MICROGRID FREQUENCY CONTROL USING MULTIPLE BATTERY ENERGY STORAGE SYSTEMS (BESSs)

A Thesis submitted in
Partial Fulfilment of the Requirements for the Degree of
Masters of Engineering

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KEY WORDS

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Power Sharing
Droop Control
Frequency Droop
Angle droop
Power Quality
Stability
ABSTRACT

Micro grids being a new developing technology operate in two distinct modes of operation, namely, the utility-grid-connected mode and the autonomous (or islanded) mode. In transition from the utility-grid-connected mode to the autonomous mode, the frequency of a micro grid can be seriously affected due to unbalance between power generation and power demand and at that moment, micro-sources may respond slowly to eliminate this unbalancing situation. To solve this interruption and to operate the micro grid steadily, some rapid response storage systems, namely Battery Energy Storage Systems (BESSs) are needed [1]. In this study, several parallel inverters control schemes with BESSs based on droop characteristics is proposed to control the frequency of the micro grid upon isolating from the utility grid. Several parallel inverters based BESSs have been implemented to deliver desired real power to the micro grid by state feedback control system. This system is used as closed loop control system to direct inverter power in the micro grid. The real power balancing in the system is achieved by controlling frequency based on the droop control method.

In this thesis, multiple inverters with BESS based on angle droop controllers are proposed to share real power in the isolated micro grid system consisting of inertia based DG and variable load. The angle of output voltage in inverter (or voltage source converter, VSC) can be changed instantaneously to control real power and this changing angle is beneficial for quick attainment of steady state. Thus with converter based BESS, load mismatch is minimized by drooping the angle droop control method for better dynamic response and also real power sharing in micro grid [2]. For accurate minimizing load unbalance, the droop gain is considered in such that they can share the load in proportion to their rating. Therefore, the choice of droop gains is often trade-off between power balancing and stability.

The proposed angle droop control method helps to balance the supply and demand in the micro grid autonomous mode through charging or discharging of the BESSs and at that moment the output power of inverters increase or decrease in such a way to keep the state of charge (SOC) of the storage device within the safe condition and also to balance of power generation and load demand.

The proposed control system is verified with simulation software MATLAB/SIMULINK to measure the performance of the proposed control system. The converters are modelled with
IGBT switches and anti-parallel diodes with associated snubber circuits. All rotating machines are modelled in detail including their dynamics [2].
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<td>V</td>
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<td>I</td>
<td>Single phase source current</td>
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<td>il</td>
<td>Converter current</td>
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<td>Rf, Lf</td>
<td>Converter’s Filter resistance and inductance</td>
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<td>Storage Voltage Source</td>
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<td>Converter switching function</td>
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<td>m</td>
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<td>SOC</td>
<td>State of Charge</td>
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<td>K</td>
<td>State feedback controller gain</td>
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<td>Hysteresis band</td>
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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.

QUT Verified Signature

Signature

Date: 2nd November 2015
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CHAPTER 1

1.1 Background and motivation

Driven by economical, technical, and environmental reasons, the energy sector is moving into an era where large portions of increases in electrical energy demand will be met through extensive installation of distributed generation (DG). The use of renewable DG is an attractive source of power, since it can deliver sustainable and clean power. The renewable energy based DGs, namely as photovoltaic (PV), wind energy source with mixture of combined heat and power plants are specified as micro grid (or hybrid plants). It can supply power to small or medium urban housing communities or to people of large rural areas. It can also be an economical, environment friendly and reliable way to supply power at distribution levels (namely, low voltage side). However, the deployment of DG increases the service reliability and also reduces the requirement for future generation expansion or grid reinforcement. It extends up the possibility of making the DG responsible for local power quality improvement, namely voltage and voltage angle regulation, power factor improvement, etc., in such a way that is not possible with conventional centralized generators [2-3].

The sources in a micro grid can be mainly classified as inertial and non-inertial in terms of power flow control [3]. The output power of inertia sources such as micro turbines, fuel cells and bio-diesel generators are used to keep the desired system frequency in an isolated micro grid. However, non-inertial sources, namely wind and PV, in which the output power depends on the environmental conditions, supply only a portion of the total power demand [2]. As a result, utilities have to handle with large numbers of small, widely distributed sources which may or may not be available during peak period.

The power from sources in a micro grid namely PV, wind generator, fuel cell and batteries connected through converters can be changed instantaneously. Micro grid can operate either in grid connected or islanded mode. The available power of all DG units should meet the total load demand for islanded operation; otherwise load shedding need to be executed. The control of real and reactive power output of the sources is required to maintain a stable operation in the islanded mode of micro grid. The frequency and voltage in an islanded (or autonomous) micro grid should be maintained within predefined limits. The frequency variations are very small in strong grids; however, large variations can occur in autonomous grids [4]. Thus power management approaches are vigorous for an autonomous micro grid in
the presence of few small DG units, where no single dominant energy source is present to supply the energy requirement [5]. Also, fast and flexible power control strategies are necessary to damp out transient power oscillations in an autonomous micro grid because there is no unlimited source available [6]. The transient fluctuations in real power and frequency are observed due to the slower governor response of the inertial DG. The output frequency of each inertial DG cannot be changed instantly according to the requested value from the frequency droop control system. The fast response of Battery Energy Storage System (BESS) with micro grid control and power management should be implemented for this frequency control strategies. The contribution of this study is to show the improved performance of the micro grid with the use of new strategy for frequency control based on droop control with inertial DGs and non-inertial DGs and multiple converter interfaced BESS. An intelligent control system (ICS) is to be proposed to manage the charging and discharging state while keeping the operating reserve of BESS to achieve system stability. To enhance a flexible operation in the micro grid maximizing the benefits of renewable energy, a control strategy based on adaptive droop is to be developed for the BESS. During the charging and discharging, the slope of the droop and other control parameters are selected appropriately by the ICS considering several limitations [2].

In this study, an advanced control system based on droop characteristics is proposed for the interfacing converter of the storage device to securely control the frequency upon isolating from the utility-grid, and also keeping the battery’s State of Charge (SOC) in allowable limits. The proposed control scheme is standalone and does not need any communication links between the micro-sources [7]. The simulations results discussed in section 3.5 that the proposed control and power management strategies have the ability to further improve the micro grid performance.

1.2 Aims and objectives of the thesis

The main aim of this research is to design and develop dynamic control strategies with inverter interfaced BESSs that will ensure the reliable operation of micro grid system in islanded mode. Power management strategies are vital in the presence of few small DG units in isolated micro grid. It requires at least a single dominant energy source present for supplying or absorbing energy requirement as frequency variations are large in autonomous grids. To minimize this, couple of fast response converter interfaced BESS with micro grid control and power management should be implemented for this frequency control strategies.
The control approach relies on the reduced model of the system which contains important system states to reduce the computation time.

To design dynamic control strategies of BESS, the following research aims are integrated to deliver the main goal of this research:

- Development of a methodology for dynamic control system of BESS in islanded micro grid to allow rapid time shifting between generation and energy consumption.
- Development of tools for identification of frequency variation with the variation of load.
- Designing the control method to address both frequency variations with load and power minimization with storage battery in discharging and charging way and also maintaining SOC of storage battery in the range of safe discharging and charging status.
- Integration of the developed control system tools and methods in islanded micro grid with battery in bi-directional way for implementing frequency variation minimization.

It is to be mentioned that applying the proposed methods in islanded micro grid system, the effectiveness of proposed approaches should be tested by MATLAB/SIMULINK simulation tools.

1.3 Significance of this research

Stringent concerns about global warming have forced legislators to provide more incentives for renewable energy sources. As a result, it is anticipated that the future LV network will see widespread use of PV and wind turbine with multiple BESSs to ensure a balance between power generation and consumption under all circumstances in islanded operation mode.

It has been discussed in the literature review section that attaining real-time matching between generation and consumption for islanded operation mode of micro grid systems comprised of small DG units and renewable energy sources is an issue of frequency fluctuation. The integration of BESS in islanded operation mode with efficient converters and their control will provide frequency control in micro grid. A single droop frequency control with BESS has been used to control the frequency considering allowable limit of SOC of the storage battery system for the isolated micro grid [1]. However, there is no work on multiple BESSs with frequency controllers that can be installed in micro grid. Hence, this study specifically focuses on finding the optimum power and location of BESS to be installed in parallel with inertia DG and an improved frequency control system based on droop
characteristic with multiple inverter interfaced BESSs is proposed to control the frequency of the isolated micro grid. The design of droop based dynamic control mechanism for load control with multiple inverter interfaced BESSs allocating specified limits of SOC of a specific model of battery in one islanded mode of micro grid system is an improved control system. It may be used to track frequency deviations and regulate system’s frequency under the above mentioned operation conditions.

1.4 Key innovations of the research

Some research has been performed by researchers globally to manage the unbalance of power between power generation and demand in an islanded mode of a micro grid maintaining SOC of BESS with the mentioned droop control method. The work to date has focused on a single BESS or one BESS along with super capacitor or one BESS with an inertial based generator in parallel [8-10]. However, to balance power generation and load in islanded mode operation of micro grid with multiple BESSs is a new research area. Therefore, this thesis develops one of the key innovations analyses of multiple BESSs in an islanded mode of micro grid and each BESS should have separate frequency control system.

The other innovation area in this research work is that SOC of multiple BESSs provide new droop line with its limits. The previous work has set hard SOC limits for the battery in the micro grid. For this, when SOC limits of the battery is hit, there is substantially strike on other generations. However, with the new droop line incorporating SOC limits, there is no longer a hard transition but there is a gentle transition for other generation.

1.5 Structure of the thesis

This thesis is organized in five chapters. An overview of the research along with aims and contributions are outlined in Chapter 1. A literature review is presented in Chapter 2 to outline the justification for doing this research.

Chapter 3 analyses the performance of angle droops of state feedback control method in an autonomous micro grid model that contains multiple single phase voltage source converter (VSC) interfaced BESS, stiff ac source and load. As VSC interfaced BESS can instantaneously change output voltage waveform, power delivering in bi-directional way can be controlled by the output voltage angle of converter interfaced BESS through droop control method in an islanded micro grid. The angle droop is able to provide proper load management without a significant steady steady frequency droop in the system. This method is analysed in chapter 4 with two converter based BESSs, inertia based generator and variable
load. Power management with two nos. converter based BESSs, inertia based generator, and variation of load is analysed in single phase system.

The general conclusion and scope of future works are given in chapter 5. Appendix A discussed the converter structure and control methods used in this thesis.
CHAPTER 2

LITERATURE REVIEW

Micro grid frequency control in hybrid system and the applications of BESS have been studied in variety of papers and they are reviewed and explained in this section.

2.1 Background

The micro grid provides a platform for integration of several Distributed Energy Resources (DERs), which include both Distributed Generation (DG) such as photovoltaic cells, wind power, fuel cell, micro turbines, and Distributed Storage (DS) units and loads [11]. In micro grids systems, DERs operate in the form of a local grid that can be connected to or disconnected from the main grid at the point of common coupling (PCC) as shown in Fig.2.1.

![Fig. 2.1: Example of a micro grid system [11]](image)

At present, a micro grid needs to be designed to have a larger power capacity and more control capabilities to fulfil higher operating efficiency, enhanced stability, and lower emission level through the sustainable micro-sources [11 - 12]. It can operate in two different operating modes, namely a utility-grid-connected mode or an autonomous (islanded) mode. In the utility-grid-connected mode, micro grid connected to the grid is either being supplied by the grid or being injected power into the grid. While in an islanding mode, micro grid operates independently by disconnecting from the utility-grid and supplying the loads by its
own generation. In both cases, the isolated part should deliver energy continuously to its connected loads [13 - 14]. It is significant that the inertia of the DGs is very low in comparison to the conventional plants. For this, in transition from the grid-connected mode to the islanded mode, frequency control is a remarkable issue because of inherent nature of DG’s time to time power variation. The unpredictable nature of DG’s generated power negatively affects the system reliability, and makes more sensitive issues of frequency stability. Moreover, the power reserve estimation becomes a difficult task and for this, the security of supply may be at risk [15]. Thus, frequency control represents a major issue in micro grid. Recent studies suggest a solution for frequency control in micro grid involving the dispatching of generators with a single inverter based energy storage systems in such a way that active power is supplied or injected through battery to minimize load imbalance with droop control method [16]. The droop control method uses the same principle of power electric systems. The inverters of DG are controlled in such a way to present active power-frequency (P-f) and reactive power-voltage (Q-V) characteristics on the basis of the droop regulation of frequency and voltage through the active and reactive powers which are stated in the following equations 2.1 and 2.2.

\[
\begin{align*}
  f &= f_o - k_f (P_0 - P) \\
  V &= V_o - k_v (Q_0 - Q)
\end{align*}
\]

where, \(P_0\) is the base active power of the unit and \(P\) is the active power of the unit and \(Q_0\) is the base reactive power of the unit and \(Q\) is the reactive power of the unit and \(f_o\) and \(V_o\) are the frequency and voltage amplitude without load and \(k_f\) and \(k_v\) are the droop coefficients of frequency and voltage respectively. In the droop control based micro grid system, there are options to connect many inverters based DGs in parallel to share the load and the equations 2.1 and 2.2 show that the active power and the reactive power depend predominantly of the frequency and the voltage, representing the relation P-f and Q-V. In a practical situation, the dynamic control of frequency is used to impose the power angle and consequently the active power. Therefore, there is a relation between active power and frequency [17]. Inverter power controllers regulate the real power outputs, by providing reference values for the voltage frequency. The reference is based on the droop - real power versus voltage frequency. This real power droop is characterized by a frequency set point and a droop coefficient shown in Fig. 2.2(a). The generated power rating, \(P_{\text{rating}}\) limits the extent to which the droop is applicable. To implement a particular droop operating point with a certain power sharing at a chosen frequency in real time, each generating unit can adjust the generator droop settings.
For inverter interfaced generating unit, such as inverter interfaced PV, inverter interfaced BESS have also different stable range for their droop coefficients. A desired droop operating point with generated power sharing, namely $P_1$, $P_2$, $P_3$ can be achieved with a range of combinations of droop coefficient characteristics, $K_{f1}$ $K_{f2}$ $K_{f3}$ shown in Fig. 2.2(b). The settings also determine how the droop operating point moves in response to external influences such as load changes. The choice of droops is an exchange between stability margin, dynamic performance, and shifts in the droop operating coefficient, namely $K_{f1}$ $K_{f2}$ $K_{f3}$ with respect to $P_1$, $P_2$, $P_3$ [18].

![Diagram](image)

**Fig. 2.2:** (a) Real power vs. Frequency droop with one droop coefficient; (b) Real power vs. Frequency droop with multiple droop coefficients.

The renewable sources are converter interfaced and power is discharging through droop control method. The power of converter based renewable sources or BESS can be controlled through output voltage angle instantaneously. The angle droop control may be derived from load flow analysis and demonstrated in a similar system of frequency droop control system. The angle of output voltage can be changed instantaneously in a voltage source converter (VSC), and this changing angle also control the real power which is always beneficial for quick attainment of steady state. Some researcher verifies that the frequency variation with frequency droop controller is significantly higher than that with the angle droop controller [19]. So for inertia-less loads and converter based DGs or BESS, load sharing can be done by drooping the converter output voltage magnitude and its angle instead of system frequency [19]. The angle droop method can be applied to share the real power amongst converter interfaced DGs or BESS. This power sharing accuracy can be increased by selecting the output inductance of converters to be inversely proportional to micro-sources rating. The angle droop control strategy is applied to all the converter interfaced micro-sources, namely DGs and BESSs in the system. The output voltages of the converters are controlled to share...
the load proportional to the rating of the DGs. As an output inductance is connected to each of the VSCs, the real power injection from the DGs or BESS source to the micro grid can be controlled by changing its angle [19].

The reliable solution to control micro grid frequency consists in improving the system stability by using inverter interfaced BESS, smart loads and more controllability of inverter interfaced DGs. This BESS designed for integration in micro grid to stable frequency through angle droop control method in micro grid is enhanced with smart control function. It exhibits very rapid active power response, and also ideal for compensating the generation limitations of conventional generators as well as fluctuations produced by renewable Energy Resources (RES) and loads [20 – 21]. The use of BESS needs to accommodate two major functions, namely balancing power generation of the renewable energy sources and load as well as managing of the state-of-charge (SOC) of batteries [22]. For this, a power converter needs the capacity to tolerate the abnormal grid disturbances and to comply with the standards given by the utility companies, such as IEEE1547 [22]. Standards over recent decades, several companies and institutions have developed multiple devices and controls in order to integrate these DERs into the main grid in a suitable manner. Therefore, many varieties of controls, interconnections, electronic interfaces, can be found, obstructing the design of a sole standard for connecting DERs to the grid. A number of standards have been developed, one of the most important being the IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems is IEEE1547 [23]. This family of standards is being developing by the IEEE Standards Coordinating Committee 21 and establishes criteria and requirements for the interconnection of distributed resources with electric power systems.

