, original message data is empty. The acknowledgement information bit contains in the control byte header (Link Protocol Data Unit-LPDU) in the data link layer. The information bit containing direction of message flow is also contained in the control byte. Link “reset” is required to enable the communication between servers in each hour. The Frame Count Bit (FCB) and Frame Count Valid bit (FCV) in the control byte are used for primary messages. Primary stations initiate the “reset” performance to a secondary station.
Primary stations synchronise the FCB so that FCB=1 expected by the secondary for the transaction following the “reset”. FCV enables the use of the FCB.

**Definition 1:** Primary message: Primary message is defined as the message initiated from the server that enables the communication. The server is known as the primary station. It can be either “Master Server” or any “Slave Servers”.

**Definition 2:** Secondary message: Secondary server is the receiving server that receives the initiated message from the primary station. It can be either “Master Server” or any “Slave Servers”. Secondary message is defined as the message received at the secondary station.

Pseudo-Transport Layer in DNP3 has limited functionality compared to the OSI model. It performs the limited functionality of Network layer and Transport layer of OSI model. As a result it is named as “Pseudo-transport” in DNP3 model. Pseudo-transport performs the assembling and dissembling of data fragments. If the original message generated in application layer is significantly larger (more than 2048 bytes), data is fragmented. As a subsequent lower layer, pseudo-transport assembles and disassembles these fragments. In the proposed algorithm, original data message is not large at all (maximum 4 bytes), so there is no functionality of pseudo-transport layer. Application layer is the highest level of the protocol. “Master Server” generates the application level request message in conjunction with the “User application” layer. Original data message is contained in the Application Service Data Unit (ASDU). When the “Master Server” request for any specific data from the “Slave Servers” such as PV generation and load data of each house; the required data type is indicated by the bit representation of the ASDU.

Below section illustrates the message formation in the operation algorithm (shown in Fig. 4.7). Overall operation process is broadly divided in two scenarios, i) only RCPVI is sufficient to address the voltage violation problem; ii) coordinated control of droop based BES and RCPVI is required to address the voltage violation problem.
5.9.1 Scenario 1: RCPVI signal only

The following actions are carried out in the scenario where only the RCPVI is sufficient to address the voltage violation problem:

1. Central server needs to run the load flow every hour to check the voltage level at each house. So “Master Server” broadcasts the REQUEST for PV generation and load data to all the houses with IPVI (Slave Servers). For this broadcast REQUEST “Master Server” sets 1 to the Least Significant Bit (LSB) of ASDU.

2. All IPVI (Slave Servers) send acknowledgement (ACK) of the REQUEST to “Master Server”. For sending the ACK message, “Slave Servers” just set the ACK bit to 1 in the control byte header. It will not require any ASDU.

3. In RESPONSE to the REQUEST from “Master Server”, now the “Slave Servers” send the information (PV generation and load data). While sending the RESPONSE, “Slave Servers” use 4 bytes (2 bytes each for PV generation data and load data) as ASDU. Data formation in ASDU is shown in Fig. 5.14. Byte 1 and byte 3 are used to represent 2 digit decimal fractions (0-99). On the other hand, byte 2 and byte 4 are used to represent the integer of PV generation data and load data respectively.

![Data formation in ASDU for PV generation and load data](image)

Fig. 5.14. Data formation in ASDU for PV generation and load data
4. Upon receiving the RESPONSE from the “Slave Servers”, the “Master Server” sends ACK message (setting the control byte header only) individually to each “Slave Server”.

5. After having the updated PV generation and load data, “Master Server” collects additional information (e.g. no of bus, Base kVA, power factor) from the central database to run the load flow.

6. Then it determines the required reactive power if the voltage is violated.

7. Now the “Master Server” sends the RCPVI signal to the respective IPVI (Slave Servers). 2 bytes are used in each ASDU message. Byte 2 which represents the integer part of the reactive power, the Most Significant Bit (MSB) is used as the sign (SGN) bit. Setting this bit to 1 represents \( -Q \), indicates the absorption of reactive power from the IPVI. While setting the SGN bit to 0 represents \( +Q \), indicates that the IPVI is supplying the reactive power. The bit representations of ASDU message are shown in Fig. 5.15.

![Fig. 5.15. Data formation in ASDU for reactive power data](image)

If any house does not require RCPVI (i.e. voltage is within the limit), “Master Server” does not send any signal and therefore does not wait for any ACK message.

8. Using the above communication protocol, “Master Server” communicates with all the “Slave Servers” to send appropriate RCPVI signal.
5.9.2 Scenario 2: Coordinated operation

In the coordinated approach, the droop based storage in BES from the PV generation starts before the voltage level reaches the upper acceptable limit (1.06 pu). Storage starts as soon as voltage exceeds the $V_{cr1}$. The following communication steps are carried out:

1. Centralised “Master Server” runs the load flow at each hour following the same signal communication protocol mentioned in Section 5.9.1, steps 1-5.

2. After running the load flow, “Master Server” determines the variable droop coefficient for all “Slave Servers” and sends the droop signal. This signal carries the amount of real power to be stored in the respective BES over the next hour. The ASDU of the signal message contains 2 bytes to represent the integer (byte 2) and fractional part (byte 1) of the stored energy. MSB of byte 2 is the SGN bit which indicates the energy storage or supply (1 represents storage and 0 represents supply). All “Slave Servers” send the ACK message, and then performs the operation accordingly. The bit representations of ASDU message are shown in Fig. 5.16.

![Fig. 5.16 Data formation in ASDU for BES energy data](image)

3. $E_{n,supplied}$ signal is sent when voltage goes below the lower acceptable range (0.94 pu). After running the load flow (steps 1-5 in Section 5.9.1), “Master Server” broadcasts the amount of energy supply to all the “Slave Servers” following the same bit representations of ASDU shown in Fig. 5.16.

All these signals are followed by ACK message from the secondary terminals.
5.10 Calculation on data throughput

To ensure the feasibility of proposed PLC network to carry the requests and responses associated with all the command signals, it is a must to measure the data throughput and maximum allowable number of clients that a central server can handle at a time. The maximum data throughput (in kbps) of a PLC communication link can be measured as,

$$\text{Data}_{\text{TP}} = \left( \frac{\text{PS}_{\text{bytes}}}{t_{\text{round}}} \right) \times \frac{8}{1024}$$

(5.14)

Where, $\text{Data}_{\text{TP}}$ is the Maximum data throughput (in kbps)

$\text{PS}_{\text{bytes}}$ is the total packet size in bytes

$t_{\text{round}}$ is the total round trip time

At first, it is required to calculate the total packet size when the central server asks for the PV generation and load data ($P_{G}, Q_{G}, P_{L}, Q_{L}$) from the “Slave Servers”. When the central server makes a “REQUEST” for data, the Application Service Data Unit (ASDU) does not contain any information, but several header bytes are added with it while going down to the message layers. In Application layer, Application Protocol Control Information (APCI) header is added with it. As the message is a “REQUEST” 2 bytes of APCI header is added and named as Application Protocol Data Unit (APDU). Size of APDU is 3 bytes (1 byte header and 2 bytes of APCI). In the pseudo-transport layer, usually larger size data (more than 250 bytes) are segmented into frames of maximum 250 byte size. The APDU from the application is often termed as Transport Service Data Unit (TSDU) in the pseudo-transport. The packet size becomes 4 bytes with one more header. After that, the data link layer includes a pair of Cyclic Redundancy Code (CRC) bytes for every 16 bytes [139]. The functionality of CRC is mainly the error detections. This layer also adds 10 bytes header to each of TSDU, finally the total packet size becomes 16 bytes (10 bytes header in data link layer, 2 bytes of CRC and 4 bytes TSDU). Finally the physical layer converts the data packet from “frame type” to “bit
stream” and transfer through the power line to the corresponding “Slave Server”. In response to this “REQUEST”, all the “Slave Servers” provide their PV generation and load data \((P_G, Q_G, P_L, Q_L)\).

Each of these data contains 2 bytes in ASDU message (1 byte for the integer and another byte for the fraction). As a “RESPONSE” message ASDU will have 1 byte header and 4 bytes APCI to form the 7 byte APDU message. Again in pseudo-transport layer this message is named as TSDU with one additional header. Overall message size becomes 20 bytes in data link layer (10 bytes header in data link layer, 2 bytes of CRC and 8 bytes TSDU). Then the responses are transmitted to the central server for each of the required data \((P_G, Q_G, P_L, Q_L)\). Finally the total data packet size becomes 96 bytes (16 bytes for the “REQUEST” from central server and 20 bytes for each of four data “RESPONSE” from each “Slave Server”). Acceptable moderate response time for the proposed coordinated algorithm is considered as 2s-30s. To accomplish the control action within the lowest acceptable time, these data packets will be send/receive in 0.5s (0.5s to collect data, another minute to run the control algorithm by central server and rest 0.5s to deliver the appropriate signal to corresponding “Slave Server”). Maximum data throughput (in kbps) is calculated using (5.14)

\[
Calculated \text{ Data}_{TP} = \left( \frac{96}{0.5} \right) \times \frac{8}{1024} = 1.5 \text{ kbps}
\]  

(5.15)

According to IEEE standard 1901.2, narrow band PLC can support data rates of up to 500 kbps [44].

Therefore, the central server will be able to support approximately 333 (500/1.5=333.33) numbers of clients i.e. “Slave Servers” perfectly at a time. As each of the sub-station will contain at least one central server or “Master Server”, the above calculations justify the suitability of PLC for the communication medium of proposed coordinated algorithm.
5.11 Modulation techniques

Signal carrier in NB PLC need to represent only two bits, i.e. one or zero. It makes the modulation technique much simpler which can be done using a single carrier. Amplitude, frequency or phase – any characteristics of the message signals can be modulated to represent the binary control bytes and transmit them through PLC. As the developed algorithm requires to transmit maximum 96 bytes at a time with a bit rate of 1.5 kbps, moderately low data rate is of PLC is sufficient. However, the performance can be affected by some factors such as signal attenuation, noise disturbance and interference.

PLC is not specially designed for any kind of signal transmission. Therefore, it is highly influenced by the mentioned factors particularly when transmitting in higher frequency to accommodate higher data rate (in the range of Mbps). Using lower frequency (<500 kHz) in transmitting comes with a disadvantage of lower data rate, but minimises the impacts of attenuation, noise and interference. As per IEEE standard 1901.2, PLC can support up to a data rate of 500 kbps which is more than sufficient for the developed algorithm. Signal attenuation shows slowly time-varying characteristics in lower frequency band as it does not generate standing waves. It reduces the likelihood of narrowband fading. Signal attenuation that arises from the network load can be of the order of 40 dB/km or 100 dB/km. In fact, attenuation arising from network loads can be minimised with evenly distributed load over the distribution line. In such case, the relation between signal attenuation and distance can be considered to be approximately exponential. For PLC network, the received signal power can be mathematically formulated as a function of the distance between the transmitting and receiving end. The received signal power at distance \( d \) (meters), \( P_{re}(d) \), from the transmitter can be approximately written as

\[
P_{re}(d) = P_{tr} \times 10^{\left(-\frac{ka*d}{10}\right)} \text{ [W]} \quad (5.16)
\]
Where, $P_t$ is the transmitted power and $k_a$ is a constant that expresses the attenuation. On a standard channel with an attenuation of 40 dB/km, $k_a$ results as 0.004. For a bad channel we might have an attenuation of 100 dB/km and thus $k_a=0.01$. It allows a reliable communication (i.e. receiver receives undistorted message from transmitter) of up to 1.5 km. Transmitting and receiving of all the signals in the proposed operation algorithm can be considered to be reliable in a distribution network.

### 5.12 Discussion

This chapter describes a coordinated operation algorithm to ensure large electricity generation from PVs keeping the voltage within acceptable limit. This is a comprehensive approach which takes into account of all network parameters and feeder characteristics. Operation algorithm introduces a novel technique of using RCPVI and a coordinated control of using RCPVI and droop based BES. The selection of the appropriate control depends on the feeder characteristics, PV generation and load profile. Such coordinated operation demand well-defined communication protocol in the entire network. Utilising the existing PLC network can be an effective solution. As an integral part of the operation algorithm unified data model, communication network architecture and protocol are briefly introduced. Overall algorithm is quite a comprehensive solution to address voltage violation problem in a residential distribution feeder assuring the continued high penetration of PV systems.
Chapter 6

Probabilistic Distribution Load Flow Analysis with high level of PVs

6.1 Background

Distribution system is basically designed as a passive network for energy delivery to end users in traditional electricity network. Increasing contribution in electricity generation from PV systems introduce several technical challenges in distribution network. Over voltage problem is the most alarming among them. Several techniques have already been proposed by researchers to address the over voltage problem. However, most of the techniques are developed based on deterministic load flow study which does not consider any variability or uncertainty. Intermittent characteristics of PV generation and load demand introduce substantial amount of uncertainty in the power flow studies in distribution network. As a result, probabilistic load flow studies with high level penetration of PV are becoming important.

Probabilistic method characterizes the variability in system input (such as generation and load) by suitable probability distribution and thus incorporates the variability or uncertainty into the analysis. Application of probabilistic analysis to the power system load flow was first introduced by Borkowska in 1974 [65]. With gradual development in the conceptual framework and analysis techniques over the decades, probabilistic approaches in power system have been widely classified in two categories; Stochastic Load Flow (SLF) [140]-[142] and Probabilistic Load Flow (PLF). SLF primarily focus
on short time variability [67]. Since this research focuses on the variability of PV generation and load in the voltage profile for a relatively wide span of time, PLF analysis is more appropriate. Among the PLF techniques, Monte Carlo (MC) is the traditional and most accurate approach. It is a numerical method which performs deterministic load flow repeatedly for a significant number of times to precisely represent the entire distribution of system inputs [143]. Huge computational burden makes this MC simulation unattractive. Most of the researchers only use it for accuracy and computation time comparison. The conventional convolution technique is another way to perform PLF analytically. Convolution of probability density function (PDF) of input random variables can only be performed if the system is linear and input variables are independent to each other [144]. The state vector and power flow outputs are represented as a linear combination of input variables after applying linearization technique and hence the convolution is performed [66]. The major drawback associated with this approach is the high requirement of storage and computation time. In the conventional convolution technique each input variable function is discretized by \( x_1 \) impulses which are convolved with another variable discretized by \( x_2 \) impulses will have \( x_1 \times x_2 \) impulses [145]. As a result, probabilistic representation of a single power flow requires extensive computation which is not feasible for real-time simulations. Moreover, the systems with several control algorithms always cannot be linearize accurately.