2.2 Dynamic Modelling of Micro grid Components

Micro grid, a part of a distribution system consists of different forms of generating units, such as PV panels, micro-turbines, wind turbines, and solid oxide fuel cells (SOFCs) and geographical distribution of the loads. Moreover, a micro grid also includes energy storage system and controllable loads. Such systems can operate in parallel with the local utility or in an islanded mode during emergency or any situation [24 - 26]. The connecting point of the micro grid to the utility grid is called the point of common coupling (PCC). There should also be an isolating device with the capability to island the micro grid in case of faults or events as described in IEEE Standard 1547. The electrical micro-sources that exist in micro grids are usually low power, under 100 kW, connected to the network via power electronic devices to provide adequate control [1].
2.2.1. Single Shaft Micro-turbine

Micro-turbines are controllable energy sources that can increase or decrease their output power based on the frequency deviation with slow response in the load following mode. Micro-turbines can use different fuels, namely diesel, natural gas but most of the available systems utilize natural gas with high efficiencies (between 28% – 30%). The main advantages of micro-turbines are that they have sophisticated combustion systems, low turbine temperatures, and low fuel-to-air ratios that result in low NOx and carbon monoxide emissions [26 - 27].

2.2.2. Fuel cell (FC)

Fuel cells work by the chemical reaction of combining hydrogen and oxygen to form electricity and water. Fuel cells have some advantages, namely, the potential for high efficiency (from 35% to 60%), low to zero emissions, quiet operation, and high reliability for the limited number of moving parts. There are several types of fuel cells currently available, including phosphoric acid fuel cell, molten carbonate fuel cell, solid oxide fuel cell (SOFC), and proton exchange membrane [26 - 27]. Electrical power output of a fuel cell is DC and this dc power is converted to AC power by an inverter to be compatible with the electric power system. The SOFC has high energy density and clean energy. However, limited by their inherent characteristics, fuel cells have a long start-up time (usually several minutes) and also slow response to instantaneous power demand [27].

2.2.3. Renewable Sources

Renewable energy resources, such as wind and solar, have an intermittent nature; hence, their output powers are unpredictable and depend on weather conditions. Therefore, in order to maintain the reliability in a desired level of power parameters using these kinds of micro-sources, it is necessary to use some kind of energy storage system to ensure an uninterruptible power supply [26].

2.2.3.1. PV Model

PV systems convert solar energy into electricity. The PV modules produce DC power which is converted into AC by an inverter to be synchronized with the power system parameters. In the PV model, maximum power point tracking (MPPT) is maintained depending on the ambient irradiation and temperature, with constant values for other parameters, namely maximum power variation with module temperature, normal operating temperature of cell (NOTC) [28].
2.2.3.2. Wind Generator System Model

Wind turbines convert the kinetic energy of wind into electrical energy with three basic types of wind turbine technologies that are currently available for interconnecting with electric power systems:

1) The wind turbine rotates the rotor shaft of an induction generator connected directly to the grid without any power electronic interface;

2) A double-fed induction generator (DFIG) requires a wound-rotor design;

3) Wind turbine design uses a conventional or permanent magnet synchronous generator to convert the wind turbine power to a variable voltage, variable frequency output that varies with wind speed. Then rectifiers and inverters are used to convert power to be compatible with the electric power system parameters [26].

2.2.4. Storage Devices Modelling

Due to the large time constants of some micro-sources, namely fuel cells and micro turbines, a storage device is the most suitable option to supply the required amount of power to balance the supply/demand in islanding mode and to prepare the micro grid stable for the next coming disturbance and load changes [1]. For that reason, BESS integration in power grids is increasing worldwide. Their popularity is due to their wide ranges of sizes, and the capability of being integrated as load or as distributed sources [7].

2.2.4.1 Overview of BESS technologies

Extensive work has been performed over the last decades to evaluate the overall benefits of integrating energy storage systems into power systems [29 – 32]. Nevertheless, small work has been accomplished particularly on advanced distributed energy storage and its deployment in emerging electrical micro grid, although foremost benefits exist in this area [33 – 34]. Furthermore, no studies have been conducted regarding a comparative analysis of these modern BESS technologies and its dynamic response in promising grid-connected or grid-independent AC micro grids applications. The dynamic performance of novel BESS technologies for stabilizing frequency of emerging grid-connected or grid-independent AC micro grids with RESs needs to be assessed. Generally, BESSs comprise new Lead-acid batteries, Nickel cadmium and Nickel metal hydride batteries, Lithium ion, lithium polymer batteries, and Sodium sulphur batteries [34 – 36]. Currently, the numerous advanced BESSs
remaining, the foremost ones are evaluated. In this sense, the design and implementation of BESSs systems are described, including the operation security of grid-independent mode.

2.2.4.2 Dynamic model of advanced BESS

The vital characteristics of a battery are defined by its cell voltage, the current capable of supplying over a given time (measured in Ah), the time constants and its internal resistance [37]. In this study, it is required to study the dynamic behaviour of the battery system. In these cases, the voltage and internal resistance of the storage battery does not possess a linear behaviour which is represented in equation 2.3. The following sub-section briefly describes some characteristics of different types of batteries required for proposing a general model of the advanced BESSs.

\[ V_i = E_0 - \eta I R_i \]  

(2.3)

Here, \( E_0 \) is the voltage at no load, \( I \) is the consumed current through the connected load, \( R_i \) is the internal resistance of the cell and \( \eta \) the polarization factor. The polarization factor summarizes the contribution of complex chemical processes that can take part inside the cell between the electrodes through the electrolyte and also depend on the battery type and the internal resistance \( R_i \) which also vary with SOC of the cell. Fig.2.3 shows a schematic diagram of a cell with load [38].

![Fig. 2.3: Equivalent circuit of a steady-state battery [38]](image)

2.2.4.3 Analysis of performance characteristics of different batteries

This sub-section discusses major performance characteristics curves of advanced BESS devices. These curves represent deviations of internal resistance depending on SOC and some
of these curves also indicate the state of discharge (SOD). The relationship between these two states, namely SOC and SOD is given by equation 2.4 as follows.

\[
\text{SOC} = 1 - \text{SOD}
\]  

(2.4)

Batteries of Pb-acid type are characterized by an internal resistance which varies depending on SOC or SOD as shown in Fig.2.4. This figure shows the variation of the internal resistance per cell vs. depth of charge or discharge [39]. It also shows a nonlinear variation of internal resistance in charging or discharging state.

In the case of Ni-MH batteries, Fig.2.5 shows the variation of the internal resistance with changing SOC. This figure was constructed for testing Ni-MH cell with discharge pulsed current from 75 mAh up to 750 mAh [40]. As shown, the internal resistance depends largely on the current drawn from the battery and the internal resistance is not only independent of the state of charge, but also of the depth of discharge. The internal resistance remains almost constant from 20% SOC [39].
Fig. 2.5: Deviation of internal resistance depending on the state of charge for Ni-MH battery at room temperature [39].

Fig. 2.6 shows for NaS battery type that depends on the SOC, charge direction and the temperature, the internal resistance and also varies up to four times its base value [37].

Fig. 2.6: Internal resistance variation depending on the state of charge/discharge in a NaS-type battery cell [39].
Fig. 2.7 was built from a test of 850 mAh capacity Li-Ion Polymer battery with discharge pulses of 80 mAh and 640 mAh. This figure represents the variation of internal resistance variation (R_{series}) for different charge states [42 - 44]. As shown, the internal resistance is not only independent of the state of charge, but also of the depth of discharge. The internal resistance remains almost constant from 20% SOC. This type of battery is most useful for microgrid application.

![Internal Resistance vs State of Charge](image)

Fig. 2.7: Variation of internal resistance depending on the state of charge for Li-ion polymer at room temperature [39]

### 2.2.4.4 Proposed general model of BESS

Fig. 2.4 through Fig. 2.7 indicates a large nonlinearity in the behaviour of the most important batteries parameters, namely internal resistance. In the case of Li-ion battery shown in Fig. 2.7, represents the best characteristic of the internal resistance which remains almost constant from 20% SOC to 100%. This feature plays the most dominant role to accurately represent the behaviour of batteries in power quality events, namely frequency stability in micro grid. The SOC of the battery is also an important factor of all the above and should be taken into account directly in the model of BESS. This factor directly influences the value of power or energy that the battery can deliver in time of occurrence of events in micro grid for frequency stability. Moreover, Li-Ion batteries have the greatest potential for future
development and optimization. In addition to small size and low weight of the Li-Ion, they offer higher energy density and high storage efficiency, making them ideal for portable devices and flexible grid-connected or grid-isolated distributed generation applications in micro grids [39, 45-48].

2.2.4.5 Different size of BESS in micro grid

At present, small size batteries would appear to be the most cost effective storage systems to use with small photovoltaic systems in residences. These might be expected to smooth transient demands for a few minutes to a few hours. However, at current prices, it would make little sense to install enough batteries to last for days or longer on systems connected to a grid. The relatively short lifetimes and high costs of batteries represent significant disadvantages for small stand-alone residential solar systems. The large amount of ongoing research focusing on batteries means their reliability and lifetimes are likely to increase and the costs should decrease. The implementation of micro grid systems allows management of both loads and sources. Just how much storage may be economical to install and where to locate it are problems that are still under investigation [42]. Couple of storage system of capacity fraction of few kilowatts to megawatts range may be installed to balance demand and generation of power in islanded operation in micro grid.

2.2.4.6 Inverter Control Schemes with BESS

Storage devices, namely BESSs are modelled as constant DC voltage source using power electronic interfaces to be coupled with the electrical network or grid [43]. In this cases, power electronic interfaces (or converters) are used at first to capture suitable DC voltage (DC link), and then DC voltage is converted into electrical network or grid-specified AC signal by means of a voltage source inverter (VSI) [26–28, 44]. The VSI is able to control the phase and magnitude of its output voltage; thus, it can determine the injected real power P and reactive power Q from the storage devices to the grid. Inverters are modelled by their control functions to control load [26 – 29, 48].

2.2.5. Load Control

Load control is the basic category of micro grid controls. The main usage of load controllers is to control micro sources and each source has a VSI control scheme which manages to set reference micro grid frequency in islanded mode [48]. The implementation of the control schemes maintains frequency stable by injecting or absorbing real power from BESS in islanded situation of micro grid. Some researcher [49] mentions that micro grid lacks
generation resources or storage energy during grid disconnection, at that moment load shedding is a common approach which has been implemented during the situation. In essence, micro grid sometimes possesses excess generation resources during islanded mode of micro grid, at that moment generation shedding is necessary to maintain frequency stable. Load shedding involves the disconnection of a specific amount of load for the purpose of preventing frequency degradation. The load shedding thresholds for these schemes are based on frequency degradation below standard limit. Moreover, it has been addressed some uncertainties and their formulation for frequency control in islanded mode of micro grid of distribution system and also various approaches have been proposed namely, generation rate, high pass filter – HPF (which filter out low frequency), low pass filter - LPF (which mainly filter out high frequency), and other time delays equipment[50-56].

2.2.5.1 Load shedding

In the case of supply shortage, load shedding which is a control action to reduce amounts of load intentionally, and the discharging action of BESSs are used to meet the balance. Load shedding is performed by the order of low priority from the viewpoint of load importance in one-owner systems. Furthermore, this scheme is widely used in existing power systems. However, in autonomous multi-participants system, this scheme is not effective for load shedding because of competing and conflicting claims of consumers for their loads. Therefore, an effective scheme for load shedding is required in islanded micro grid operation based on autonomous multi participants [57]. High Pass Filter (HPF) which allows to passes high signals and attenuates the signals with frequencies lower than the cut-off frequencies may be used with specific loads, namely water heaters, air conditioners for every participant owner to eliminate low frequency in islanded mode of micro grid [58 – 59].

2.2.5.2. Low Pass Filter (LPF)

The main function of Low Pass Filter (LPF) is to filter out range of high frequencies and also to eliminate harmonic components in micro grid [60]. In the islanded mode of micro grid operation, the frequency control is a challenging issue by the active power droop controllers since the micro grids mainly comprise converter-based inertia-less DGs. However, some virtual inertia, namely LPF can be provided with the droop controllers for restoration of islanded micro grid frequency to the rated value [61 - 62]. LPFs with the cut-off frequency are used for power calculation and this low cut-off frequency is also selected in order to
properly filter out the oscillatory components of powers considering the high frequency and harmonic distortion [60].

In this study, load control is implemented as a decentralized method and aimed to control operating points of the micro-sources. The most common method of load control is droop-based control system [63 - 64]. The distinct merit of the droop-based control method is that it grants plug-and-play capability to the DER systems. It should be pointed out that the load control may also be applied to the loads, for rapid and continuous frequency control, or even for load shedding [65].

2.2.6. Droop Control Scheme

When the micro grid is connected to the main grid, inverters use the frequency and voltage of the utility grid as the references. But, in islanding mode, the references of the utility grid are lost, so the inverters must find new references to continue the generation and enabling of generation control in the micro grid. The inverter of the storage device could be used for the frequency and voltage references during islanding operation. In this study, an improved model of the droop control method is proposed, which considers the battery’s SOC. This control scheme is used to connect the main storage device to the micro grid and represents the frequency reference for the micro grid during the transferring to islanding mode; this control method causes the SOC of the battery to be preserved in the allowable limits. Fig. 2.8 shows the proposed scheme for modelling the power frequency droop control method [1]. In Fig.2.8, the following equations are applicable:

\[ \text{SOC}_{MB} = \text{SOC}_{\text{initial}} - \text{SOC}_{\text{consumption}} \]  
(2.5)

\[ \text{SOC}_{\text{consumption}} = K_{\text{SOC}} \left\{ \int_{0}^{t} \text{P}(t) \text{dt} \right\} \] 
(2.6)

\[ K_{\text{soc}} = 100 / (3600 * (\text{Wh}_{\text{rated}})) \]

Here, SOC\text{MB} is the actual charge, SOC\text{initial} is the initial stage charge and SOC\text{consumption} is consumed charged of storage battery in microgrid as well as P(t) is the utility power, Wh\text{rated} is the estimated energy in one hour and K_{soc} is co-efficient.

2.2.7. Algorithm for Generation Control of the Microgrid

The algorithm is illustrated in Fig.2.8 which is proposed one BESS with non-inertia based DGs in islanded mode of micro grid [1]. The objective of the method is to maintain the system frequency and battery SOC at the desired values, meanwhile sharing the load according to BESS controller.
Transition from the grid-connected mode to the islanded mode establishes an imbalance between the supply and demand whether in a positive or in a negative direction. In this condition, the storage device control system compensates the power mismatch by absorbing/injecting power through the selection of a suitable droop line according to the monitored SOC of the batteries by using the following rules [1].

- When the SOC is in the range of a safe charging status, i.e., 20 < SOC < 80, a normal droop line is selected. The controllable energy resources intervene to nullify the required charge/discharge of the storage system in the process of stabilizing the frequency.
- If SOC is in an unsafe low condition, i.e., SOC < 20, then the droop line is shifted downward by 0.1 Hz, forcing the storage device to be charged in the frequency control process until SOC > 50.
- If SOC is in an unsafe high condition, i.e., SOC < 80, then the droop line is shifted upward by 0.1 Hz, compelling the storage device to be discharged in the frequency control process until SOC < 50.

2.3. Conclusion

In this study, a control strategy for the one storage system in the micro grid is suggested that shows low inertia of the micro-sources to restore the frequency deviation in transferring from utility-connected mode to the islanding mode. With ongoing system restructuring, continuous change of load and operating conditions, the uncertainty issue in power system operation and control has increasingly become a challenge. For that reason, droop control based multiple inverters interfaced Battery Energy Storage System (BESS) converter with 30% to 70% SOC limits of storage battery may be implemented to maintain stable frequency in islanded operation of micro grid. This control system is discussed in the next chapter.
CHAPTER 3

POWER CONTROLLING WITH MULTIPLE CONVERTER INTERFACED BESS SOURCES IN ISLANDED MODE OF MICROGRID

3.1. Introduction

Energy storage system, namely BESS is an enabling technology for power system integration of renewable sources. This storage system has high cycle life periods of charge and discharge operations and provides fast access to power [66]. It can be used for controlling both frequency deviation and also peak demand estimation. In this study, a bi-directional power converter was proposed for isolated micro grid with battery storage, and a bi-directional power flow was achieved among ac source, battery storage, and load. The power balance with converter interfaced storage battery is maintained in a micro grid keeping within constraints of state of charge of the battery. The storage battery is charged or discharged during transients with controller using feedback loop. Depending on the rate of frequency variation in micro grid, the storage battery can be switched to a power control mode to inject or reject the required real power determined by the proposed controller.

In this chapter, two inverter interfaced BESS, a stiff ac source and load are considered in an isolated mode of micro grid. The output power of inverter interfaced BESS is controlled in such a manner that the output real power of battery is controlled in order to keep frequency within acceptable limits during a power shortage or power excess. In this inverter based BESS control system, a conventional frequency droop control is demonstrated. As BESSs are converter interfaced, it is possible to control the output voltage angles instantaneously. The proposed angle droop control is derived from variation of reference real power and demonstrated discharged or charged power from BESS through inverter angle change.