There are some other popular analytical PLF techniques such as point estimation method (PEM) and multi-linear simulation method (MLSM). PEM calculates the statistical moments of the power flow by running \( 2m \) number of calculations for \( m \) number of input random variables. All the \( 2m \) calculations are weighted following certain procedures [73], [146]. Though this method comes with reasonable computation time, its accuracy is sensitive to the complexity of the system. Another analytical PLF technique, MLSM requires linearization of power flow equations around several operating points which is not suitable for systems with complex control algorithms [147]. In recent time, moment based PLF techniques such as Cumulants Combined with Gram-Charler expansion (CCGC), Cornish Fisher (CF) expansion are becoming popular. Application of CCGC in power system problems with integration of renewable energy
are discussed in [67], [148]. It uses cumulants and Gram-Charlier series to express the PDF and cumulative distribution function (CDF) to represent each input random variable to consider their variability. The power flow calculations are performed using consecutive summation of weighted derivatives of PDF/CDF up to a chosen order of expansion to ensure the convergence. For non-Gaussian PDF, CCGC faces serious convergence problem. Moreover, the increase in expansion order cannot assure the convergence or any improvement in results [149]. On the other hand, CF gives better result in the similar situation without any computation burden; however, its accuracy degrades significantly for complex systems [150].

Usually most of the control algorithms developed to address the over voltage problem in distribution network require complex calculations. A control algorithm to utilize the reactive capability of PV inverter based on grid voltage and another coordinated control algorithm to utilize the reactive power and droop based energy storage in batteries is already developed in previous works (Chapter 3, Chapter 4). Droop co-efficient is calculated using the sensitivity matrix obtained from Jacobian after running the load flow. Deterministic load flow is used for both the algorithms. The algorithms give good performance in maintaining the acceptable voltage profile in different scenarios such as urban and rural networks. Moreover, linearization of power flow equations can be performed using the DC load flow equations in transmission system. High X/R ratio of transmission line gives the flexibility to neglect the resistance and hence the linearization is adequate. However, such linearization procedures are not applicable to distribution networks. In this chapter a PLF technique with Latin Hypercube Sampling (LHS) to address the over voltage problem is proposed. Rank correlation between the input random variables are also considered in this research using Cholesky Decomposition (CD).

This chapter is organized as: Section 6.2 gives a brief description of the LHS technique and rank correlation with Cholesky decomposition. Section 6.3 introduces the test distribution system under study. It includes PV generation profile and load profile distribution with associated variation. This section also contains all the simulation results. Section 6.4 contains the validation of results with real network data.
6.2 Latin Hypercube Sampling

Initial application of LHS is found in literature [152] as reactor safety study of nuclear power plant. It can estimate the safety by measuring the uncertainty of favourable outcomes of any system with multiple input variables. Now-a-days LHS is being used in power system analysis that involves the interaction of multiple random variables and as a result, intensive computation is required to obtain the outputs [71], [74]. LHS is based on the basic concepts of sampling and permutation. LHS yields stratified sample of all the input random variables. Sampling in LHS is performed in a way to characterize the entire distribution of each input random variable with sufficient number of representative samples. LHS makes equal probability interval from the distribution during sampling. These intervals may not be of equal distance along the distribution realization but of equal probability. Single sample is chosen from these non-overlapping intervals. The number of intervals is equal to the sample size. One significant feature of LHS is its sampling over the entire spectrum of the distribution without discarding any tail-end values. As the tail-end values are less likely to occur, its realization interval distance is much longer compared to that of most likely values so that equal probability interval is maintained for the entire distribution. Similarly more sample values are obtained from highly probably segments (distribution realization interval is smaller due to equal probability interval). The sampled values thus actually represent the distribution. Same sampling procedure is individually applied for all the input random variables.

Let us consider an output variable \( Y \) obtained from \( k \) number of input variables.

\[
Y = f(X)
\]

(6.1)

\( X \) is the input variable matrix such as,

\[
X = [X_1, X_2, \ldots, X_k]
\]

(6.2)

All the input random variables constitute a distribution vector \( D \) which represents their corresponding distribution such as,
\( D = [D_1, D_2, \ldots, D_k] \) (6.3)

Fig. 6.1. Latin Hypercube Sampling with rank correlation

Sampling from equal probability interval is performed individually for all the \( k \) input random variables. Fig. 6.1 shows the cumulative distribution of a random variable \( X_t \) (consider, \( X_t \) is random PV generation values at 12 noon time). The distribution is divided into equal probability intervals along the Y-axis which results in variable distance of realization interval in the X-axis. At tail-end values the intervals are longer than the intervals of central values. Single sample value is taken from each of these non-overlapping intervals as the mid-point of it. This is the mid-point from equal probability interval along the Y-axis. The sample value may not be the mid-point of corresponding realization interval along the X-axis. The corresponding value from each realization interval is mapped from the mid-point of probability interval (shown in dotted lines from mid-point of probability interval in Fig. 6.1). In the similar way, sample point \((x_s)\) is taken for all the intervals \((I, 2, \ldots, N2; N2 \text{ is the LHS sample size})\). Thus the sampling vector \((S_{X_t})\) is constructed for the input random variable \( X_t \) such as,

\[
S_{X_t} = [x_{s1}, x_{s2}, \ldots, x_{si}, \ldots, x_{sj}, \ldots, x_{sN2}]
\] (6.4)
Same sampling and mapping methods are continued for all the input random variables in vector \( X \) to form the sampling matrix \( (S_X) \) with dimension \( N2 \times k \).

\[
S_X = [S_{X1}, S_{X2}, \ldots, S_{Xk}]
\]

(6.5)

Where, \( S_{Xk} \) is the sampling vector for \( k^{th} \) input random variable and defined similar to (6.4).