Section 3.2 of this article describes the advanced control system with inverter interfaced BESS and then section 3.3 proposes algorithm of battery charging–discharging mode for frequency stability with multiple inverter interfaced BESS. Section 3.4 proposes angle based power control. The simulation study of islanded micro grid with multiple inverters interfaced BESS is described in section 3.5. The computation of the expected inverter angle delay due to modulation is discussed in section 3.6 and conclusion in section 3.7.

3.2 Develop an advanced control strategy with BESS in island operation of micro grid
Several reliable control strategies of multiple converter interfaced BESSs connected parallel with other sources have been analysed for frequency control system in an islanded operation mode of a micro grid. An advanced control algorithm has also been investigated as the optimization tool for battery charging or discharging with two inverter interfaced BESS systems in order to balance real power in micro grid for frequency stability applications [1].

The advanced frequency control system based on droop characteristic is used to stabilize frequency of the micro grid upon isolating from the utility grid. The storage battery having the capacity of rapid frequency control through transfer of the SOC of the lithium-ion storage battery to the range 30% <SOC<70% has been developed. This developed control system expresses the specific way of finding the optimum power and energy values after the optimum selection of control technology and SOC of BESS.

This study presents the rapid charge/discharge control of SOC of inverter interfaced BESS within specified range which can be installed parallel to an ac source in the distribution feeder to control frequency, especially in the islanded mode of micro grid. A distribution model with the modified controlled system with two converters interfaced BESSs in micro grid may be utilized for the optimum frequency deviation control.

### 3.3. Proposed Algorithm for frequency control of micro grid

A new frequency control model may be developed based new droop control method as shown in Fig.3.1.

![Proposed scheme for one element of BESS power frequency droop control method.](image)

Fig.3.1: Proposed scheme for one element of BESS power frequency droop control method.
The new proposed control system should be inserted in parallel with the ac source of a distribution system. This system should possess the following features:

The storage device, namely BESS of the control system compensates the power mismatch through bi-directional power flow method by selecting droop line according to the monitored state of charge (SOC) of the BESS following advanced droop control rules. The SOC of lithium-ion battery technology is in the range of a safe charging status, i.e., $30\% < \text{SOC} < 70\%$ [67], a normal droop line is selected when frequency of the system is 50 Hz. The BESS interfere for the required charge or discharge of the storage system for stabilizing the frequency. If frequency is higher than 50.0 Hz and SOC is in low condition, i.e. SOC $> 30\%$ or SOC $< 70\%$, and then the droop line forces the storage device to be charged in the frequency control process until SOC $< 70\%$. Again, if frequency is below 50.0 Hz and SOC is in high condition, i.e., SOC $< 70\%$ or SOC $> 30\%$, then the droop line forces the storage device to be discharged in the frequency control process until SOC $< 30\%$.

As shown in Fig.3.1, when the micro grid is in islanded mode, it may lead to a drop or increase in frequency due to mismatch of power generation and demand. It can be deduced that this mismatch of power generation and demand is proportional to the frequency variation. This imbalance power between the supply and demand just after isolation from the grid is compensated by the power of the storage battery. The inverter interfaced BESS controller is implemented to balance the power supply and demand through the battery storage device and also the frequency is restored to desired value by its fast operation. It is significance that when frequency is below 50.0 Hz and SOC is in the range of $30\% < \text{SOC} < 70\%$, the developed control system discharges the battery by following the droop equation:

$$f_s - f = K_f \left( \frac{P_{MB}}{P_{rating}} \right)$$

(3.1)

Here, $K_f$ is the droop co-efficient, $P_{MB}$ is the exported battery power, $P_{rating}$ is the battery power rating, $f_s$ is the synchronous frequency (i.e. 50 Hz value) and $f$ is micro grid frequency. To examine the process of setting droop gain, let us consider the case where a 1 Hz drop is required to produce rated power. The numeric value of droop equation will now be:

$$50.0 - 49.0 = K_f \left( \frac{P_{MB}}{P_{rating}} \right)$$
Here, the battery power, $P_{MB}$ is the exported real power with respect to the rated battery power, $P_{\text{rating}}$. The droop coefficient, $K_f$ can be calculated using defined values of minimum and maximum frequency, namely frequency difference (1 Hz) and the rated real power output of the battery.

On the other hand, if frequency is higher than 50.0 Hz and SOC is in the range of 30% < SOC < 70%, the control system charges the battery by the same droop equation mentioned in 3.1. The numeric value of droop equation will be:

$$50.0 - 51.0 = K_f \left( \frac{P_{MB}}{P_{\text{rating}}} \right)$$

Here, the battery power, $P_{MB}$ is the imported real power with respect to the rated battery power, $P_{\text{rating}}$. In this condition, micro grid injects their excess power to the battery in order to charge.

This exported or imported power from storage battery governed by control system depends on the droop coefficient, $K_f$, storage battery rating and micro grid frequency. The main purpose of the battery control system is to manage the required power in islanded micro grid effectively and also maintain micro grid stable. For this case of 1 Hz offset, this battery power can be expressed as:

$$P_{MB} = \frac{1}{K_f} \cdot P_{\text{rating}}$$

This method is the most severe way to control the frequency and establish a reference real power (or rating of the storage battery multiplied by droop coefficient) for controller of BESS to follow as shown in Fig.3.1. The reference power of the BESS’s controller is adapted to restore the frequency which is comparable for shifting real power vs frequency shown in Fig 3.1. In fact, the process can be controlled in transient response, and high dependency on converter output impedance [68-70]. It is possible for a converter to instantaneously change its output voltage waveform and also power sharing in micro grid by controlling the output voltage angle through droop control. If the transient load disturbances occur, the converter interfaced battery can change its output voltage angle instantaneously to minimize the transient oscillations. The islanded micro grid shows frequency lower than 50.0 Hz for higher load, converter interfaced BESS starts to pick up the extra load by changing its output voltage angle higher than parallel connected source. Again, the islanded micro grid shows frequency higher than 50.0 Hz for lower load, converter interfaced BESS starts to absorb excess power by providing output voltage angle lower than parallel connected source. In fact, power sharing
through converter interfaced BESS is proportional to their rating by changing droop coefficient shown in equation 3.1. In this study, the angle droop control strategy is applied to converter based BESS. It is assumed that total power demand in the micro grid can be supplied by DGs such that no load shedding is required. The output voltage angles of the converter are controlled to share the load proportional to the rating of the DGs. The multiple storage batteries having a unique value for the droop coefficient for each battery may operate in islanded micro grid with frequency droop control method. The different droop coefficients allow sharing the total load power requirement according to a predefined ratio [2]. For example, the total load power requirement of a micro grid can be shared proportional to rated real power output of each converter interfaced storage battery. As an output inductance is connected to each of the converter, the real power injection or rejection from the DG source to the micro grid can be controlled by changing its angle [19].

Fig. 3.2 shows the power flow from converter interfaced BESS to the micro grid through angle droop control where the rms values of the voltages and current are shown and the output impedance is denoted by $jX_{\text{line}}(jwL_{\text{line}})$.

**Fig.3.2: Inverter interfaced BESS connection**

### 3.4. Angle Droop Control and Power Sharing

Let the instantaneous real powers flowing from the inverter interfaced BESS to the micro grid be denoted by $P$. This instantaneous powers in passed through a low pass filter to obtain the average real power, $P$ shown in Fig.3.3.
This power can be calculated in the steady state pure sine of angle case and pure inductor with the following equation:

\[ P = \frac{EV\sin(\delta - \delta t)}{X_{\text{line}}} \]  

(3.3)

It is to be noted that the voltage angle \((E\angle\delta)\) of VSC does not have any direct control over \(V\angle\delta t\). Hence, from equation 3.3, it is clear that if the angle difference \((\delta - \delta t)\) is small, the real power can be controlled by controlling \(\delta\). Thus the power requirement can be distributed among the DGs, similar to conventional droop by dropping the angle as

\[ \delta = \delta_{\text{rated}} - m*P_{\text{rated}} \]  

(3.4)

where, \(\delta_{\text{rated}}\) is the rated angle of the DG, when it is supplying the load to its rated power levels of \(P_{\text{rated}}\). The coefficients \(m\) indicate the voltage angle drop vis-à-vis the real power output. The value is chosen as frequency regulation requirement in the islanded micro grid and also the value is considered in such that they can share the load in proportion to their rating [19].

To derive the power sharing with angle droop, a simple system with two identical converter based BESS, a stiff ac source and a three parallel resistive load is considered as shown in Fig. 3.4.
Fig. 3.4: Single phase Micro grid model with stiff ac source, two inverters interfaced identical battery and load for power sharing.

### 3.4.1. Micro grid Model Overview

The parameters of single phase micro grid shown above are described in Table 3.1 as follows:

<table>
<thead>
<tr>
<th>System Quantities</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>System frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>BESS voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>BESS capacity</td>
<td>150 Ah</td>
</tr>
<tr>
<td>BESS response time</td>
<td>30.0 seconds</td>
</tr>
<tr>
<td>BESS’s internal resistance</td>
<td>0.04 ohm</td>
</tr>
<tr>
<td>Inverter rating</td>
<td>1000KVA</td>
</tr>
<tr>
<td>Snubber resistance</td>
<td>5000 ohm</td>
</tr>
<tr>
<td>Snubber capacitance</td>
<td>50e-9 f</td>
</tr>
<tr>
<td>Ron</td>
<td>10e-3 ohm</td>
</tr>
<tr>
<td>Forward Voltage [Device ( V_f ), Diode ( V_{fd}(V) )]</td>
<td>[1.0 1.0]</td>
</tr>
<tr>
<td>Filter</td>
<td>( L_f = 0.23 ) mh, ( C_f = 25.0 ) uf</td>
</tr>
<tr>
<td>Filter resistance</td>
<td>( R_f = 0.02 ) ohm</td>
</tr>
<tr>
<td>Line inductor</td>
<td>( L = 6.6 ) mh</td>
</tr>
<tr>
<td>Line inductor resistance</td>
<td>( R_l = 0.002 ) ohm</td>
</tr>
<tr>
<td>AC voltage source</td>
<td>( V = 312.0 ) V, ( f = 50 ) Hz</td>
</tr>
<tr>
<td>Load</td>
<td>( R = 3.0 ) ohm,</td>
</tr>
</tbody>
</table>

Table 3.1: A Single Phase micro grid system Parameters
The dc power source used in this study is Lithium-ion battery for BESS of capacity: voltage 600V, capacity 150.0 Ah, and an internal resistance 0.04 ohm. However, the response time of BESS is chosen as default value i.e.30 seconds. The inverter with sinusoidal pulse-width modulation (SPWM) is used as a single-phase voltage source inverter (VSI). It contains two arm bridges with two IGBTs and two diodes in each arm. Each IGBT has a forward voltage of 1.0V and each diode has also forward voltage of 1.0V. Between the inverter output and the load, there is a single-phase LC filter. The inductance and capacitance values are 0.23 mh and 25.0 uf, respectively. Moreover, there is a small resistor (of value 0.02 ohm) in series with the filter inductor to represent the resistive losses. The main purpose of the LC filter is to reduce current harmonics delivered to the micro grid loads, especially higher order harmonics near the switching frequency of the control system. This in turn helps to reduce the total harmonic distortion delivered to loads. Each inverter is connected parallel with the ac stiff source (magnitude 312V, angle 0 degree) through line impedance (of value 6.6mh inductance and 0.002 ohm resistance). The parallel connected three sources are also connected with three parallel connected resistive load (of magnitude 9.0 ohm each) to supply power.

The power sharing in the mentioned islanded micro grid with two inverters interfaced BESS is demonstrated through a droop control strategy that sets power which is described in equation 3.4 and thus defines the angle. As the battery sources are inverter interfaced, it is possible to control the output voltage angle instantaneously. With this angle controlling strategy, real power can be controlled instantly for quick attainment of state micro grid frequency [2,19]. Thus inverter interfaced BESS can perform exporting or importing power by droop control strategy of the inverter output voltage angle. The power exporting and importing through inverter interfaced BESS is analysed with the single phase micro grid through angle droop control strategy in the simulation study.

**3.4.2. Control Scheme for Inverter interfaced BESS in isolated micro grid**

The aspect of the inverter interfaced BESS focused on this study is the modelling and controlling of the inverter for balancing of generated power and demand of micro grid loads. The control strategy of inverter interfaced BESS in an islanded micro grid needs to be performed to control power flow and also maintaining SOC of the battery for controlling battery discharging and charging operations respecting its SOC limits. The energy source for the inverters, namely BESS is modelled by means of Li-ion storage battery source in this study. The model and necessary description of Li-ion storage battery source is discussed in the next sub section.
3.4.2.1. BESS model for frequency control in isolated micro grid

The exact model of the Li-ion is generic battery model. A dc- link capacitor needs to be inserted parallel with storage battery for smoothing action of voltage across it. A 10000 microfarad capacitor is added in parallel with the BESS to maintain a regulated dc source with low ripple.

This generic model of the storage battery offer various level of flexibility relating to charge and discharge rate of the system. It is critical to follow manufacturer’s recommendation for both periods in order to formulate the correct charge and discharge rates. The efficiency of battery is strongly affected by current, time and temperature. Now, consider equivalent model of storage battery shown in Fig.3.5 below [71].

![Diagram of Storage battery model](image)

**Fig.3.5: Storage battery model [71]**

This model is represented by voltage source (Eo), internal resistance (Rbatt), capacitance (Co) and an overvoltage resistance (Ro). The term Co represents the battery capacity that is used to store energy. The disadvantage of the model is that elements are assumed to be constant but its value should actually depend on battery condition [71].

Fig.3.6 shows the equivalent circuit of battery model selected for this work. This model is based on a modified version of the parameterized battery model found in MATLAB/SIMULINK software.
The model shown in Fig.3.6 is the inherent behaviour of the dynamics of a battery. It runs by sensing the current, \( i_{\text{batt}} \), passing through the internal resistance of the battery. This current is fed to an integrator that relates the current with respect to time and thus allowing to track the amount of current being delivered for a given period. The no-load voltage \( E' \) is calculated as follows [72]:

\[
E' = E_0 - K \frac{Q_{\text{batt}}}{Q} + Ae^{(-Bt_{\text{batt}})}
\]  
(3.5)

Where, \( E_0 \) = constant voltage (V), \( K \) = polarization voltage (V), \( Q \) = rated battery capacity (Ah), \( A \) = exponential voltage (V), \( B \) = exponential capacity (Ah), \( i_{\text{batt}} \) = battery current and \( t \) = time.

The battery output voltage is given by

\[
E = E' - R_{\text{batt}}i_{\text{batt}}
\]  
(3.6)

This equation is used to follow the behaviour of a battery. The user can modify the battery parameters, namely battery type, voltage, state of charge, capacity. The value of \( E \) is reduced by voltage drop across internal resistance of the battery yielding actual battery voltage [72].

The assumption is made in order to simplify the model is that internal resistance is constant during charging and discharging cycles if SOC is considered from 70% to 30% for Li-ion battery.

### 3.4.2.2. Control of SOC of BESS in isolated micro grid for frequency control

To establish a good sense of SOC, an accurate battery model, namely Li-ion battery is used to track SOC through the varying power demanded by the loads. Storage battery datasheets
provide voltage and SOC characteristics for the battery undertaking current discharge or charge capacity. Therefore, the storage battery model developed in this study is utilized to vary an open loop coulomb-counting SOC algorithm. The coulomb counter is initiated to count how many coulombs of charge being pumped into or out of the battery. This coulomb counts by integrating current and also estimating the change of SOC for its accurate measurement of direct charge flow which can be stated by the following equation:

\[
SOC_{\text{actual}} = SOC_{\text{initial}} + \int_{t_1}^{t_2} I \, dt
\]  

(3.8)

The effective change of SOC is measured by integrating discharging or charging current over time, namely \((t_2-t_1)\) and this is called consumption or conservation battery’s SOC over time. With the bi-directional power flow of BESS, the upper and lower SOC limits of the storage battery and also the amount of reserve energy required for backup purposes in the islanded operation mode of micro grid needs to be considered. For the purpose, the upper and lower SOC limit is defined at 0.7pu and 0.3pu respectively. The marginal limit is defined at below 0.3pu which is designated to be the limit at which the battery needs to be charged to regain the normal droop characteristic defined by flow set-point [73-74]. In this droop control method, the frequency in micro grid drops is proportion to the difference between power demand and total generated power. In that instance, the SOC-limit controller of the energy storage system shown in Fig. 3.7 needs to be considered in this micro grid islanded mode.