LHS technique then pairs the values individually sampled from different input variables for \( k \)-dimensional system. Pairing scheme is simple for uncorrelated input random variables. Usually the input random variables are correlated for a distribution network. Let us consider, PV generation and load demand at 12 noon are the input variables for the system. Individual sample points taken by LHS method contain significant correlation between them. The correlation between the samples of two input variables can be minimized using Cholesky decomposition. Instead of making random pair of input variables, a particular permutation is considered according to the rank correlation matrix. During this process, an ordering matrix \( L \) is generated from the ranks of all input variables. \( L \) is the ordering matrix such as,

\[
L = [L_1, L_2, \ldots, L_k]
\]

(6.6)

\( L_1, L_2, \ldots, L_k \) denote the rank of corresponding input random variables such as \( X_1, X_2, \ldots, X_k \). Each of \( L_1, L_2, \ldots, L_k \) are column vectors or ranking vectors with elements equal to the sample size. Finally, the ordering matrix \( L \) is generated with the dimension \( N2 \times k \). The generation procedure of ordering matrix \( (L) \) is also shown in Fig. 6.1. It starts after generating the sample point vector of a particular input random variable. In the previous paragraphs, a vector for sample points \([x_{s1}, x_{s2}, \ldots, x_{si}, \ldots, x_{sj}, \ldots, x_{sN2}]\) is already generated for the input random variable \( X_i \) (random PV generation values at 12 noon). Each of these \( N2 \) numbers of samples are found out in the elementary random PV generation matrix (obtained during Monte Carlo with a large sample size of \( N1 \)) and map the corresponding “index” from random PV generation matrix as the “rank” of input random variable \( X_i \). This constructs the ranking vector \( L_i \) for \( X_i \). Then ranking vector \( L_2 \) is constructed for input random variable \( X_2 \) and paired with \( L_i \) in the next column. Similarly all the ranking vectors are constructed and form the ordering matrix.
$L$ of dimension $N_2 \times k$. After the formation of $L$, the correlation between the ranks of input random variables is calculated as,

$$
\rho_L = \frac{\text{cov}(L)}{\sigma_{L_1} \ast \sigma_{L_2} \ast \ldots \ast \sigma_{L_k}}
$$

(6.7)

Where, $\rho_L$ is the correlation matrix of $L$ with a dimension of $k \times k$. $\text{cov}(L)$ is the covariance between the ranking vectors of all input variables. It results a covariance matrix of dimension $k \times k$. $\sigma_{L_n}$ is the standard deviation of $n^{th}$ ranking vector; $n = 1, 2, \ldots, k$

As $\rho_L$ is positive definite and symmetric, it can be decomposed by Cholesky decomposition in the following form,

$$
\rho_L = P \ast P^T
$$

(6.8)

Where, $P$ is the lower triangular matrix with dimension $k \times k$. It should be noted that, $\rho_L$ to be positive definite and symmetric, LHS sample size should be larger than number of input random variables ($N_2 > k$).

After that, a decomposed matrix ($G$) is constructed to have the rank correlated sampling matrix. $G$ is matrix of dimension $k \times N_2$ and is constructed following,

$$
G = P^{-1} \ast L^T
$$

(6.9)

The correlation matrix of $G$ results in an identity matrix of dimension $k \times k$. If the correlation matrix of the decomposed matrix is different from identity, need to perform the Cholesky decomposition of it again and follow the same procedure. Then (6.9) is replaced by (6.10).

$$
G = (P^T \ast (P^{-1})^T) \ast L^T
$$

(6.10)

As the elements of $G$ may not be integer, it is unable to indicate the rank of sampling matrix ($S_X$). So, all the ranking vectors (column) of ordering matrix ($L$) are updated as per the ascending order of each row in $G$. This procedure gives the updated ordering
matrix \((L_{up})\) after the “rank correlation” by the decomposed matrix \((G)\). The process of rank correlation preserves the order of samples taken from each interval even with correlation between the input random variables \([153], [154]\). \(L_{up}\) is used to rank the permutations of input random variables in the sampling matrix \((S_X)\). In this way, the rank-correlated Latin Hypercube Sampling with Cholesky Decomposition (LHS-CD) is performed. The importance of rank correlation is explained more in later part of this chapter. The major steps are briefly outlined in below diagram:

![Fig. 6.2. Steps for the LHS with rank correlation by Cholesky decomposition](image)

This updated sampling matrix is used as the input during the load flow studies with coordinated algorithm to address over-voltage problem in distribution network. LHS is a preferred choice for sampling procedure when computationally demanding and non-linear models are being studied. In power distribution system load flow studies are very crucial in determining the voltage, angle and line flows. Non-linear nature of load flow
Developed algorithm to utilize the reactive power from PV inverter to address the overvoltage problem in urban network and relevant simulations are performed with deterministic load flow. On the other hand, droop based coordinated algorithm is developed using the sensitivity matrix obtained from deterministic load flow [151]. In this part of research, same reactive control and droop based control algorithms are used for probabilistic load flow to maintain the voltage profile in different scenarios such as urban and rural networks. The objective of this paper is to introduce LHS as an efficient and generally applicable tool in power distribution system to perform the probabilistic load flow with high level penetration of PVs maintaining acceptable voltage profile. Usually, the acceptable voltage profile is considered to be within ± 6% of nominated voltage (1.06 pu to 0.94 pu) for a residential distribution feeder [22].

### 6.3 Test case and simulation results

A radial distribution network fed with 11kV/240 V transformer is considered as the test case for simulation studies in this research (Fig. 6.3). 12 houses are connected to the backbone feeder in the network. The backbone feeder is 120 m long with a distance of 20 m between the consecutive buses and having a unity R/X ratio. Distance between each house and corresponding bus at backbone feeder is considered 100 m with high R/X ratio (5.6). Such high R/X ratio is considerable for a rural network that is highly resistive in characteristics. Each of the houses are equipped with 6 kW solar PV and integrated battery storage system (BES). The PV generation profile is represented as a normal distribution with 24 hours of a day as in (6.11).

\[
f(x_{\text{time}}) = \max_{PV} \frac{1}{\sigma_{PV} \sqrt{2\pi}} e^{-\frac{(x - \mu_{PV})^2}{2\sigma_{PV}^2}}
\]

(6.11)

Where, \(\max_{PV}\) is the maximum capability of PV inverter (6 kVA). \(\mu_{PV}\) and \(\sigma_{PV}\) are mean and standard deviation of PV generation. \(\mu_{PV}\) is considered as the midday (12 noon) when the PV generation is maximum with a \(\sigma_{PV}\) of 2. It gives a PV generation
distribution that starts generation from 6 am and ends at 6 pm, reaching the peak at 12 noon.

Distribution of load demand for each house is taken from an Australian Distribution Network Service Provider (DNSP) graph [116] and can be formulated as in (6.12):

\[
 f(x_{\text{load demand}}) = \max_{\text{demand}} \left( a_8 x^8 + a_7 x^7 + \ldots + a_2 x^2 + a_1 x + a_0 \right) \tag{6.12}
\]

Where, \( \max_{\text{demand}} \) is the maximum demand which usually arises at evening (around 8 pm) for residential distribution network. \( a_0, \ldots, a_8 \) are constants having the values \( a_8 = 6.1 \times 10^{-9}, a_7 = -5.2 \times 10^{-7}, a_6 = 1.7 \times 10^{-5}, a_5 = -0.0003, a_4 = 0.002, a_3 = -0.03, a_2 = 0.122 \) and \( a_0 = 0.067 \). Eq. (6.12) is developed from the DNSP graph using plotting tool of Matlab.

Fig. 6.3. Test distribution network

The over-voltage problem becomes severe at 12 noon when the residential load demand is relatively low in compared to PV generation. The severity of over-voltage problem is also highly dependent on the variation of PV generation and load demand at a particular time. As a result, values of both the input variables at 12 noon are considered to be a normal distribution following,

\[
 f(x, \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{6.13}
\]

Where, \( \mu \) and \( \sigma \) are mean and standard deviation of corresponding input variables (PV generation, load demand). Normal distribution of PV generation has a mean of 4.5 kW
and standard deviation of 0.45. The distribution reaches the maximum capacity (6 kW) for some realizations at the tail. On the other, load demand has a normal distribution with a mean of 1.8 kW (average load demand at 12 noon) and standard deviation 0.18.