![Fig. 3.7: BESS’s SOC control model in a single phase micro grid model](image)

The control scheme shown in Fig. 3.7 connected to the BESS in the micro grid measure consumed or conserved SOC by integrating discharged or charged reference current of the storage battery within a certain time and multiplying it to a co-efficient, namely \(K_{\text{SOC}}\) as shown in equation 3.9 [6].
SOC\_consumption/SOC\_conservation=K\_{SOC}\int_{t1}^{t2} I\_{ref} \, dt \tag{3.9}

K\_{SOC} = \frac{100}{(t2-t1)\times(I\_sec\_rated)}

Here, I\_{sec\_rated} is the rated current through inverter interfaced BESS in 1 second and (t2-t1) is the period for discharging or charging.

This consumed or conserved SOC may be deducted from the initial SOC to get actual SOC. The equation may be deduced for discharging and charging case shown below:

SOC\_actual = SOC\_initial + K\_{SOC}\int_{t1}^{t2} I \, dt \tag{3.10}

As discussed above, the actual SOC’s limit is between 30% and 70%. The developed control system goes to the battery discharging mode if micro grid frequency is lower than nominal frequency value, namely lower than 50Hz. Again, the control system goes to the battery charging mode if micro grid frequency is higher than nominal frequency value, namely higher than 50Hz.

In case of storage battery, battery’s life time needs to be considered. The storage batteries are reliable, and have a limited life. However, the batteries have moderate power density and good response time. Depending on the power conversion technology incorporated, batteries can go from accepting energy to supplying energy instantaneously. The batteries are also affected by SOC and must be maintained in order to achieve maximum life expectancy \[74\].

In the case of multiple storage battery system in islanded micro grid, the turn-off of a battery without warning is not good for power sharing. A gradual turn off is desired for battery discharging or charging case for effective power sharing in islanded micro grid. For that reason, equation 3.1 needs some modification when SOC is below 40% for the discharging case as well as SOC is above 60% for the charging case.

From the above discussion, when SOC is below 40%, then the discharged SOC may be considered with the following formula:

SOC\_new=\frac{(SOC-30\%) \times 10\%}{10\%} \tag{3.11}

Then, battery discharging equation for SOC<40% may be considered with the following formula:

P\_MB= (f_s - f)\times(1/ Kf)\times Prating\times (SOC-30\%) \times 10\% \tag{3.12}

However, if SOC is above 60%, in the case of battery charging, the charged SOC may be considered with the following equation:
SOC_{new} = (SOC-70\%) / 10\% \quad (3.13)

Then, battery charging equation may be considered with the following formula:

\[ P_{MB} = (fs - f)(1/ Kf) \times Prating \times (-SOC+70\%) / 10\% \quad (3.14) \]

The battery discharging and charging is performed through proper inverter control technique which is discussed in the next section.

### 3.4.2.3. Control of inverter interfaced BESS in isolated micro grid for frequency control

The control strategy of inverter interfaced BESS in micro grid can be considered in organizing power flow and control of power inverters [75] and this VSI control system needs to manage the output real power quality as well as tracking reference signals.

With respect to Fig.A.3 in Appendix A, a state vector is defined as

\[ x^T = [i_f \ i_1 \ V_{cf}] \]

The reference voltage, V_{cref} across Cf is given by V_{t} + j* I_{ref} * w L_1. Given V_{t} is the terminal voltage and L_1 is inverter line inductance. Note that, I_{ref} are derived from reference power (P_{ref}) divided by ac source voltage, V_{t}. Inverters are used both for feeding power from distributed generators and also for draining power to various types of electronic loads through controlling the sign of P_{ref}. The sign of P_{ref} sets the sign of the angle of V_{cref} with respect to V_{t}. The Inverter goes from power discharge or charge mode with respect to ac generator’s voltage, V_{t}. When islanded micro grid needs more power to stabilize micro grid frequency, V_{cref} angle needs to be increase in a positive sense from V_{t} to discharge power to system, the feedback process is to make the ac generator’s voltage angle stable. On the other hand, when islanded micro grid needs reject power to stabilize microgrid frequency, V_{cref} angle needs to be reduced with respect to V_{t} to feed power from the microgrid. This power angle, \pm \delta change with respect to V_{t} is predominantly dependent on P_{ref}. In the range of deviation of power angle, the relationship between \pm P and \pm \delta with respect to V_{t} can be regarded as almost linear [76-77]. By using these characteristics, the reference voltage to the inverter are set, and the voltage generated controlled by Pulse Width Modulation (PWM) to get the required values of power from inverter interfaced storage battery source.

In this thesis, two H-bridge converters with LCL filter are connected to a stiff ac source and load shown in Fig.3.4. The frequency of the triangular waveform (v_{tri}) is taken as 10 kHz and the numerical integration step size is chosen 2\mu s. To generate switching function (u), equation a.12 in Appendix A.3 is used for battery power discharging and charging operation.
Simulations are performed with the mentioned single phase islanded micro grid model to verify the performance of the converter interfaced BESS discharging and charging operation with reference power.

### 3.5 Simulation study

To show the effectiveness of proposed approaches, some case studies are simulated for each approach. In this research, MATLAB/SIMULINK is considered for simulation. Matlab is a platform for both coding and Model-Based Design of the system [78]. In this project, the sim power system toolbox is mainly used as it provides models of many components used in power electronics.

The single phase inverter interfaced energy storage models existing in sim power system toolbox and the proposed control system is used with a stiff ac source, and load to represent micro grid in islanded mode. This model is followed by a presentation of a selected number of simulation plots that depict important findings.

To validate the performance of the control system developed with single phase islanded micro grid shown in Fig.3.3 are depicted by the simulation study results. The parameters used for the simulation are mentioned in the Table 3.1. Power discharged or charged with two single phase inverters interfaced energy storage systems with sharing of the sources and loads are described over a 30 seconds time scales.

The analysed discharging and charging mode of inverter interfaced BESS are described in the next subsection.

#### 3.5.1 Simulation study: BESS discharging mode

For BESS discharging mode, the reference power ($P_{ref}$) is considered in three different values in three cases, namely case 1 with 10000W, case 2 with 15000W and case 3 with 20000W with two identical converter interfaced BESS which are described below:

**Case-1: The reference power ($P_{ref}$) is considered as 10000W.**

In this case, reference power ($P_{ref}$) is considered as 10000W, the inverter voltage, current through line inductance, and inverter voltage magnitude and angle are shown below by simulating the model for 0.4 second.
Fig. 3.8: $P_{ref}=10000$W case: (a) Inverter voltage, (b) Inverter line current, (c) Inverter voltage (magnitude); (d) Inverter voltage angle.

The inverter voltage and line current through inductor shown in Fig.3.8(a) and Fig.3.8(b) are 645V and 120 amp respectively with their first cycle transient due to switching effect. The inverter line current is shown some harmonics couple of cycles after its first cycle transient due to switching effect, and then it is stabilized at 120 amps.

The inverter voltage and inverter voltage angle shown in Fig.3.8(c) and 3.8(d) show zero in their first cycle and transient in the second cycle, and then stabilise at 341.6V magnitude and 22.7 degree respectively during the rest of the simulation time.

The BESS’s exported power can be found from the equation 3.3 as follows:

Here, $E=341.6/\sqrt{2}$, $V=312.0/\sqrt{2}$, $\delta=22.70$, $X_{line}=2*3.1416*22*6.6e-3$;

$P= 9918.12$ W
From the calculated real power value, it can be stated that BESS’s exported power also tracks the reference power. Then model is simulated for 30 seconds to analyse the BESS’s SOC, and exported power from BESS and power transferred through line impedance as below:

![Fig.3.9: P_{ref}=10000W case: (a) Li-ion storage battery’s SOC, (b) Storage Battery’s Exported Power, (c) Power transferred through line inductance from BESS.](image)

The Fig.3.9(a), Fig.3.9(b), and Fig.3.9(c) show the simulated value of BESS’s SOC, exported battery power and power transferred through line inductance from BESS which are mentioned as follows in steady state:

BESS’s SOC 69.92%
Exported battery power 9950 W
Power transferred through line inductance from BESS 9890 W

The case studies results represent that state of charge (SOC) decreases 0.08% in 30 seconds. For this, rate of discharge of SOC per minute is 0.16%. This storage battery discharged forces the exported power to 9950W and at that time, the transfer power through line inductance is 9890W. The difference power (between BESS’s exported battery power and power transferred through line inductance) is dissipated in inverter, filter resistance and imperfect line inductance.
The rise and fall of measured values such as power in response to a transient is asymptotic. The values begin to rapidly change soon after the transient and settle down over time. If plotted on a graph, the approach to the final values of power forms exponential curves. In this case, the measured values of discharged and transferred power are taken with low-pass filter of time constant value of 5.0 seconds that permit passing low frequency signals and attenuating higher frequency signals to show the smooth values of measured power. The smooth values of power are shown in the exponential curve form in Fig.3.9. However, the drawback of the selection is that it does not focus on the transient values of power but the smooth values of the power give the accurate measurement of power. From the figure, it is shown that the values of power reach 63.3% of its steady state value in its time constant value of 5.0 seconds.

**Case-2: The reference power ($P_{ref}$) is considered as 15000 W**

In this case, increasing reference power from 10000W to 15000W, the inverter voltage, current through line inductance, inverter voltage magnitude and angle are shown below by simulating the model for 0.4 second.

![Figure 3.10](image)

**Fig.3.10:** $P_{ref}$=15000W case: (a) Inverter voltage, (b) Inverter line current, (c) Inverter voltage (magnitude); (d) Inverter voltage angle.
The inverter voltage and line current through inductor shown in Fig.3.10(a) and Fig.3.10(b) are 645V and 190 amp respectively with their first cycle transient as before. The inverter line current looks some harmonics couple of cycles after its first cycle transient as previous, and then it is stabilized at 190 amps. The line current shows some increased value with increased reference power.

The inverter voltage and inverter voltage angle shown in Fig.3.10(c) and 3.10(d) represent zero in their first cycle and transient in the second cycle then stabilise at 373.2V and 32.14 degree respectively as shown in Fig.3.10(c) and 3.10(d).

The BESS discharged power can be found from the equation 3.3 as follows:

Here, E= 373.2/sqrt(2), V= 312.0/sqrt(2), del= 32.14, X_{line}=2*3.1416*6.6e-3;
P= 14953.40 W

From the computed real power value, it can be said that BESS’s exported power is also track the reference power with some deviation. It is shown that inverter angle is increased to the expected value, namely near 1.5 times of the previous value with increased reference power. Then model is simulated for 30 seconds to analyse the BESS’s SOC, and exported power and power after line impedance as below:

Fig.3.11: P_{ref}=15000W case: (a) Li-ion storage battery’s SOC, (b) Storage Battery’s exported Power, (c) Power transferred through line inductance from BESS
The Fig.3.11(a) and Fig.3.11(b), and Fig.3.11(c) show the simulated value of BESS’s SOC, exported power and power transferred through line inductance from BESS which are mentioned as follows in steady state:

BESS’s SOC  69.88%

Discharge battery power 14962 W

Power transferred through line inductance from BESS 14896 W

The case studies results indicate that state of charge (SOC) decreases 0.12% in 30 seconds. For this, rate of discharge of SOC per minute is 0.24%. This storage battery discharged forces the exported power to 14962W and at that time, the transfer power through line inductance is 14896W. The difference power (between BESS’s exported battery power and power transferred through line inductance) is dissipated in inverter, filter resistance and imperfect line inductance.

The measured values of discharged or transferred power are chosen with low-pass filter of time constant value of 5.0 seconds that permit passing low frequency signals and attenuating higher frequency signals to show the smooth values of power as previous. In this case, the smooth values of power are shown in the exponential curve form in Fig.3.11. However, the transient values of power are also disappeared as before but the smooth values of the power give the accurate measurement of power. From the figure, it is shown that the power values reach approximately 63.3% of its steady state value in its time constant value of 5.0 seconds.

Case-3: The reference power ($P_{ref}$) is considered as 20000 W

Again, reference power is increased from 15000 W to 20000 W, the inverter voltage, current through line inductance; inverter voltage magnitude and angle are shown below by simulating the model for 0.4 second.
Fig.3.12: $P_{ref}=20000\text{W}$ case: (a) Inverter voltage, (b) Inverter line current, (c) Inverter voltage (magnitude); (d) Inverter voltage angle.

The inverter voltage and line current through inductor shown in Fig.3.12(a) and Fig.3.12(b) are 645V and 220 amp respectively with their first cycle transient as before. The inverter line current looks some harmonics for couple of cycles after its first cycle transient, and then it is stabilized at 220 amps.

The inverter voltage and inverter voltage angle shown in Fig.3.12(c) and 3.12(d) represent zero in their first cycle and transient in the second cycle as before then stabilise at 413.8V and 39.6 degree respectively shown in Fig.3.12(c) and 3.12(d).

The BESS discharged power can be found from the equation 3.3 as follows:

Here, $E=\frac{413.8}{\sqrt{2}}$, $V=\frac{312.0}{\sqrt{2}}$, $\delta=39.6$, $X_{line}=2\times3.1416\times22\times6.6\times10^{-3}$;

$P=19864.59\text{W}$
From the computed real power value, it can be stated that BESS’s exported power is also track the reference power with some deviation. It can be mentioned that inverter angle is increased near 1.5 times of the previous value with increased reference power which is the expected value. Then model is simulated for 30 seconds to analyse the BESS’s SOC, and exported power and power after line impedance as below:

**Fig.3.13:** $P_{ref}=20000 \text{W}$ case: (a) Li-ion storage battery’s SOC, (b) Storage Battery’s Exported Power, (c) Power transferred through line inductance from BESS.

The Fig.3.13(a) and Fig.3.13(b), and Fig.3.13(c) show the simulated value of BESS’s SOC, exported battery power and power transferred through line inductance from BESS which are mentioned as follows in steady state:

- BESS’s SOC 69.84%
- Exported battery power 19935.0 W
- Power transferred through line inductance from BESS 19860.0 W

The case studies results indicate that state of charge (SOC) decreases 0.16% in 30 seconds. For this, rate of discharge of SOC per minute is 0.32%. This storage battery discharged forces the exported power 19935.0W and at that time, the transfer power through line inductance remains 19860.0W. This difference power (between BESS’s discharge battery power and
power transferred through line inductance) is dissipated in inverter, filter resistance and impure line inductance.

The measured values of discharged or transferred power are taken with low-pass filter of time constant value of 5.0 seconds that allow passing low frequency signals and attenuating higher frequency signals to show the smooth values of power as previous. The smooth values of power are shown in the exponential curve form in Fig.3.13. However, the transient values of power are unable to be seen with this long time constant on the measurement. From the figure, it is illustrated that the values of power reach 63.3% of its steady state value in its time constant value of 5.0 seconds.

**Comparison of cases**

From the simulation results, storage battery’s decreased SOC and exported power with variation of reference power (Pref) are given below in steady state in the following table:

<table>
<thead>
<tr>
<th>P_{ref} (KW)</th>
<th>Decreased SOC (% per minute)</th>
<th>Simulated value of Discharged power from Battery (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>0.16</td>
<td>9950.0</td>
</tr>
<tr>
<td>15.0</td>
<td>0.24</td>
<td>14962.0</td>
</tr>
<tr>
<td>20.0</td>
<td>0.32</td>
<td>19935.0</td>
</tr>
</tbody>
</table>

Table 3.2: Simulated values of battery’s decreased SOC, exported power with requested Power.

From the above Table 3.2, it can be stated that with decent decreasing BESS’s SOC, power exported from inverter interfaced BESS are tracking the increasing of Pref. When the decreasing SOC is 1.5 times or double, battery’s exported power is almost 1.5 times or twice value.

Again, from the simulation results, it is shown that the magnitude of inverter voltage, variation of inverter angle and storage battery’s exported power are almost expected value with the variation of Pref (namely 10000W, 15000W and 20000W). To validate the value of magnitude of inverter voltage, and inverter angle, the following equations may be considered:

The reference for the capacitor current and voltage are given by

\[ i_{ref} = I_{refm} \ast (\cos(\text{angvt}) + j \ast \sin(\text{angvt})) \]  

(3.15)
Here, $v_t$ is voltage of ac stiff voltage source;

\[ \text{angvt is the angle of ac stiff voltage source;} \]

\[ z_l \text{ is the inverter line impedance;} \]

$I_{refm}$ is derived from $P_{ref}$ and voltage of ac stiff voltage source.

The inductor current and voltage are given by

\[ i_{in} = i_{ref} + v_{cref}/(-j*\omega*c_f); \]  \hspace{1cm} (3.17)

\[ v_{invref} = v_{cref} + j*x_f*i_{in} + i_{in}*r_f \] \hspace{1cm} (3.18)

Here, $c_f$ is the filter capacitor;

\[ r_f \text{ is the filter resistance;} \]

Considering the equations, inverter voltage, and inverter angle are derived and also compare the values with simulated value of magnitude of inverter voltage, and inverter angle with variation of $P_{ref}$ (namely 10000W, 15000W and 20000W) which are shown in Table 3.3. In addition, the simulated values of storage battery’s exported power and transferred power through line inductor with variation of $P_{ref}$ are also presented below:

<table>
<thead>
<tr>
<th>Pref (KW)</th>
<th>Cal. Value of Inverter Voltage magnitude (from equation 3.14)</th>
<th>Sim. Value of Inverter Voltage (V) with % of deviation</th>
<th>Cal. Value of Inverter voltage angle (from equation 3.14)</th>
<th>Sim. Value of Inverter voltage angle (Angle) with % of deviation</th>
<th>Sim. exported Storage Battery Power (w)</th>
<th>Cal. Transfer power through inductor, $P=(EVsindel/X_{line})$</th>
<th>Measured Power after inductor (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0</td>
<td>342.0262</td>
<td>341.6 (0.123)</td>
<td>22.88</td>
<td>22.7 (0.786)</td>
<td>9950.0</td>
<td>9918.12</td>
<td>9890.0</td>
</tr>
<tr>
<td>15.0</td>
<td>374.0504</td>
<td>373.2 (0.227)</td>
<td>32.4858</td>
<td>32.14 (1.064)</td>
<td>14962.0</td>
<td>14953.40</td>
<td>14896.0</td>
</tr>
<tr>
<td>20.0</td>
<td>415.9361</td>
<td>413.8 (0.514)</td>
<td>40.3334</td>
<td>39.6 (1.818)</td>
<td>19935.0</td>
<td>19864.59</td>
<td>19860.0</td>
</tr>
</tbody>
</table>

Table 3.3: Comparison of simulated value of inverter voltage, angle, storage battery exported power with calculated value of inverter voltage and angle with respect to reference power.

From the Table 3.3, it can be shown that simulation value of inverter voltage and angle is close to the calculated value of inverter voltage and angle with a little bit deviation with increasing of reference power ($P_{ref}$). It can be stated from the table that simulation value of inverter angle, storage battery exported power is positively increasing with increasing of
reference power (Pref). This reference power is almost tracking the inverter interfaced BESS exported power with a little bit deviation. In this analysis, simulation step size is chosen 2e-6 and it involves delay time which may be full simulation step size [79]. This time delays introduce a phase shift in the control loop which reduces the achievable control angle and it may involve small reduction of the expected real power.

3.5.2 Simulation study: BESS charging mode

For BESS charging mode, $P_{\text{ref}}$ considered in three different values in three cases, namely case 1 with -10000 W, case 2 with -15000 W and case 3 with -20000 W two identical converter interfaced BESS which are described below:

**Case-1: The reference power ($P_{\text{ref}}$) is considered as -10000 W**

In this case, reference power ($P_{\text{ref}}$) is considered as -10000 W, the inverter voltage, current through line inductance, inverter voltage magnitude and angle are shown below by simulating the model for 0.4 second.

![Simulation results](image)

Fig.3.14: $P_{\text{ref}}$= -10000W case: (a) Inverter voltage, (b) Inverter line current, (c) Inverter voltage (magnitude); (d) Inverter voltage angle.
The inverter voltage and line current through inductor shown in Fig.3.14(a) and Fig.3.14(b) are 645V and -120 amp respectively with their first cycle transient due to switching effect. The inverter line current looks some harmonics for couple of cycles after its first cycle transient also due to switching effect, and then it is stabilized at -120 amps.

The inverter voltage and inverter voltage angle shown in Fig.3.14(c) and 3.14(d) represent zero in their first cycle and transient in the second cycle due to switching effect, then stabilise at 338.15V and -23.1 degree respectively shown in Fig.3.14(c) and 3.14(d).

The BESS’s imported power can be found from the equation 3.3 as follows:

Here, E=338.15/sqrt(2), V=312.0/sqrt(2), del=-23.1, X_line=2*3.1416*22*6.6e^-3;

P=-9981.56 W

From the computed real power value, it can be stated that BESS’s imported power also track the reference power. Then the model is simulated for 30 seconds to analyse the BESS’s SOC, and imported power and power after line impedance from BESS as below:

Fig.3.15: P_ref= -10000W case: (a) Li-ion storage battery’s SOC, (b) Storage Battery’s charged Power, (c) Power transferred through line inductance from BESS
The Fig.3.15(a) and Fig.3.15(b), and Fig.3.15(c) show the simulated value of BESS’s SOC, imported battery power and power transferred through line inductance from BESS which are mentioned as follows in steady state:

BESS’s SOC  30.08%

Battery charged power -9910.0 W

Power transferred through line inductance from BESS – 9995.0 W

The case studies results represent that state of charge (SOC) increases 0.08% in 30 seconds. For this, rate of charge of SOC per minute is 0.16%. This storage battery charged compels the storage battery’s imported power at -9910.0W and at that time, the transfer power through line inductance is -9995.0 W. The difference power (between power transferred through line inductance and BESS’s charge battery power) is dissipated in inverter, filter resistance and impure line inductance.

The rise and fall of measured values of power in response to a transient is asymptotic. The values begin to rapidly change soon after the transient and settle down over time. If plotted on a graph, the approach to the final values of power forms exponential curves. In this case, the measured values of charged and transferred power are taken with low-pass filter of time constant value of 5.0 seconds that only permits passing low frequency signals and attenuating higher frequency signals to demonstrate the smooth values of power. The smooth values of charged and transferred power are illustrated in the exponential curve form in Fig.3.15. However, the negative aspect of the selection is that it is unable to show the transient values of power but the smooth values of the power give the accurate measurement of steady state power. From the figure, it is shown that the power values reach 63.3% of its steady state value in its time constant value of 5.0 seconds.

**Case 2: The reference power (P_{ref}) is considered as -15000 W**

In this case, increasing reference power from -10000W to -15000W, the inverter voltage, current through line inductance, inverter voltage magnitude and angle are shown below by simulating the model for 0.4 second.
Fig.3.16: \( P_{\text{ref}} = -15000 \) W case: (a) Inverter voltage, (b) Inverter line current, (c) Inverter voltage (magnitude); (d) Inverter voltage angle.

From Fig.3.16, the following statements can be said:

The inverter voltage and line current through inductor shown in Fig.3.16(a) and Fig.3.16(b) are 645V and -190.0 amp respectively with their first cycle transient as before. The inverter line current looks some harmonics for couple of cycles after its first cycle transient as before, and then it is stabilized at -190 amps.

The inverter voltage and inverter voltage angle shown in Fig.3.16(c) and 3.16(d) represent zero in their first cycle, and transient in the second cycle as previous then stabilise at 370.2V and -33.8 degree respectively shown in Fig.3.16(c) and 3.16(d).

To determine total BESS charged power, the equation 3.3 is considered.
Here, \( E=370.2/\sqrt{2}, V=312.0/\sqrt{2}, \delta=-32.4, X_{\text{line}}=2*3.1416*6.6e-3; \)
\( P= -14924.18 \) W
From the computed real power value, it can be stated that BESS charged power also track the reference power. It is shown that inverter angle is increased near 1.5 times of the previous value with increased reference power which is the expected value. Then model is simulated for 30 seconds to analyse the BESS’s SOC, and imported power and power after line impedance as below:

![Graph showing SOC, imported power, and transferred power](image)

**Fig.3.17:** \( P_{\text{ref}} = -15000 \text{W} \) case: (a) Li-ion storage battery’s SOC, (b) Storage Battery’s imported power, (c) Power transferred through line inductance from BESS

The **Fig.3.17(a)** and **Fig.3.17(b)**, and **Fig.3.17(c)** show the simulated value of BESS’s SOC, battery’s imported power and power transferred through line inductance from BESS which are mentioned as follows in steady state:

- **BESS**’s SOC  30.12%
- Battery imported power -14886.0 W
- Power transferred through line inductance from BESS -14930.0 W

The case studies results represent that state of charge (SOC) increases 0.12% in 30 seconds. For this, rate of charge of SOC per minute is 0.24%. This storage battery charged compels the imported power at -14886.0W and at that time, the transfer power through line inductance is -14930.0W. The difference power (between BESS’s charged battery power and power
transferred through line inductance) is dissipated in inverter, filter resistance and impure line inductance.

The measured values of charged or transferred power are chosen with low-pass filter of time constant value of 5.0 seconds that allow passing low frequency signals and attenuating higher frequency signals to show the smooth values of power as before. The smooth values of power are shown in the exponential curve form in Fig.3.17. However, the transient values of power are also not visible as in the previous case but the smooth values of the power give the perfect measurement of power. From the figure, it is illustrated that the power values reach 63.3% of its steady state value in its time constant value of 5.0 seconds.

**Case 3: The reference power \((P_{\text{ref}})\) is considered as \(-20000\) W**

In this case, reference power is increased from \(-15000\) W to \(-20000\) W, the inverter voltage, current through line inductance; inverter voltage magnitude and angle are shown below by simulating the model for 0.4 second:

![Figure 3.18: \(P_{\text{ref}}\) = -20000W case: (a) Inverter voltage, (b) Inverter line current, (c) Inverter voltage (magnitude); (d) Inverter voltage angle.](image-url)
From fig.3.18, the following statements can be said:
The inverter voltage and line current through inductor shown in Fig.3.18(a) and Fig.3.18(b) are 645V and -230.0 amp respectively with their first cycle transient as previous. The inverter line current looks some harmonics for couple of cycles after its first cycle transient as before, and then it is stabilized at -230 amps.

The inverter voltage and inverter voltage angle shown in Fig.3.18(c) and 3.18(d) represent zero in their first cycle, and transient in the second cycle as previous then stabilise at 409.2V and -41.8 degree respectively.

To determine total BESS imported power, the equation 3.3 is considered.

Here, \( E = \frac{409.53}{\sqrt{2}} \), \( V = \frac{312.0}{\sqrt{2}} \), \( \delta_e = -40.7 \), \( X_{\text{line}} = 2 \times 3.1416 \times 6.6 \times 10^{-3} \);

\( P = -19930.78 \) W

From the calculated real power value, it can be stated that BESS’s imported power also track the reference power. It is shown that inverter angle is increased to 2.0 times of the first case value with increased 2.0 times of reference power which is the expected value. Then model is simulated for 30 seconds to analyse the BESS’s SOC, and imported power and power after line impedance as below:

Fig.3.19: \( P_{\text{ref}} = -20000 \)W case: (a) Li-ion storage battery SOC, (b) Storage Battery’s charged Power, (c) Power transferred through line inductance from BESS
The Fig.3.19(a) and Fig.3.19(b), and Fig.3.19(c) show the simulated value of BESS’s SOC, battery’s imported power and power transferred through line inductance from BESS which are mentioned as follows in steady state:

BESS’s SOC 30.16%
Battery’s imported power -19855.0 W
Power transferred through line inductance from BESS -19910.0 W

The case studies results represent that state of charge (SOC) increases 0.16% in 30 seconds. For this, rate of charge of SOC per minute is 0.32%. This storage battery charged compels the imported power at -19855.0W and at that time, the transfer power through line inductance is -19910.0W. The difference power (between power transferred through line inductance and BESS’s charged battery power) is dissipated in inverter, filter resistance and impure line inductance.

The measured values of charged or transferred power are taken with low-pass filter of time constant value of 5.0 seconds that permit passing low frequency signals and attenuating higher frequency signals to show the smooth values of power as before. The smooth values of power are shown in the exponential curve form in Fig.3.13. However, the transient values of power are also disappeared as previous but the smooth values of the power give the accurate measurement of power. From the figure, it is shown that the values power reach 63.3% of its steady state values in its time constant value of 5.0 seconds.

**Comparison of cases**

From the above simulation results, the storage battery’s increased SOC and imported power with variation of $P_{\text{ref}}$ (namely -10000 W, -15000 W and -20000 W) are given in steady state in the following table below:

<table>
<thead>
<tr>
<th>$P_{\text{ref}}$ (KW)</th>
<th>Increased SOC (% per minute)</th>
<th>Simulated value of Charged power from Battery (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10.0</td>
<td>0.16</td>
<td>-9910.0</td>
</tr>
<tr>
<td>-15.0</td>
<td>0.24</td>
<td>-14886.0</td>
</tr>
<tr>
<td>-20.0</td>
<td>0.32</td>
<td>-19855.0</td>
</tr>
</tbody>
</table>

Table 3.4: Simulated values of battery’s increased SOC, imported power with requested power.
From the Table 3.4, it can be stated that with decent increasing BESS’s SOC, power imported from inverter interfaced BESS are tracking the increasing of \( P_{\text{ref}} \). When the increased SOC is 1.5 times or double, battery’s imported power is almost 1.5 times or twice value.

Again, from the simulation results, it is shown that the magnitude of inverter voltage, variation of inverter angle and storage battery’s imported power are almost expected value with the variation of \( P_{\text{ref}} \) (namely -10000W, -15000W and -20000W). To certify the value of magnitude of inverter voltage, and inverter angle, the equations (namely 3.15, 3.16, 3.17, and 3.18) are derived and also compare the values with simulated value of magnitude of inverter voltage, and inverter angle with variation of \( P_{\text{ref}} \) (namely -10000W, -15000W and -20000W) in Table 3.5. In addition, the simulated values of storage battery’s imported power and transferred power through line inductor with variation of \( P_{\text{ref}} \) are stated below as previous:

<table>
<thead>
<tr>
<th>( P_{\text{ref}} ) (KW)</th>
<th>Cal. Inverter voltage magnitude (from equation 3.14)</th>
<th>Sim. Value of Inverter Voltage (V) and % of deviation from calculated value</th>
<th>Cal. Inverter Voltage angle (from equation 3.14)</th>
<th>Sim. Value of Inverter voltage (Angle) and % of deviation from calculated value</th>
<th>Sim. Charged Storage Battery Power (W)</th>
<th>Cal. Transfer power through inductor, ( P = (\text{EVslindel/X}) )</th>
<th>Measured Power after inductor (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10.0</td>
<td>339.4459</td>
<td>338.6 (0.249)</td>
<td>-24.5873</td>
<td>-23.2 (0.229)</td>
<td>-9910.0</td>
<td>-9981.56</td>
<td>-9995.0</td>
</tr>
<tr>
<td>-15.0</td>
<td>371.9816</td>
<td>370.2 (0.478)</td>
<td>-34.2830</td>
<td>-33.8 (1.4)</td>
<td>-14886.0</td>
<td>-14924.18</td>
<td>-14930.0</td>
</tr>
<tr>
<td>-20.0</td>
<td>411.7207</td>
<td>409.53 (0.532)</td>
<td>-42.6386</td>
<td>-41.8 (1.94)</td>
<td>-19855.0</td>
<td>-19930.78</td>
<td>-19910.0</td>
</tr>
</tbody>
</table>

Table 3.5: Comparison of simulated value of inverter voltage, inverter angle, storage battery charged power with calculated value of inverter voltage and angle with respect to reference power

From the Table 3.5, it can be shown that simulation value of inverter voltage and angle is close to the calculated value of inverter voltage and angle with a little bit deviation with increasing of reference power (\( P_{\text{ref}} \)). It can be stated from the table that simulation value of inverter angle, storage battery charged power is negatively increasing with increasing of
reference power, \((P_{\text{ref}})\) negatively. This reference power is almost near the charging value of the inverter interfaced BESS with a little bit deviation. In this analysis, simulation step size is chosen \(2\times10^{-6}\) and it causes delay time which may be full simulation step size [79]. This time delays introduce a phase shift in the control loop which reduces the achievable control angle and it may involve some reduction expected real power.

In the next section, the reason of inverter angle delay is analysed.

### 3.6 Computation of the expected inverter angle delay due to modulation

In this study, numerical integration step size is chosen \(2\times10^{-6}\). This simulation step size implies a small time delay in the controller. As simulation step size is low, the delay time may extend to full simulation step period. The computed output PWM shows one full cycle period delay of inverter output angle which are mentioned in simulation studies. In practice, the sampling period is usually chosen to be just enough to complete data sampling and control signal calculation to achieve fast response of the controller. The time delays introduce a phase shift in the control loop, which reduces, the achievable control angle [79].

In this analysis, the symmetric triangular carrier is used for the PWM generation. The samples are taken every half pulse period exactly at the middle and at the end/beginning of each pulse interval shown in Fig.3.20 which is explicitly shown for \(t = -0.5T_p\) and \(t = 0\).

![Diagram](attachment:image.png)

**Fig.3.20:** Delays occurring due to current acquisition (two-times oversampling and moving averaging of inductor current)
The calculation of the relative on-times of the PWM outputs, one pulse period is reserved, therefore generating an additional delay of a quarter pulse period $sT_p/4$. The relation of the input phase voltages which determines the switching states employed for forming the input current, the control commands and the calculation of the relative on-times of the PWM outputs one pulse period is reserved (shown in Fig. 3.20) [80]. As can be proven by simulations and/or analytical calculations, this introduces an additional delay time of a half pulse period of $e^{-T_p/2}$. This makes some angle deviation from calculated value.

This angle deviation is between 0.6 and 1.8 degree. This deviation can be considered as an offset value. During computation of $V_{cref}$, a 1.2 degree offset may be considered to minimise this error.