Initially, the PLF is performed by Monte Carlo (MC) simulation with 1,000 realizations from both the input variables. Fig. 6.4 shows the normal distribution curve fitted with the histogram for 1,000 realizations of PV generation and load demand respectively. Then the MC simulation is run in the test distribution network for two cases of each scenario (urban and rural); i) without any control algorithm to observe the over-voltage severity and ii) with the application of control algorithm (only reactive control algorithm for urban scenario and coordinated control algorithm for rural scenario) to observe the output voltage level within acceptable limit (1.06 pu). Simulations are run for four different cases (two cases for urban network and two cases for rural networks) as shown in Fig. 6.5 and Fig. 6.6 respectively. Network parameters for urban and rural scenarios are shown in Appendix I.

The over-voltage problem is more prominent towards the end of the feeder for a radial distribution network. Moreover, two houses connected at the same bus also show almost identical profile. For these reasons, only the voltage at the last house (H#12) is
plotted for simplicity in both the figures. Fig. 6.5 shows the voltage plot of H#12 with two cases of MC simulations for urban scenario. Results are shown for 1,000*1,000 permutations of two input random variables (total 1 million permutations). 2nd plot of Fig. 6.5 indicates the presence of all voltages within the limit after applying the coordinated control algorithm whereas; most of the voltages are above 1.06 pu for the simulations without any control algorithm (1st plot, Fig. 6.5). Similar results are shown for rural scenario in Fig. 6.6. The objective of this research is to perform PLF with developed control algorithms to maintain the voltage profile considering the variability of input random variables. PLF with MC technique gives improved performance in maintaining the voltage profile. However, it comes with the expense of huge computational time. Even with the High Performance Computing (HPC) support, it takes several hours to get simulation results which left MC an unpopular choice. As a result, LHS is introduced as the sampling method with Cholesky decomposition to consider the impact of correlation between input random variables. The performance of LHS-CD is compared with other sampling techniques such as linear sampling (LS) and random sampling (RS). The procedure to perform the rank correlated LHS-CD has already been described in section 6.3.

Fig. 6.5. Voltage profile of MC simulation i) without any control (top plot), ii) with reactive control algorithm (bottom plot) for urban scenario
Fig. 6.6. Voltage profile of MC simulation i) without any control (top plot), ii) with coordinated control algorithm (bottom plot) for rural scenario

Linear sampling considers a linear approximation for the distribution of each input random variables between the maximum and minimum values. It is then performed by dividing the distributions in equal distance non-overlapping intervals and taking single sample point from each of them (Fig. 6.7). Difference between the maximum and minimum values of range is divided by the sample size ($N_2$) to determine the equal distance intervals ($w_{\text{linear}}$). Sample points vector for each random variable in LS can be obtained following:

$$x_{r,\text{linear}}^n = \min(X_1) + \frac{(2n-1) \cdot w_{\text{linear}}}{2}$$  \hspace{1cm} (6.14)

Where, $\min(X_1)$ is the minimum value of input random variable $X_1$, $x_{r,\text{linear}}^n$ is the $n^{th}$ sample for $X_1$, $w_{\text{linear}}$ is the width of equal distance interval.

On the other hand, random sampling selects $N_2$ samples at random from the realization of each input variables. If $N_2$ samples from the entire distribution have been chosen completely at random, there is a possibility that the samples would form a cluster and some parts of the distribution would not be investigated.
Now, the comparison of these sampling techniques is performed with respect to the robust MC technique. TABLE 6.1 shows the comparison of mean and standard deviation of input random variables after applying LS, RS and LHS-CD (with sample size of 100). Following error indices are considered to indicate the sampling accuracy:

\[
err_\mu = \left| \frac{\mu_{MC} - \mu_{sampled}}{\mu_{MC}} \right| \times 100\% \quad (6.15)
\]

\[
err_\sigma = \left| \frac{\sigma_{MC} - \sigma_{sampled}}{\sigma_{MC}} \right| \times 100\% \quad (6.16)
\]

Where, \(err_\mu\) and \(err_\sigma\) is the error in mean (\(\mu\)) and standard deviation (\(\sigma\)). \(\mu_{MC}\) and \(\sigma_{MC}\) are mean and standard deviation of MC respectively. Whereas, \(\mu_{sampled}\) and \(\sigma_{sampled}\) are mean and standard deviation of other sampling (LS, RS, LHS-CD) respectively.

Though linear sampling gives a moderate approximation of mean for PV generation (2.06% of error) and load (2.11% of error), it gives outrageous results on both the variances (% error of 97.8 and 92.9 for PV generation and load respectively). Obviously, the linear approximation of distributions turns them to be an equal probability in equal distance and the original characteristics of the distributions are lost. The other technique with conceptual simplicity and ease of implementation, random sampling, gives quite good approximation of input variables in terms of mean and variance (mean % error of
only 0.28% and 0.70% for PV generation and load; mean % error of 9.57% and 6.09% for PV generation and load). LHS-CD gives the best performance (% error of less than 1 for all mean and variance). Though RS gives quite acceptable moments for the distribution, its performance can be evaluated more accurately by plotting the histogram. Fig. 6.8 and Fig. 6.9 show the fitted distribution with the histogram plot of samples selected by RS and LHS-CD. Histograms of Fig. 6.9 show much better fit with the distribution for both the input variables (PV generation and load demand). On the other hand, histograms obtained from RS (Fig. 6.8) only matches with the pattern of distribution. There are lots of sample points that are not outside the fitted distribution. Moreover, the fitted histogram distributions of LHS-CD (Fig. 6.9) also match more closely with that of MC (Fig. 6.4). Therefore, LHS-CD is undoubtedly the best technique for PLF in distribution network with computationally demanding control algorithm.

**TABLE 6.1. Comparison of mean and standard deviation between different sampling techniques and MC**

<table>
<thead>
<tr>
<th></th>
<th>mu_PV generation</th>
<th>Error (%)</th>
<th>sigma_PV generation</th>
<th>Error with MC (%)</th>
<th>mu_Load</th>
<th>Error with MC (%)</th>
<th>sigma_Load</th>
<th>Error with MC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>4.48</td>
<td>0.00</td>
<td>0.45</td>
<td>0.00</td>
<td>1.80</td>
<td>0.00</td>
<td>0.18</td>
<td>0.00</td>
</tr>
<tr>
<td>Linear</td>
<td>4.58</td>
<td>2.06</td>
<td>0.89</td>
<td>97.8</td>
<td>1.84</td>
<td>2.11</td>
<td>0.34</td>
<td>92.9</td>
</tr>
<tr>
<td>Random</td>
<td>4.47</td>
<td>0.28</td>
<td>0.49</td>
<td>9.57</td>
<td>1.81</td>
<td>0.70</td>
<td>0.17</td>
<td>6.09</td>
</tr>
<tr>
<td>LHS_CD</td>
<td>4.48</td>
<td>0.02</td>
<td>0.45</td>
<td>0.71</td>
<td>1.80</td>
<td>0.04</td>
<td>0.18</td>
<td>0.78</td>
</tr>
</tbody>
</table>
As mentioned in section 6.2, the significance of “rank correlation” based on Cholesky decomposition is briefly mentioned with simulation results in this paragraph. Only LHS performs well for the systems with uncorrelated input random variables. However, in the analysis of power distribution system with PV, where the generation is influenced by weather and load demand always has the impact of weather on it; as a result both the input random variables have significant correlation between them. This correlation is faded by performing the rank correlation between the ranks of input
variables. The rank correlation process correlates the rank of sample points of each input random variable and thus shapes the pairing order of sampling matrix. This rank correlated sampling matrix has the reduced correlation between the samples of individual input variable. In this way, the sampling matrix owns the characteristic and pattern of the elementary input variable matrix. Fig. 6.10 shows the 3D plot of bivariate normal distribution with probability density. Highly probable samples are gathered at the intersection of both the means. Fig. 6.11 shows the same 3D plot of probability density for LHS without rank correlation (1st plot) and with rank correlation (2nd plot). As rank correlation is not applied to the samples of 1st plot, it shows strong correlation between the input variables and all the paired samples are placed diagonally. It does not reflect the characteristics of elementary input variables (Fig. 6.10) at all. On the other, 2nd plot of Fig. 6.11 is plotted for the updated sampling matrix after applying rank correlation. It owns the basic characteristics and distribution of the elementary input matrix. The importance of rank correlation can also be expressed using scatter plot (Fig. 6.12). 1st plot shows strong correlation between the samples of input variables as their ranks are uncorrelated. In contrast, the 2nd plot shows less correlation between the samples of input variables due to their correlated ranks.

In the final phase of this research PLF based LHS-CD is applied with reactive control and coordinated control algorithms to maintain the voltage profile in residential distribution network shown in Fig. 6.3 for urban and rural scenario. The development and significance of both the control algorithms are described in Chapter 3 and Chapter 4, therefore, not described in details here. Both the algorithms use deterministic load flow during the computations. However, the variability of PV generation and load require the application of probabilistic load flow techniques LHS-CD. MC simulations provide the most accurate results. Requirement of immense computation time make it an unfavorable choice particularly for real time simulations. The required time even increases exponentially for systems with complex computations. Now-a-days MC simulations are often used just to compare the accuracy and computation time with other techniques. Exactly the same comparison is performed here. The accuracy and computation time of LHS-CD method is compared with MC. Different sample sizes (N2=50, 100, 250, 500) are considered for LHS-CD as well for both the scenarios.
Fig. 6.10. Probability distribution of bivariate normal distribution

Fig. 6.11. Probability density with bivariate normal distribution for LHS i) without rank correlation (top plot) and ii) with rank correlation (bottom plot)
Fig. 6.12. Scatter plot of PV generation vs load demand for LHS i) without rank correlation (top plot) and ii) with rank correlation (bottom plot)

A series of PLF studies with MC and LHS-CD are carried out on the test distribution network (Fig. 6.3) for urban and rural scenarios. The programs are run on high performance computing (HPC) service with Intel Xeon processor E5-2680v2 (25M cache, 2.80 GHz) with 128 GB RAM. Matlab R2013b (8.2.0.701) is used as the simulation tool. MC simulations are run at first for 1,000 realizations of both the input random variables (PV generation and load demand) for two cases of each scenario; i) in normal scenario without any kind of control algorithm and ii) with coordinated control algorithm. Application of reactive control requires around 1.71 times higher computation time. On the other hand, coordinated control algorithm requires around 13 times higher computation time. It can be clearly observed that, runtime increases sharply with the complexity of control algorithm. Total time requirement of both of the simulations are listed in TABLE 6.2.

LHS-CD is run for sample sizes of 50, 100, 250 and 500 for both the scenarios. Fig. 6.13 and Fig. 6.14 show the corresponding voltage plots of H#12 for the different sample sizes for urban and rural scenarios. All the voltages are kept within upper limit (1.06 pu) with significant savings in computation time. TABLE 6.3 shows the comparison of runtime with corresponding MC simulation with control algorithm for both the scenarios.
TABLE 6.2. Runtime comparison of MC simulations with and without the coordinated control algorithm

<table>
<thead>
<tr>
<th>Simulation technique</th>
<th>Run time (urban)</th>
<th>Run time (rural)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC without coordinated control</td>
<td>36.9 min</td>
<td>38 min</td>
</tr>
<tr>
<td>MC with coordinated control</td>
<td>63.26 min</td>
<td>8 hrs 12 min</td>
</tr>
</tbody>
</table>

TABLE 6.3. Runtime comparison of LHS-CD with different sample sizes with MC simulation for both the scenarios

<table>
<thead>
<tr>
<th>sample size</th>
<th>Runtime (urban) in seconds</th>
<th>Runtime (rural) in seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LHS-CD</td>
<td>MC</td>
</tr>
<tr>
<td></td>
<td>LHS-CD</td>
<td>MC</td>
</tr>
<tr>
<td>50</td>
<td>27.45</td>
<td>3,795.39</td>
</tr>
<tr>
<td>100</td>
<td>114.2</td>
<td>3,795.39</td>
</tr>
<tr>
<td>250</td>
<td>122.9</td>
<td>3,795.39</td>
</tr>
<tr>
<td>500</td>
<td>154.83</td>
<td>3,795.39</td>
</tr>
</tbody>
</table>

Fig. 6.13. Voltage profile for different sample size of LHS-CD with reactive control for urban scenario
Fig. 6.14. Voltage profile for different sample size of LHS-CD with coordinated control for rural scenario

Fig. 6.15. Stored energy for different sample size of LHS-CD with coordinated control algorithm for rural scenario
Due to the complexity of coordinated algorithm compared to the reactive control algorithm, computation time saving is more prominent for rural scenario. As BES sizing is a significant outcome for the coordinated algorithm, the stored energy is also compared for different sample sizes of LHS-CD with MC simulations. The amount of stored energy is also in the similar range with that of MC. All the comparison of results with runtime and percentage of error in mean are listed in TABLE 6.4.

From, TABLE 6.4 it can be observed that, sample size of 100 gives the optimum results with the best possible mean (for output voltage and stored energy) with reasonable low runtime. LHS-CD with sample size 100 takes less than 2 minutes to run the probabilistic load flow with coordinated control algorithm which is more than 250 times lower than that of MC technique.

TABLE 6.4. Comparison of mean and runtime for different sample size of LHS-CD with MC simulations

<table>
<thead>
<tr>
<th>Sample size</th>
<th>Average stored energy</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHS_CD</td>
<td>MC</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.4107</td>
<td>0.4739</td>
</tr>
<tr>
<td>100</td>
<td>0.4429</td>
<td>0.4739</td>
</tr>
<tr>
<td>250</td>
<td>0.4335</td>
<td>0.4739</td>
</tr>
<tr>
<td>500</td>
<td>0.4272</td>
<td>0.4739</td>
</tr>
</tbody>
</table>

6.4 Validation with DNSP Network

Application of LHS-CD provides more significant contribution in computation time for the coordinated algorithm. For this reason, developed PLF simulations with LHS-CD method is verified with an Australian DNSP network data collected from a rural network in South-East Queensland region (Fig. 6.16).
The network has variable distance between the buses. The last bus of the feeder (P6134-H) is considered for comparing the performance of LHS-CD (sample size of 100) with MC simulations. The performance is evaluated in terms of accuracy of output voltage and computation time in TABLE 6.5.