3.7 Conclusion

A controller with voltage angle loop is proposed for bi-directional power flow (namely power export or import) through multiple parallel connected inverters interfaced BESS. The efficacy of angle droop in voltage source converter based islanded micro grid is demonstrated in this chapter. It is noted that angle droop requires measurement of angle with respect to reference power and SOC of BESS. It is shown that controller can exported and imported power through multiple parallel connected inverters interfaced BESS with respect to requested power. In the next chapter, this controller is analysed with inertia generator and multiple parallel connected inverters interfaced different capacity BESS and variable load in islanded micro grid to validate its performance how it acts to meet the required power demand for stabilizing frequency.
CHAPTER 4

FREQUENCY CONTROL WITH INERTIA BASED GENERATOR AND MULTIPLE INVERTERS INTERFACED BESS IN AUTONOMOUS MICROGRID

4.1. Introduction

The ultimate goal is to provide conditions for frequency stability of isolated power systems. This requires a satisfactory control of active power flow in the system. In other words the balance for generation and demand and consequently frequency in the system should be kept constant.

In this chapter, a stand-alone micro grid model is considered with low-inertia rotating prime movers, multiple inverters interfaced different capacity BESSs and variable resistive loads. The low inertia of the electrical system implies that load steps will impose changes in the speed of the generators, creating fluctuations in system frequency [81-82]. The variation of frequency with varying load is to be kept frequency 50.0 Hz by droop control in a controlled and stable manner. In that case, the frequency increases or decreases in response to the level of balancing for generation and demand. The frequency droop controls are the most common methods used to share the real power in an islanded micro grid [83]. The two inverter interfaced BESSs connected parallel with the low inertia of the electrical generator is implemented with droop control system for load sharing in micro grid. The angle based droop control system is used to share the real power through converter based BESS [84]. Thus, the angle controlled inverters interfaced BESS can be effective solution in stabilizing frequency through controlling real power in a stand-alone micro grid. The main focus of this chapter is to control the battery output power in such a manner that the frequency remains within acceptable limits during a power shortage or power excess due to load change.

Section 4.2 of this thesis describes the micro grid structure, then section 4.3 proposes dynamic model of droop control on inertia generator. The simulation study of frequency stability with the inertia generator, multiple converter interfaced BESS and variable resistive loads is discussed in Section 4.4. The efficacy of using multiple inverters interfaced BESS in islanded micro grid is analysed in section 4.5 and section 4.6 describes conclusion.

4.2 Micro grid Structure and Control

In this study, the islanded mode micro grid has one synchronous machine with two nos. inverter interfaced BESSs, and variable resistive load. The storage battery is controlled using
both frequency deviation and a power demand estimation method. A multi-directional power converter is proposed in the standalone hybrid system with battery storage system, and a bi-directional power flow was achieved among inertia based generator, battery storage, and variable load. The power balance is maintained in a micro grid, and the SOC of the battery is controlled. A control algorithm described in section 3.3 is utilized for inertia based generator as the main power source and batteries as the complementary source. The main focus of the present research is to control the battery output in such a manner that system frequency remains within acceptable limits during a power shortage or excess due to load change. A micro grid system with a battery backup is taken as the test bed for the present study. A controller is used to determine the reference power injection needed from the battery to hold the frequency. During power disturbance in the system, the proposed controller determines the battery reference power. During normal operation, the battery floats with the local bus voltage without any power injection or rejection, and the battery is charged or discharged during transients with a high-gain feedback loop. Depending on the rate of frequency fall or rise, it is switched to a power control mode to inject or reject the required power from the reference power value determined by the proposed controller. The inverter power controllers regulate the real power outputs, by providing reference values for the output voltage phase. The reference is based on droop: real power vs. voltage angle. The real power droop is characterised by a frequency set point $f_{\text{set}}$ and a droop gain. The synchronous generator rating in the islanded mode micro grid limits the extent to which the droop is applicable [85]. The inverters interfaced BESS is connected in parallel with synchronous generator, at that case, inverter interfaced BESS shares the real power demand as the complementary source until the islanded mode micro grid frequency is stable. The inverter interfaced BESS shares the required real power with particular droop operating point at a chosen frequency.

This study presents design and implementation of droop control based synchronous generator and power controllers of the inverter interfaced BESSs with variable resistive loads. Simulation model of a synchronous generator connected to load are described below.

### 4.3 Dynamic Model of the Droop Control on a Prime Mover

To observe the behaviour of a generator set on a droop control scheme, a model was created that modelled a prime mover of synchronous machine driving a rotating generator connected to an ac generator with varying frequency, as shown in Figure 4.1[86].
The droop control is referenced to the prime mover, not the electrical generator, and rewriting the original droop equation reveals that the output power of the prime mover can be stated by the equation 4.1 (which has been discussed in 2.1 equation before).

\[ w - w_o = k_f (P - P_o) \]  

(4.1)

\( P_o \) and \( w_o \) are pre-determined set-points that are known, so it follows that if the speed of the system is known, output power of the generator can be determined. The set-points of the droop control are chosen for a particular application and can be changed by the controller, if disturbances are present or if the configuration of the system changes, such as adding or rejection of loads or generators [86].

While equation (4.1) can be used to find the output power of the prime mover, the speed of the system needs to be determined. How the speed of the system changes with load disturbances can be found using the dynamic relationship shown in Equation (4.2).

\[ \int \frac{d\omega}{dt} = \int (P_m - P_e) \, dt \]  

(4.2)

Where, \( J \) is the inertia ratio, \( \omega \) is the angular speed deviation, and \( P_m \) and \( P_e \) are the mechanical power input and electrical power output of the synchronous machines. The kinetic energy is stored in the prime mover of synchronous machine in the system. If the load in the system suddenly exceeds the rated electrical power (\( P_e \)), mismatch between \( P_m \) and \( P_e \) appears. Kinetic energy will be released and transferred as electric energy to the power system. Since the governor at that moment is slow, the initial power increase is solely obtained by this inertial response. During this process the generator speed decreases and so does the electric frequency. Some seconds after load increases, primary frequency control
makes the governor to meet the increased power and the frequency is below the value of nominal. On the other hand, if load goes below the rated electrical power (Pe), the speed of the machines on the system increases to meet the demand. The frequency behaviour after the load changes, is determined only by the inertial response of the generator and hence the amount of stored kinetic energy [87].

For modelling and simulation, Pe/J was calculated for the entire system; the dynamic speed is for the system. The input to the unit is mechanical power divided by inertia (Pm/J). The angular acceleration is equal to 1 / J multiplied by the sum of two terms, namely Pm (positive) and Pe(negative). Integrating this angular acceleration gives angular velocity and again integrating the velocity gives angle which is the change in the output position. This angle is added to controlled voltage source of magnitude 310v, frequency 50 Hz. This controlled voltage source is multiplied with the current to generate instantaneous value of power shown in Fig.4.2.

![Fig.4.2: Droop Controlled based inertia generator](image)

In this model, the system data used for the inertia generator and resistive loads are given in Table 4.1.
### System Quantities

<table>
<thead>
<tr>
<th>System Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>AC voltage</td>
<td>343.5V</td>
</tr>
<tr>
<td>Resistive load (rated)</td>
<td>20 ohm</td>
</tr>
<tr>
<td>Inertia (J)</td>
<td>74.07 kg·m²</td>
</tr>
<tr>
<td>Electrical output power</td>
<td>5900W</td>
</tr>
</tbody>
</table>

Table 4.1: Inertia generator parameters

#### 4.4 Load frequency control in islanded micro grid

Control of frequency in islanded mode is very important for stability of the islanded micro grid. In this thesis, two inertialess DGs, namely converter based BESSs is connected parallel with inertia DG with varying load in an islanded mode of micro grid shown in Fig.4.3.

![Fig.4.3: Single phase islanded micro grid model with inertia generator, inverter interfaced BESS and load.](image)

Here, inertia based generator is utilized as the main power source and batteries as the complementary source. As mentioned in section 3.4, converter interfaced BESSs can pick up quickly the change of power demand by controlling output voltage angle of inverter. The droop control described in section 3.4 has been employed here. In this section, it is shown that optimum load sharing and a rapid steady state attainment are achieved in islanded mode.
of micro grid while the state feedback ensures better response in voltage control mode of inverter interfaced BESS response (as discussed in Appendix A.3)[19].

4.4.1 The reference generation

The aim of the BESS controller is to balance load demand and generation. The battery output needs to be controlled in such a way that system frequency remains within acceptable limits during load change (both power shortage or excess condition). The controller is used to determine the reference power from the battery to hold the frequency. In the proposed islanded micro grid, the reference power is considered as the battery rating times inverse of droop co-efficient. During power disturbance in the system, the proposed controller determines that the battery reference power will be discharging mode or charging mode. If SOC of BESS is between the limits of 30% to 70% and micro grid requires more power by inserting resistive loads, then controller forces inverter to the discharging mode. The converter discharges real power to micro grid till frequency goes to 50.0 Hz and also SOC limits is reached until 30%. Again, if micro grid possesses excess power by relieving resistive loads, then controller forces inverter to the charging mode. The converter imports real power from micro grid till frequency goes to 50.0 Hz and also SOC limit is reached until 70%.

4.4.2 Proposed Control System

As discussed earlier, better load sharing and a quick steady state attainment are achieved when multiple inverters interfaced BESS are implemented in the islanded micro grid while the state feedback ensures better response (Details converter control techniques are discussed in Appendix A). The multiple inverters interfaced BESS operate under state feedback control, the battery sources are switched to voltage control mode. These are switched back to the state feedback control after synchronization [2].

4.4.3 Simulation Study

Simulation studies are carried out with different ratings of storage battery, resistive loads and different operating conditions to check the system response and controller action. The results for converter interfaced BESS’s discharged and charged condition are discussion below.

The system data used for inertia generator and resistive loads are given in Table 4.1. In addition, the data of two identical inverter interfaced same rating or different rating BESS which is inserted in parallel with one inertia generator and resistive load in islanded mode micro grid are given in Table 4.2 below.
<table>
<thead>
<tr>
<th><strong>System Quantities</strong></th>
<th><strong>Values</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>System frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Inverter rating</td>
<td>10KVA</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>1000kHz</td>
</tr>
<tr>
<td>Sampling time</td>
<td>10e-6</td>
</tr>
<tr>
<td>Snubber resistance</td>
<td>5000 ohm</td>
</tr>
<tr>
<td>Snubber capacitance</td>
<td>50e-9 f</td>
</tr>
<tr>
<td>Ron</td>
<td>10e-3</td>
</tr>
<tr>
<td>Forward Voltage [Device Vf(v), Diode Voltages]</td>
<td>[1.0 1.0]</td>
</tr>
<tr>
<td>Filter</td>
<td>L=0.23 mh, C=25.0 uf</td>
</tr>
<tr>
<td>Filter resistance</td>
<td>Rf=0.002 ohm</td>
</tr>
<tr>
<td>Line inductor</td>
<td>L=22.0 mh</td>
</tr>
<tr>
<td>Line inductor resistance</td>
<td>Rl=0.02 ohm</td>
</tr>
<tr>
<td>Droop coefficient</td>
<td>3.6</td>
</tr>
<tr>
<td>Bat.1 (namely, BESS-1) voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>Bat.1 (namely, BESS-1) capacity</td>
<td>15 Ah</td>
</tr>
<tr>
<td>Bat.1 (namely, BESS-1) internal resistance</td>
<td>0.4 ohm</td>
</tr>
<tr>
<td>Bat.2 (namely, BESS-2) voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>Bat.2 (namely, BESS-2) capacity</td>
<td>22.5 Ah</td>
</tr>
<tr>
<td>Bat.2 (namely, BESS-2) internal resistance</td>
<td>0.26667 ohm</td>
</tr>
<tr>
<td>Bat.3 (namely, BESS-3) voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>Bat.3 (namely, BESS-3) capacity</td>
<td>0.15 Ah</td>
</tr>
<tr>
<td>Bat.3 (namely, BESS-3) internal resistance</td>
<td>0.1 ohm</td>
</tr>
</tbody>
</table>

Table 4.2: A Single Phase inverter rating

**4.4.3.1 Simulation study of two inverter interfaced BESS’s discharging mode in islanded micro grid**

In this study, the islanded microgrid is considered with inertia source, namely synchronous generator of capacity 5900.0W, two inverter interfaced BESSs and rated resistive and switching resistive load. The switching resistive load, is inserted in parallel through a change over switch in the mentioned islanded micro grid. This additional load in micro grid demands extra power from inverter interfaced BESSs for balancing power generation and power demand. In this model, the extra resistive load is considered as 12.0 ohm which is switched at 2.0 seconds with rated resistive load of 20 ohm, then total load is 7.5 ohm. Some cases are
analysed with same rating and different rating BESSs to validate the converter interfaced BESS’s performance of discharging mode in islanded microgrid in Table 4.3 below:

<table>
<thead>
<tr>
<th>Cases</th>
<th>System Parameters</th>
<th>Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-1</td>
<td>Inertia generator, rated load and switching load</td>
<td>To analyse system frequency and power with transient load injection situation.</td>
</tr>
<tr>
<td>Case-2</td>
<td>Inertia generator, two inverters interfaced identical rating storage battery with same SOC, rated load and switching load</td>
<td>To analyse system frequency and power sharing with transient load injection situation.</td>
</tr>
<tr>
<td>Case-3</td>
<td>Inertia generator, two inverters interfaced different rating storage battery with same SOC, rated load and switching load</td>
<td>To analyse system frequency and power sharing with transient load injection situation.</td>
</tr>
<tr>
<td>Case-4</td>
<td>Inertia generator, two inverters interfaced different rating with different SOC storage battery, rated load and switching load.</td>
<td>To analyse system frequency and gently power sharing in between different rating inverter interfaced BESSs with transient load injection situation.</td>
</tr>
</tbody>
</table>

Table 4.3: Different cases with identical and different rating BESS of discharging mode in islanded micro grid.

The simulation studies of the mentioned cases are described below:

Case -1: As mentioned above in the first case (namely case-1), inertia generator and rated valued resistive load and switching resistive load is considered as an islanded microgrid shown in Fig.4.4.

![Fig.4.4: Micro grid islanded case: Single phase islanded micro grid model with inertial generator, rated and switching load.](image)

As mentioned earlier, rated resistive load is 20.0 ohm and switching resistive load is R5 (of magnitude 12.0 ohm) which is added in parallel to 20 ohm resistive loads with a change over
switch of duration 2.0 seconds to 10.0 seconds. After switching load, frequency and synchronous’s generator’s supplied power are shown in Fig.4.5 below.

![Graph](image)

Fig.4.5: Micro grid islanded case: (a) Frequency of the circuit with inertia generator and load; (b) Power of inertial generator.

From Fig.4.5, it is shown that the inertial generator goes to its steady state value after 0.8 seconds. A disturbance such as switching a load occurs at 2.0 seconds in the island mode of the micro grid, then the frequency goes down linearly to a steady state value of 32.0 Hz at 6.0 second shown in Fig.4.5(a). When frequency drops linearly, the application of droop equation of 4.2 makes the power increase linearly to 12200.0W as seen in Fig.4.5(b) within very little time, namely 0.2 second after switching load due to extra power drawn from inertia to meet the additional power demand. Then the synchronous generator’s power goes back to its initial level of 5900W at 6.0 second after a linear decreases in power from 12200.0W to 5900W with a linear decreases in frequency from 50.0 Hz to 32.0 Hz as shown in Fig.4.5(b) and Fig.4.5(a) during the period 2.2 seconds to 6.0 seconds. This also agrees with the mentioned droop equation of 4.2. The rest of the time from 6.0 second to 10.0 second, frequency in islanded microgrid is stabilized at 32.0 Hz, and in steady state the synchronous generator’s power goes back to its initial level of 5900W.

**Case-2:** In the second case, two identical energy rating bat.1 (namely, BESS-1) with inverter is considered with inertia generator and rated valued resistive load and switching resistive load as shown in Fig.4.6.
Fig.4.6: Identical battery case: Single phase islanded micro grid model with inertia generator, two inverters interfaced same rating BESS and rated and switching load.

As discussed above, the islanded micro grid model is considered with two inverter interfaced battery, BESS-1 with the synchronous generator and rated valued resistive load of 20 ohm value and switching resistive load of 12 ohm value. The power rating and state of charge for both storage battery is considered 9000W and 70% SOC and droop co-efficient is set 1/3.6 for each battery. In the islanded microgrid, the two inverters interfaced BESS-1 is on at 1.5 seconds and the switching load is on at 2.0 seconds, the frequency goes down after switching load. At that stage, the two inverter interfaced BESSs start exporting power with decreasing SOC of BESS-1. The BESS’s SOC and discharged power along with power transferred through line inductance are shown in Fig.4.7 below within 10 seconds simulation period:
Fig. 4.7: Identical battery case: (a) SOC, (b) Discharged Power, (c) Power transfer through line inductance.