**TABLE 6.5. Performance comparison of LHS-CD with MC Simulation**

<table>
<thead>
<tr>
<th></th>
<th>Avg. voltage (pu)</th>
<th>% error</th>
<th>Computation time (s)</th>
<th>Times of MC simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHS-CD</td>
<td>1.04</td>
<td>1.58</td>
<td>19</td>
<td>299</td>
</tr>
<tr>
<td>MC</td>
<td>1.03</td>
<td>--</td>
<td>5192</td>
<td>--</td>
</tr>
</tbody>
</table>

The results show significant resembles with the detail simulations performed so far with the test network. Output voltage from LHS-CD simulations matches with that of MC only with a percentage error of 1.58%. However, a significant improvement in the computation time (decreased by 299 times) is observed which makes LHS-CD the most suitable method for PLF in distribution network with control algorithms.
6.5 Discussion

This research introduces LHS combined with Cholesky decomposition for rank correlation in distribution system control algorithms to address the over voltage problem. LHS is preferred choice for PLF when computationally demanding models are being studied. LHS-CD has the greatest advantage of conceptual simplicity and ease in implementation. This method is extremely efficient when complex computations are required. LHS performs dense sampling from the highly probable segments of the cdf. Equal probability and non-overlapping intervals across the probability distribution result in smaller intervals in highly probable region and larger intervals in tail-end values. As a result, more samples are selected from highly probable region across the realizations of each input random variable. Rank correlation with Cholesky decomposition takes care about the correlation between the input random variables. The rank correlation procedures using Cholesky decomposition considers the correlation in ranking of all the input variables and the ordering matrix is generated accordingly. This process reduces the correlation between the sample values of different input variables and accurately represents the characteristics of elementary distribution. LHS-CD provides accurate results with reasonably low computation time when compared to MC technique. This is significant when dealing with large distribution networks with high level of rooftop PVs generation.
Chapter 7

Conclusions and Recommendations for Further Research

7.1 Summary of work

The overall research objective was broadly defined as the enabling of large penetration of renewable energy sources in the distribution grid while maintaining the acceptable voltage profile. Among the available renewable resources, roof top PV systems have become the most popular choice in residential distribution network. However, the mismatch in the PV generation peak and the load demand peak results in an unacceptable voltage profile. In the first phase of the research, after discussing on the advantages and disadvantages of other available methods to address the voltage violation problem for distribution networks in particular, a novel reactive control algorithm was developed. The effectiveness of the control algorithm was quantified in terms of network parameters such as line resistivity and feeder distance. The developed algorithm was also then evaluated with a test network for different scenarios such as urban and rural networks.

In the second phase of the research, the developed reactive control algorithm underwent substantial modification to add the coordinated control of reactive capability of PV inverter and energy storage. As an outcome of the research from the first phase, it was evident that the resistive characteristic of the distribution network limited the
effectiveness of the reactive control. In order to provide real power support to maintain the acceptable voltage profile, BES was integrated in the developed coordinated algorithm. The droop based charging algorithm of the BES during the peak PV generation period was developed as a part of the algorithm with necessary mathematical formulation. The discharging process was also distinctly developed with a flow chart in this segment of the research. The specific “triggering condition” to charge/discharge from the BES system and coordinated reactive control was also identified and described both narratively and graphically. The developed coordinated algorithm was then validated using a test network and DNSP data as well.

The PV generation profile is completely intermittent in nature. A suitable probabilistic approach is required to forecast the weather, that is, the PV generation and load demand. The net generation (which comes from subtracting the load demand from PV generation) was defined as a discrete time Markov chain in this research. As hourly data were considered for the analysis, the data series can be considered as a discrete one. Moreover, forecasting the data for the next time interval depended only on the present time and all the past data were considered in the immediately next data using the conditional probability theorem. The net generation profile was then represented as the Pearson 5 distribution. In these probabilistic estimation steps, clearness index and variability index of PV generation were also considered. To get these indexes, solar data were taken from the University of Queensland website. The third phase of the research analysed the BES sizing and percentage of utilisation with seasonal variation, and the impact of R/X ratio and customer participation on battery sizing; these factors were discussed by reference to the necessary graphs in order to make the developed coordinated algorithm complete. A brief economic analysis was also performed. For the smooth operation of the coordinated algorithm, it is essential to have a well-defined data representation and communication structure. A low-cost solution for realising the developed coordinated control algorithm was proposed with a clear definition of message signals using the power line carrier. The formation of message signals and simple calculation to estimate the required bit rate were also included here.

The final part of research included an investigation of the PLF in distribution network. Due to the intermittent characteristic of generation in distribution system, the
traditional deterministic load flow may not be a suitable solution. The load flow calculations may need a probabilistic approach such as stochastic load flow or PLF. Both the numerical (Monte Carlo) and analytical approach from PLF were considered in this part of the research. Among several analytical approaches, the Latin Hypercube Sampling with Cholesky Decomposition (LHS-CD) method was considered. Cholesky decomposition is required to order the rankings of correlated input random variables. The conducted research included the performance of comparative analysis between the numerical (Monte Carlo) and analytical (LHS-CD) approaches. The results were demonstrated using a test network and DNSP network as well. Comparisons of computation time with accuracy (in terms of output distribution’s mean and standard deviation) are also shown.

7.2 Scope for further research

Directions in future research can be suggested based on the research conducted so far. The most promising directions in future research relate to: probabilistic planning; scenario-based planning; community-based planning; and the dynamic studies.

A. Probabilistic planning with future grid communication:

In Chapter 5 (Section 5.2), a probabilistic estimation method was developed to forecast the generation, probability of the occurrence of voltage violation and hence the BES capacity utilisation was also determined. The probabilistic approach can also be incorporated in the distribution planning as well. Although DNSPs have different planning criteria and constrains, the major steps in the distribution planning process can be identified as:

1. Perform the demand forecast
2. Determine the contingencies
3. Determine the unfavourable outcomes resulting from the contingencies
4. Find the optimal solution
5. Perform the financial feasibility analysis, and identify the compliance issues and other issues related to final approval

For smooth operation of the electricity network, the transmission and distribution system needs to ensure supply of sufficient electricity considering all the contingencies. With the integration of renewable energies, the distribution network is also become a significant supplier of electricity. The list of contingencies becomes lengthier following the incorporation of intermittent energy supply from the renewable sources integrated in the distribution network. Most of the contingencies can be treated as random variables. Taking into account the probabilities of an unfavourable outcome from the contingency (e.g. lack of PV generation due to cloud transience and so on) and applying different probability laws (e.g. conditional probability) can help the DNSP to plan more effectively and efficiently.

Moreover, in the future grid with smart meters and servers at different levels, the communication realisation will also be an emerging concern during planning phase. It will be required to ensure proper order among all the equipment, particularly in a large and complicated network. The hierarchy of the network equipment should be well-defined in order to avoid any kind of miscommunication. Such miscommunication can lead to the delivery of inappropriate message signals to the connected equipment. As all the servers, smart meters and other equipment are connected within the network; a single miscommunication may result in a total disaster. Therefore, all the equipment can be represented as a tree structure and a specific ancestor-descendant relation should be defined among them. While any kind of reactive support or energy support from the BES is required in the network, the objective function can be defined as a function of distance. The algorithm may find the optimal path to ensure smooth operation. Other constraints can also be incorporated in the objective function depending on the complexity level of the network.

B. Scenario-based planning:

Another potential direction for future research relates to scenario based planning. This research can be included with the probabilistic planning. The effective
incorporation of uncertainties depends on the horizon of the planning level and the frequency of any particular uncertainty. For example, there are some uncertainty events that happen more frequently and can be modelled with suitable probability distribution (e.g. the hourly generation from a PV module can be modelled based on the weather forecast by defining it as an appropriate probabilistic process). The traditional deterministic forecast method is based on the peak demand which does not focus on the maximum utilisation of available resources. The discussion on the load duration curve in Chapter 5 (Fig. 5.7) already identified the drawbacks of such deterministic planning. The concept of value-based planning emerged where the focus is to identify available but “unutilised” resources in order to optimise the overall electricity production and management. In the future, the concept of scenario-based planning may be adapted to focus on “what the situation should be” rather than just “to predict the future situation”. Varying from different scenario to scenario, such planning method will identify “ideal” situations that can utilise all the resources to the maximum level and motivate all the relevant “stakeholders” towards it. Scenario-based planning may require dynamic or stochastic programming to identify “ideal” situations in uncertain future scenarios. There is ample scope for extensive study and research in this field.

C. Community-based planning

There will be different levels of PV penetration in different communities. Depending on the level of PV penetration and end-users’ participation, the communities can provide support to each other in order to maintain the voltage profile. Community-based planning can be beneficially incorporated with scenario-based planning in future work.

D. Dynamic studies

The scope of present research is confined in power system domain. However, the control algorithm can be implemented in power electric domain as future extensive research. It may be a potential field to implement the controller using PSCAD or Matlab Simulink in order to have a study on the dynamic response. It can be implemented by using either a detailed model (modelling PV cells with a suitable maximum power point
tracking technique such as incremental resistance, perturb & observe) or an average model. The research can be conducted on both single-phase and three-phase systems. The phase-locked loop or hysteresis technique can be applied to synchronise the frequency in the overall system. Different battery models also can be included in such future research in order to observe the charging and discharging dynamics. So, the developed algorithm can be applied in the power electronic domain as well.
Appendices

I. Line Parameters for test networks

Urban LV network parameters (percentage on 1 MVA base) [155]:

<table>
<thead>
<tr>
<th>Circuits</th>
<th>R (%)</th>
<th>X (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>95 mm² Al</td>
<td>103</td>
<td>42.5</td>
</tr>
</tbody>
</table>

Rural network parameters are chosen to maintain higher R/X ratio (5.6) using urban network data. After the calculation line parameters for urban and rural cases are given in TABLE I and TABLE II respectively.

TABLE I. Line Parameter for Urban Case

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter Value</th>
<th>Value for 20m</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>1.18 ohm/km</td>
<td>0.0314</td>
</tr>
<tr>
<td>X</td>
<td>.96 mH/km</td>
<td>0.0314</td>
</tr>
</tbody>
</table>

TABLE II. Line Parameter for Rural Case

<table>
<thead>
<tr>
<th>Component</th>
<th>Backbone Feeder</th>
<th>SWER Line</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameter Value</td>
<td>Value for 20m</td>
</tr>
<tr>
<td>R</td>
<td>1.18 ohm/km</td>
<td>0.0314</td>
</tr>
<tr>
<td>X</td>
<td>.345 mH/km</td>
<td>0.0113</td>
</tr>
</tbody>
</table>
II. Pearson 5 Distribution

Pearson Type 5 distribution is known as Inverse Gamma Distribution with location parameter) [135]. The PDF for “Inverse Gamma Distribution” is defined over the support $x>0$ as,

$$f(x; \alpha, \beta) = \frac{\exp(-\beta / x)}{\beta \Gamma(\alpha / \beta)^{\alpha+i}}$$

Where $\Gamma\alpha$ and $\beta$ are shape parameter and scale parameter respectively. $\Gamma\alpha$ is the gamma distribution of $\alpha$.

But location parameter ($\gamma$) needs to be incorporated in this particular distribution due the shifting towards negative values. Thus the distribution becomes the Pearson 5 distribution (Inverse Gamma Distribution with location parameter). The PDF is now defined over the support $\gamma < x < +\infty$ as,

$$f(x; \alpha, \beta) = \frac{\exp(-\beta / (x-\gamma))}{\beta \Gamma(\alpha / \beta)^{\alpha+i}}$$
III. Kolmogorov-Smirnov test for goodness of fit

The Kolmogorov-Smirnov test is used to decide if a sample comes from a population with a specific distribution [156], [157].

The Kolmogorov-Smirnov test is defined by:

\[ H_0: \text{The data represents a specified distribution} \]

\[ H_a: \text{The data do not represent the specified distribution} \]

Test Statistic: The Kolmogorov-Smirnov test statistic is defined as

\[ D = \max_{1 \leq i \leq N} \left( F(Y_i) - \frac{i-1}{N}, \frac{i}{N} - F(Y_i) \right) \]

where \( F(Y_i) \) is the theoretical cumulative distribution of the data set denoted by \( Y_i (i=1, 2, \ldots, N) \). The data set must be fully specified (i.e., the scale, and shape and location parameters must be defined).

Significance Level: \( a \)

Critical Values: The hypothesis regarding the distributional form is rejected if the test statistic, \( D \), is greater than the critical value. The critical value depends on the scale, and shape and location parameters of the distribution. Using easy fit software the critical values can be calculated and thus goodness-of-fit test can be performed. EasyFit is a data analysis and simulation software which enables the user to fit and simulate statistical distributions with sample data, choose the best model [136].
IV. Basic properties of PDF and CDF

The probability density function of a random variable \( x \) represents the relative likelihood of \( x \) for a specific value. Integral of the density of \( x \) is calculated over a range (gives an area under a curve) to get the probability of \( x \) falling within a particular range. If random variable \( x \) is having a density function \( f_x \), its probability within a range \([x_1, x_2]\), where \( x_2 > x_1 \), can be defined as:

\[
\Pr[x_1 \le x \le x_2] = \int_{x_1}^{x_2} f_x(x) \, dx
\]

Some basic properties of PDF are:

i) PDF is non-negative everywhere
ii) Its integral over the entire space is equal to 1.

The probability cumulative distribution function of a random variable \( x \) can be defined as:

\[
F(x_0) = \Pr(x \le x_0)
\]

Some basic properties of CDF are:

i) \( F(+\infty)=1, F(-\infty)=0 \)
ii) It is a non-decreasing function, if \( x_1 < x_2 \), then \( F(x_1) < F(x_2) \)
iii) \( \Pr(x_1 < x < x_2) = F(x_2) - F(x_1) \)
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[82] L. Xiaoming, L. Qingfen, Y. Xianggen, and X. Jianghui, “A new on-load tap changing system with power electronic elements for power transformers,” in


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