Fig. 4.7 shows that SOC of each BESS decreases 0.25% in 10 seconds and discharged power is 5050 W for each inverter interfaced BESS and the power passing through the line inductance is almost 5005 W. The measured power is taken with low-pass filter of cut-off frequency 25 Hz that allows passing low frequency signals and attenuating higher frequency signals. For that reason, discharged power or transferred power is shown 0.3 seconds delay and attenuation of higher frequency signals. In addition, the transferred power from BESS is used for balancing demand and total generated power. At that stage, the micro grid frequency is almost 49.75 Hz and the average power supplied by the synchronous generator is 5940.0 W as shown in Fig 4.8 below.
The case study results are in response to disturbances such as inverter interfaced BESS turns on at 1.5 second and switching a load occurs at 2.0 seconds in island mode of the micro grid. From the Fig.4.8(b), it is shown that inertia generator goes to its steady state value after 0.8 seconds. The first interruption, namely, the inverter interfaced BESS turning on at 1.5, it discharges only a small amount of power 150W to -100W which makes a small frequency fluctuation from its nominal value during 1.5 seconds to 2.0 seconds shown in Fig.4.8(a). Again, another interruption, such as, switching load in island mode occurs in the system, then the regulating power is effectively shared between the synchronous generator and two identical inverter interfaced BESS as shown in simulation results, namely Fig.4.7(b) and Fig.4.8(b). A resistance of 12.0 ohm value is switched on at 2.0 second, at that instance, microgrid frequency goes down linearly. Then each inverter interfaced BESS provide their proportional share of same power amounting 5050W to balance the power demand and generation from 2.1 to 10.0 seconds. The frequency during this period remains almost 49.75 Hz. The deviation from 50.0 Hz is the droop offset value. The total discharged power from two batteries is almost equal to storage battery rating multiplied by inverse of droop coefficient and droop offset which is mentioned in equation 3.1 in chapter 3. The equation is shown below:

$$P_{MB} = (f_s - f)(1/K_f)Prating$$
However, the average power supplied by the synchronous generator is sharp upward at 6800W for a short time near 0.1 seconds after switching load at 2.0 second shown in Fig.4.8(b) and frequency also decreases to 49.6 Hz during this period shown in Fig.4.8(a). After 2.1 second to 10 second, power supplied is stabilized at 5940w due to stabilization of frequency at 49.75 Hz.

**Case -3:** In the third case, two different energy rating battery namely, bat.1 and bat.2 (specification mentioned in Table 4.2) with inverter are considered with inertia generator and rated resistive load and switching resistive load as shown in Fig.4.9.

![Diagram](image)

Fig.4.9: Different rating battery case: Single phase islanded micro grid model with inertia generator, different capacity storage battery sources with identical converter and rated and switching load.

As for the previous model, a rated resistive load and switching resistive load are considered with value 20.0 ohm and 12.0 ohm respectively. This switching load is also added in parallel to 20 ohm resistive loads with a change over switch of duration 2.0 seconds to 10.0 seconds as previous. In this case, the two inverters interfaced different energy rating battery with the synchronous generator and rated valued resistive load and switching resistive load is considered as an islanded micro grid. The power rating for bat.1 (namely,BESS-1) and bat.2 (namely,BESS-2) are considered different, namely 9000W and 13500W and state of charge (SOC) and droop co-efficients are selected to be the same, namely 70% SOC and 1/3.6 for both batteries. When the switching load turns on and frequency goes down, then inverter interfaced both BESS starts exporting power and at that moment SOC of BESS also decreases. The SOC and discharged power along with power transferred through line
inductance of BESS-1 and BESS-2 are shown in Fig.4.10 below within 10 seconds simulation period:

Fig.4.10: Different rating battery case: (a) SOC of BESS-1 and BESS-2, (b) Discharged Power of BESS-1 and BESS-2, (c) Power transfer of BESS-1 and BESS-2 through line inductance.

Fig.4.10 shows that the decrease of SOC is 0.084% for BESS-1 and 0.083% for that of BESS-2. The discharged power from inverter interfaced BESS-1 and BESS-2 is 3900W and 5900W respectively and power passing through line inductance are 3850W and 5850W. The measured power is taken with low-pass filter of cut-off frequency 25 Hz that allows passing low frequency signals and attenuating higher frequency signals. For that reason, discharged power or transferred power is shown 0.3 seconds delay and attenuation of higher frequency signals as before. In addition, the transferred power from BESS-1 and BESS-2 is used for balancing demand and total generated power. After the two inverter interfaced BESS’s
operation, micro grid frequency is almost at 49.8 Hz from 2.1 seconds to 10.0 seconds and average power supplied by synchronous generator during this period is 5960W shown in Fig. 4.11 below:

![Graph showing frequency and power](image)

Fig.4.11: Different rating battery case: (a) Frequency of the islanded micro grid, (b) Power of inertial generator.

The simulation results in this case indicate the interruptions as previously, namely inverter interfaced BESS turns on at 1.5 seconds and switching load occur at 2.0 seconds in the islanded micro grid, the change of power required is effectively shared between the synchronous generator and two inverter interfaced BESS. The first interruption, namely, the inverter interfaced BESS turning on at 1.5 seconds, it discharges only a small amount of power 150W to -100W which makes a small frequency fluctuation from its nominal value during 1.5 seconds to 2.0 seconds shown in Fig.4.11(a) as before. Again, another interruption, such as, switching a load in island mode occurs in the system at 2.0 second, at that moment, microgrid frequency goes down linearly and then the two inverter interfaced BESS start discharging power to meet the additional power requirement. The two sources, namely inverter interfaced BESS-1 and BESS-2 provide its proportional share of power amounting 3900W and 5900W respectively (shown in Fig.10(b)) for balancing the power demand and generation in the islanded micro grid from 2.1 to 10.0 seconds. The difference in discharged
battery power from BESS-1 and BESS-2 is due to different battery rating which complied with equation 3.1 in chapter 3 with respect to frequency variation. The micro grid frequency during this period 2.1 to 10.0 seconds remains almost 49.8 Hz and the droop offset is 0.2 value. The total discharged power from two batteries is almost equal to storage battery rating multiplied by inverse of droop co-efficient and droop offset. The equation is shown below:

\[ P_{MB} = (f_s - f) \times (1/K_f) \times Prating \]

On the other hand, the average power supplied by the synchronous generator makes a small jump for 0.1 second amounting 6600W due to sharp decreases frequency at 49.6 Hz after switching load shown in Fig.4.11(a) and 4.11(b). From Fig.4.11(b), it is shown that inertia generator goes to its steady state value after 0.8 seconds as before. During the period 2.1 second to 10 second, power supplied is stabilized at 5940W with levelled off frequency at 49.8 Hz shown in Fig.4.11(a) and 4.11(b).

**Case -4:** In the fourth case, two different energy rating battery namely, bat.3 and bat.1 (rating mentioned in table 4.2) with inverter is considered with inertia generator and rated valued resistive load and switching resistive load as shown in Fig.4.12 below.

![Diagram](Fig.4.12: Different rating and SOC battery case: Single phase islanded micro grid model with inertia generator, different capacity storage battery sources with identical converter and rated and switching load.)

As previous model, rated resistive load and switching resistive load is also considered 20.0 ohm and 12.0 ohm respectively. This switching load as before, is added in parallel to 20 ohm rated resistive loads with a change over switch of duration 2.0 seconds to 30.0 seconds. In
this case, the power rating for bat.3 (namely, BESS-3) and bat.1 (namely, BESS-1) are considered 12000W and 9000W and SOC of BESS-3 and BESS-1 is selected as 45.0% and 70.0% and the droop co-efficient is set 1/3.6 for both battery and the both battery sources are on in 1.5 second in the mentioned islanded micro grid. When the switching load is on at 2.0 seconds and frequency goes down, then inverter interfaced BESS starts exporting power and at that moment SOC of BESS starts decreasing. As SOC of BESS-3 is considered 45.0%, it follows the new droop line equation 3.12 in chapter 3 when SOC goes below 40%. The equation is mentioned below:

\[ P_{MB} = (f_s - f) \times (1/ K_f) \times Prating \times (SOC - 30\%) / 10\% \]

When SOC goes below 40%, the discharged power is decreased linearly following the discharged new droop equation 3.12. In this islanded micro grid, another inverter interfaced BESS, namely BESS-1’s SOC is considered 70%, it supplies the required power demand following formal droop equation mentioned in equation 3.1 in chapter 3. The equation is shown below:

\[ P_{MB} = (f_s - f) \times (1/K_f) \times Prating \]

The SOC and discharged power along with power transferred through line inductance of BESS-3 and BESS-1 are shown in Fig.4.13 below within 30 seconds simulation period:
Fig. 4.13: Different rating and SOC battery case: (a) SOC of BESS-3; (b) SOC of BESS-1 (c) Discharged Power of BESS-3 and BESS-1; (d) Transferred power through line inductance of BESS-3 and BESS-1.

Fig. 4.13(a) and 4.13(b) show that the decreased SOC is 5% for BESS-3 and 0.03% for that of BESS-1 from 2.0 second to 5.1 seconds. The discharged power from inverter interfaced BESS-3 is levelled off 5750W value until SOC’s limit is reached 40% and also discharged power from inverter interfaced BESS-1 is levelled off 4200w value during this period shown in Fig. 4.13(c). After SOC’s limit of BESS-3 is 40%, it decreases linearly but slower than before following equation 3.12 until 30% of SOC value during the period 5.1 second to 21.6 second. When SOC of BESS-3 reaches 30% value, it maintains linearly decreasing power
from 5750W to zero value during the mentioned period. However, SOC of BESS-1 decreases little bit rapidly than previous when SOC of BESS-3 is below 40% from 5.1 seconds to 21.6 seconds to discharge the micro grid required power from inverter interfaced BESS-1 and to stable the micro grid frequency. At 21.6 seconds, the BESS-3 approaches its SOC limit and discharged power is zero. However, BESS-1’s discharged power ramps up to 9960W to cover the transition and SOC of BESS-1 decreases little bit rapidly than previous. Fig.4.13(c) shows that after 21.6 seconds to 30.0 seconds, power supplied by inverter interfaced BESS-3 is zero and the required power is supplied by inverter interfaced BESS-1 is 9960W after smooth transition of power from inverter interfaced BESS-3 to inverter interfaced BESS-1. Again, Fig. 4.13(d) shows that power transferred from line inductor is almost near to the discharged power from BESS-3 and BESS-1 and this power is utilized to stable the system frequency. The measured power is taken with low-pass filter of cut-off frequency 25 Hz that allows passing low frequency signals and attenuating higher frequency signals. For that reason, discharged power or transferred power is shown 0.3 seconds delay with attenuation of higher frequency signals as before. In this islanded micro grid, after introducing the two inverters interfaced BESS, micro grid frequency and power of inertial generator is maintained stable during this period which are shown in Fig4.14 below.

Fig.4.14: Different rating and SOC battery case: (a) Frequency of the islanded micro grid, (b) Power of inertial generator.

From Fig.4.14, it is shown that the micro grid frequency is almost at 48.8 Hz from 2.0 seconds to 5.1 seconds and average power supplied by synchronous generator during this
period is 5940W. After 5.1 seconds to 21.6 seconds, frequency is decreasing from 49.8 Hz to 49.5 Hz due to inverter interfaced BESS-3 decreasing discharged power. After 21.6 seconds, frequency is stabilized at 49.5 Hz when total power demand is supplied by inertial generator and inverter interfaced BESS-1. The different discharged battery power from BESS-3 and BESS-1 is due to different battery rating which complied with equation 3.1 in chapter 3. The micro grid frequency during 2.0 seconds to 5.1 seconds is 49.8 Hz and the droop offset is 0.2. Again, micro grid frequency during 21.6 seconds to 30.0 seconds is 49.5 Hz and the droop offset is 0.5. The total discharged power from two batteries or one battery is almost equal to storage battery rating multiplied by inverse of droop co-efficient and droop offset which complied with the equation 3.1. During this period from 2.0 seconds to 5.1 seconds synchronous generator’s supplied power is 5930W and during 21.6 seconds to 30.0 seconds, it is stabilised at 5950W shown in fig.4.14. However, synchronous generator’s supplied power is fluctuating between 5930W to 5960W during the period 5.1 seconds to 21.6 seconds.

The simulation results in this case indicate that the interruptions, namely inverter interfaced BESS is on at 1.5 seconds and switching load occur at 2.0 seconds in the islanded micro grid, the required power is effectively shared between the synchronous generator and two inverter interfaced BESS as before. The first interruption, namely, the inverter interfaced BESS turning on at 1.5 seconds, it discharges only a small amount of power 150W to -100W which makes a small frequency fluctuation from its nominal value during 1.5 seconds to 2.0 seconds shown in Fig.4.14(a) as before. Again, another interruption, such as, switching a load in island mode happens in the system at 2.0 second, at that moment microgrid frequency goes down linearly and then, the two inverter interfaced BESS start discharging power to meet the additional power requirement. In this case, the battery source, namely inverter interfaced BESS-3 provides power until its 30% SOC limit and then the another battery source, namely inverter interfaced BESS-1 having SOC limits in upper level, (namely 70%) provides the required power through smooth transition strategy. Thus this multiple battery strategy implemented in islanded microgrid can stabilize microgrid frequency.

From the analysis, it can be stated that inverter interfaced BESS can supply the required power in islanded micro grid. As multiple inverters interfaced BESS are considered, any inverter interfaced BESS possessing the required SOC limit can supply the necessary amount power following the reference power with gently transition of power and also maintain the micro grid frequency stable.
4.4.3.2 Simulation Study of converter interfaced BESS’s charging mode in islanded micro grid

As discussed earlier, the islanded microgrid is considered with 20.0 ohm rated load (two parallely connected resistive load) with inertia source of 5900.0w and two inverter interfaced BESS.

In charging case, the circuit is considered with 20.0 ohm rated resistive load, namely two parallel connected resistive loads. If one parallel connected resistive load is disconnected by a change over switch, then islanded microgrid mentioned is more than rated load (namely more than 20 ohm) and frequency becomes more than 50 Hz. At that situation, the extra power needs to be rejected from the mentioned microgrid through inverter interfaced BESSs for balancing power demand and generated power. In this model, the circuit is also considered with 20.0 ohm rated resistive load (20.1 ohm resistor and 4020.0 ohm resistor connected in parallel) with inertial source, namely synchronous generator of capacity 5900.0W and two inverter interfaced BESS. The resistance of 20.1 ohm is discharged with a change over switch at 2.0 seconds, then the total circuit is considered 4020.0 ohm resistance. Some cases are analysed with different rating BESSs to validate the converter interfaced BESS’s performance of charging mode in islanded microgrid shown in Table 4.4 below.

<table>
<thead>
<tr>
<th>Cases</th>
<th>System Parameters</th>
<th>Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case-1</td>
<td>Inertia generator, fixed load and switching off load.</td>
<td>To analyse system frequency and power with transient load rejection situation.</td>
</tr>
<tr>
<td>Case-2</td>
<td>Inertia generator, two inverters interfaced identical rating storage battery with same SOC, fixed load and switching off load.</td>
<td>To analyse system frequency and power sharing with transient load rejection situation.</td>
</tr>
<tr>
<td>Case-3</td>
<td>Inertia generator, two inverters interfaced different rating storage battery with same SOC, fixed load and switching off load.</td>
<td>To analyse system frequency and power sharing with transient load rejection situation.</td>
</tr>
<tr>
<td>Case-4</td>
<td>Inertia generator, two inverters interfaced different rating storage battery with different SOC, fixed load and switching off load.</td>
<td>To analyse system frequency and gently power sharing in between different rating inverter interfaced BESSs with transient load rejection situation.</td>
</tr>
</tbody>
</table>

Table 4.4: Different cases with identical and different rating BESS of charging mode in islanded micro grid.
The simulation studies of the mentioned cases are described below:

**Case -1:** In the first case, inertia generator and rated valued resistive load namely two parallel connected resistive loads are considered as an islanded microgrid shown in Fig.4.15.

![Diagram of Microgrid Islanded Case](image)

Fig.4.15: Micro grid islanded case: Single phase islanded micro grid model with inertia generator, and fixed and switching off resistive load.

As mentioned earlier, two parallel connected rated value resistive load is considered as 20.0 ohm in this islanded microgrid. The switching off resistive load is 20.1 ohm which is added in parallel to 4020.0 ohm resistive loads with a change over switch of duration 2.0 seconds to 150.0 seconds. After switching off load, the frequency and power of inertia generator are shown in Fig.4.16 below.

![Graphs of Microgrid Islanded Case](image)

Fig.4.16: Micro grid islanded case: (a) Frequency of the circuit with inertia generator and load (without BESS source); (b) Power of inertial generator.
From the graph, it is shown that inertial generator goes to its steady state value after 0.8 seconds as before. A disturbance namely switching off 20.1 ohm resistive load occurs at 2.0 seconds in the island mode of the micro grid, frequency goes up linearly from 50.0 Hz to 700.0 Hz during the period 2.0 seconds to 140.0 seconds and stabilise to new steady state value of 700.0 Hz at 140.0 second shown in Fig.4.16(a). When frequency increases linearly, the application of droop equation of 4.2 makes power goes down linearly at 29.0w shown in Fig.4.16(b) within very little time, namely 0.2 second after switching off load due to less power drawn from inertia to meet the less power demand. Then the synchronous generator’s power goes back to its initial level of 5900W at 140.0 second after linearly increases from 29.0W to 5900W during the period 2.2 seconds to 140.0 seconds which is also agreed with the mentioned droop equation of 4.2. The rest of the time from 140.0 second to 150.0 second, frequency in islanded microgrid is stabilized at 700.0 Hz which makes the synchronous generator’s power goes back to its initial level of 5900W.

**Case -2:** In the second case, two identical energy rating bat.1 (namely, BESS-1) with inverter is considered with inertia generator and rated valued two parallel connected resistive load as shown in Fig.4.17 below.

![Diagram](image)

**Fig.4.17:** Identical battery case: Single phase islanded micro grid model with inertia generator, two inverters interfaced same rating BESS and fixed and switching off resistive load.

The model is considered with two identical inverters interfaced BESS and it acts charging when frequency is beyond 50.0 Hz. At 2.1 second, when frequency is more than 50.0 Hz, the inverter interfaced BESS then starts importing power through its controller. At that situation, the BESS’s SOC, imported power along with power transfer through line inductance are shown in Fig.4.18 below.
Fig. 4.18: Identical battery case: (a) SOC of BESS-1 and BESS-1, (b) BESS-1 and BESS-1’s charged power; (c) Power transfer through line inductance to charge BESS-1 and BESS-1.

Fig. 4.18 shows that both BESS’s SOC increases 0.058% and imported power and power transferred through line inductance is -2960W and -3000W for both inverter interfaced BESS. The measured power is taken with low-pass filter of cut-off frequency 25 Hz that allows passing low frequency signals and attenuating higher frequency signals. For that reason, charged power or transferred power is shown 0.3 seconds delay with attenuation of higher frequency signals. In this model, the transferred power through line inductance is used to charge BESS which is used for balancing demand and total generated power. With inverter interfaced BESS’s operation, micro grid frequency is almost 50.15 Hz and average real is 5880W after micro grid stabilized shown in Fig 4.19(a) and (b). The Fig 4.19(a) shows frequency control with inverter interfaced BESS which is better than Fig 4.16(a), frequency control without inverter interfaced BESS.
The simulation results from the case studies are in response to disturbances such as inverter interfaced BESS turns on at 1.5 second and switching off load occurring at 2.0 second in island mode of the micro grid. When the inverter interfaced BESS turns on at 1.5 second, it discharges only a small amount of power 150W to -100W shown in Fig.4.19(b) which makes a small frequency fluctuation from its nominal value during 1.5 seconds to 2.0 seconds shown in Fig.4.19(a) and again Fig.4.19(b) shows that inertia generator goes to its steady state value after 0.8 seconds as before. In addition, another interruption, namely a 20.1 ohm resistor is discharged with a change over switch of duration 2.0 seconds to 10.0, the control system of synchronous generator forces the governor to increases its speed (i.e frequency also increased) from 2.0 seconds to meet the reduced power demand. After switching off, frequency goes to 50.28 Hz linearly within 0.1 second and at that instance, synchronous generator also supplies nearly 5280W power. After 2.1 seconds, the inverter interfaced BESS starts as a load to balance the power demand and generation during the period 2.1 to 10.0 seconds. During this period, synchronous generator supplies almost 5880W power shown in Fig.4.19(b) and micro grid frequency is stable at 50.15 Hz shown in Fig.4.19(a). The deviation from 50.0 Hz is the droop offset value. The total charged power of two batteries is almost equal to storage battery rating multiplied by inverse of droop co-efficient and droop offset which is mentioned in equation 3.1 in chapter 3. The equation is shown below:
Case -3: In the third case, the two different energy rating batteries namely, bat.1 and bat.2 (specification mentioned in Table 4.2) interfaced inverters are considered with inertia generator and 20.0 ohm rated valued two parallel connected resistive load as shown in Fig.4.20.

![Diagram](image)

Fig.4.20: Different rating battery case: Single phase islanded micro grid model with inertia generator, two inverters interfaced different rating BESS and fixed and switching off resistive load.

This model is also considered with 20.0 ohm rated load, namely 20.1 ohm resistor and 4020.0 ohm resistor connected in parallel with inertia source of 5900.0W and two different energy rating inverter interfaced battery as previous. The difference in this case is the different energy rating battery, bat.1 (namely BESS-1) and bat.2 (BESS- 2) with inverter and the synchronous generator and fixed valued resistive load and switching off resistive load which are considered as an islanded micro grid. The power ratings for BESS-1 and BESS-2 are considered different, namely 9000W and 13500W and state of charge (SOC) and droop coefficient are selected to be the same, namely 30% SOC and 1/3.6 for both battery. The resistance of 20.1 ohm is discharged with a change over switch of duration 2.0 seconds to 10.0 as previous, then the total circuit is considered as 4020.0 ohm resistance. When the switching load is off and frequency goes up, then inverter interfaced both BESS starts importing power and at that moment SOC of BESS also increases. The SOC and charged power along with power transferred through line inductance of BESS-1 and BESS-2 are shown in Fig.4.21 below within 10 seconds simulation period:
Fig. 4.21: Different rating battery case: (a) SOC of BESS-1 and BESS-2, (b) BESS-1 and BESS-2’s charged power; (c) Power transfer through line inductance to charge BESS-1 and BESS-2.

Fig. 4.21 shows that the increased SOC is 0.045% for BESS-1 and 0.046% for that of BESS-2. The imported power from inverter interfaced BESS-1 and BESS-2 is -2400W and -3500W respectively and power passing through line inductance is -2500W and -3600W. The measured power is taken with low-pass filter of cut-off frequency 25 Hz that allows passing low frequency signals and attenuating higher frequency signals. For that reason, charged power or transferred power is shown 0.3 seconds delay with attenuation of higher frequency signals as before. In addition, the transferred power is used for balancing demand and total generated power. With inverter interfaced BESS’s operation, micro grid frequency is almost 50.12 Hz and average real power is 5880w after micro grid is stabilized shown in Fig 4.22.
This simulation results in the case specify that disturbances such as inverter interfaced BESS turns on at 1.5 second and switching off load happens at 2.0 seconds in island mode of the micro grid as before. The inverter interfaced BESS turns on at 1.5, it discharges only a small amount of power which makes a small frequency decreased 0.05 Hz from its nominal value during 1.5 seconds to 2.0 seconds shown in Fig.4.22(a). During the period, synchronous generator’s supplied power is 5940W. Again, another interruption, a 20.1 ohm resistor is discharged with a change over switch of duration 2.0 seconds to 10.0, the control system of synchronous generator forces the governor to increases its speed (i.e frequency also increased) from 2.0 seconds to meet the reduced power demand. At that instance, the inverter interfaced BESS starts as a load to balance the power demand and generation. Fig.4.22(a) shows that after switch off the resistive load at 2.0 second, frequency is above 50.25 Hz and at that instance, synchronous generator supplies near 5280W for 0.1 second duration as before shown in Fig.4.22(b). After 2.1 seconds, the inverter interfaced BESS starts as a load to balance the power demand and generation during the period 2.1 to 10.0 seconds and micro grid frequency is stable at 50.15 Hz shown in Fig.4.22(a). The deviation from 50.0 Hz is the droop offset value. The total charged power of two batteries is almost equal to storage battery rating multiplied by inverse of droop co-efficient and droop offset which is mentioned in equation 3.1 in chapter 3. The equation is shown below:

\[ P_{MB} = (f_s - f) \times (1/K_f) \times Prating \]
However, from the Fig.4.22(b), it is shown that inertia generator goes to its steady state value after 0.8 seconds as before. During the period 2.1 second to 10 second, synchronous generator supplies almost 5880W power shown in Fig.4.22(b) as micro grid frequency is stabilized at 50.12 Hz.

Case -4: In the fourth case, two different energy rating battery namely, bat.3 and bat.1 (rating mentioned in table 4.2) with inverter is considered with inertia generator and 20.0 ohm rated valued two parallel connected resistive load as shown in Fig.4.23.

![Diagram](https://example.com/diagram.png)

Fig.4.23: Different rating and SOC battery case: Single phase islanded micro grid model with inertia generator, two inverters interfaced different rating BESS with fixed and switched resistive load.

This model is also considered with 20.0 ohm load, namely 20.1 ohm resistor and 4020.0 ohm resistor connected in parallel with inertial source of 5900.0W and two different energy rating inverter interfaced battery. In this case, the two inverters interfaced different energy rating battery, bat.3 (namely BESS-3) and bat.1(namely, BESS-1) with the synchronous generator and 20.0 ohm rated resistive load is considered as an islanded micro grid mode. The power rating for BESS-3 and BESS-1 are considered 12000W and 9000W and SOC of BESS-3 and BESS-1 is selected 56.70% and 30.0% and droop co-efficient is set 1/3.6 for both case. The resistance of 20.1 ohm is discharged with a change over switch,S of duration 2.0 seconnds to 40.0, then the total circuit is considered as 4020.0 ohm resistance. When the switching off load is happened at 2.0 seconds and frequency goes up, then inverter interfaced BESS starts importing power and at that moment SOC of BESS also starts increasing. The SOC of BESS-3 is considered 56.70%, and it follows the equation 3.14 in chapter 3 when SOC goes beyond 60% and at that moment charged power is also decreased linearly following the new droop
line equation 3.14 in chapter 3. In this islanded micro grid, another inverter interfaced BESS, namely BESS-1’s SOC is considered 30%, it absorb the required power demand following formal droop equation mentioned in equation 3.1 in chapter 3.

The SOC and charged power along with power transferred through line inductance of BESS-3 and BESS-1 are shown in Fig.4.24 below within 40 seconds simulation period:

Fig.4.24: Different rating and SOC battery case: (a) SOC of BESS-3; (b) SOC of BESS-1; (c) Charged Power of BESS-3 and BESS-1; (d) Transferred power through line inductance of BESS-3 and BESS-1.
Fig. 4.24(a) and 4.24(b) show that the increased SOC is 3.3% for BESS-3 and 0.42% for that of BESS-1 from 2.0 second to 6.2 seconds. The charged power from inverter interfaced BESS-3 is levelled off -3650W value until 60% SOC limit and also charged power from inverter interfaced BESS-1 is levelled off -2660W during this period as shown in Fig. 4.24(c). After SOC limit of BESS-3 is 60%, it increases linearly but slower than before following the new droop line equation 3.14 in chapter 3 until 70% of SOC value during the period 6.2 second to 34.8 second as shown in fig. 4.24(a). The equation 3.14 in chapter 3 is mentioned below:

\[ P_{MB} = (f_s - f)*(1/K_f)*Prating*(-SOC + 70%)/10\%

At 34.8 seconds, the charged power is zero when SOC of BESS-3 is 70% value which maintains linearly increases power from -3650W to zero value during the period from 6.2 seconds to 34.8 seconds as shown in Fig. 4.24(c). However, BESS-1’s charged power ramps down to -6240W after linearly decreases from -2660W to -6240W value to cover the transition and SOC of BESS-1 also increases little bit rapidly than previous during the period. Fig.4.24(c) shows that after 34.8 seconds to 40.0 seconds, power supplied by inverter interfaced BESS-3 is zero and the required power is absorbed by inverter interfaced BESS-1 is -6240W with gently transition.

Again, Fig. 4.24(d) shows that power transferred from line inductor is almost near to the charged power from BESS-3 and BESS-1 and this power is utilized to stable the system frequency. The measured power is taken with low-pass filter of cut-off frequency 25 Hz that allows passing low frequency signals with attenuating higher frequency signals. For that reason, charged power or transferred power is shown 0.3 seconds delay with attenuation of higher frequency signals as before.

In this model, after the two inverter interfaced BESS’s operation, micro grid frequency is almost at 50.12 Hz from 2.0 seconds to 6.2 seconds shown in Fig.4.25(a) and average power supplied by synchronous generator during this period is 5880W shown in Fig.4.25(b). After 6.2 seconds to 34.8 second, frequency is increasing from 50.12 Hz to 50.27 Hz due to inverter interfaced BESS-3 decreasing charged power. After 34.8 seconds, frequency is stabilized at 50.25 Hz when total power demand and supply is balanced by inertia generator and inverter interfaced BESS-1 shown in Fig.4.25(a). The deviation from 50.0 Hz is the droop offset value. The values are varying from 2.0 seconds to 6.2 second, again 6.2 second to 34.8 second and finally from 34.8 second to 40.0 second. The total charged power of two
batteries is complied with the mentioned droop equation 3.1 in chapter 3. The equation is shown below:

\[ P_{MB} = (f_s - f) \frac{1}{K_f} \frac{1}{Prating} \]

However, from Fig.4.25(b), it is shown that inertial generator goes to its steady state value after 0.8 seconds as before. During the period 2.0 seconds to 6.2 second, synchronous generator supplies almost 5880W, and from 34.8 second to 40.0 second, synchronous generator supplies almost 5850W and again during the period 6.2 seconds to 34.8 second, synchronous generator’s supplied power is fluctuating between 5850W and 5880W shown in Fig.4.25(b).

![Figure 4.25: Different rating and SOC battery case: (a) Frequency of the islanded micro grid, (b) Power of inertia generator.](image)

The simulation results in this case indicate that the interruptions, namely inverter interfaced BESS turns on at 1.5 second and switching off load occurs at 2.0 second in the islanded micro grid, the required power is effectively shared between the synchronous generator and two inverter interfaced BESS as before. When the resistance is switched off at 2.0 second, then the microgrid frequency goes up linearly and at that moment the two inverter interfaced BESS start charging power to meet the surplus power. In this case, the battery source, namely inverter interfaced BESS-3 absorbs power until its 70% SOC limit is reached and then the another battery source, namely inverter interfaced BESS-1 absorbs the required power with smooth transition as its SOC limits is currently at a lower level, namely 30% SOC. Thus
multiple battery strategy implemented in islanded microgrid is useful to make microgrid frequency stable.

From the analysis, it can be stated that inverter interfaced BESS can absorb the required power in islanded micro grid. If multiple inverters interfaced BESS are considered, then any inverter interfaced BESS possessing the required SOC limit can absorb the necessary amount power following the reference power with gently transition of power and also maintain the micro grid frequency stable.

4.5 Efficacy of using multiple inverters interfaced BESS in islanded micro grid

In this thesis, micro grid control and power management with multiple inverters interfaced BESSs are studied with inertial DG and variable load in micro grid islanded mode. The control system for the multiple inverters interfaced BESS are proposed to manage the charging and discharging while maintaining the operating reserve in the BESS to achieve system stability. The function of this control strategy is to improve the transient behaviour and dynamic load power sharing in an autonomous micro grid [88]. The results show in simulation studies that the proposed control and power management strategies have the ability to stabilize the micro grid system.

The advantage of implementing multiple inverters interfaced BESSs with inertia DG and variable load in micro grid islanded mode is that at least one storage battery can supply power during load demand situation in micro grid. The SOC of storage battery in this system maintains upper level limit when the micro grid is stable situation as there is a soaring threat of future needs for the battery. For that frequency control should operate to provide a higher reserve of energy in the battery and there is a high possibility to get return for using the storage battery at a particular time.

In islanded micro grid, transient behaviour, namely load inserted or load rejection situation may appear. In the case of load inserted or rejection, multiple inverters interfaced BESSs can export or import the required power if the SOC limit of BESS is between 30% and 70%. With the introduction of the new droop line with SOC limits, we see smooth transition to another power generator or battery source. In fact, the SOC limit has an important effect on frequency stability in islanded micro grid. If any of BESS’s SOC is not in the SOC limits range or lower limit, then load shedding may be implemented if demand is excess than generation in micro grid. On the other hand, generation shedding needs to be implemented if any of BESS’s SOC hits upper limits in the case of excess generation in islanded micro grid.
4.6 Conclusions

Dynamic response of inertial DG and non-inertial DGs (namely, converter interfaced BESS in a micro grid is different. The inertial based DGs show a slower response while non-inertial DGs can respond very quickly [85]. In this thesis, better control strategies with multiple inverters interfaced BESS are proposed for a hybrid micro grid operating in autonomous mode to improve the transient behaviour and dynamic load power sharing. The angle based droop control strategy is proposed for multiple inverters interfaced BESSs to enhance a better dynamic power sharing with smooth transition for another power generation while minimizing transient oscillations in the micro grid. It has been shown that proposed control and power management strategies have the ability to ensure the micro grid stability.
CHAPTER 5

CONCLUSIONS

The general conclusions of the thesis and future scope of the work are presented in this chapter. The conclusions are based on the work done and reported in the earlier chapters.

5.1 General Conclusion

The summarized conclusions of the thesis are below:

1. In the case of bi-directional two nos. inverter interfaced BESSs, power discharged and charged is achieved with drooping the output voltage angles of the converters. Angle droop controllers provide desirable power discharged and charged power with lower frequency deviations [2].

2. The system response can be improved significantly by changing state feedback controller in islanded mode of operation.

3. Power quality of islanded operation of micro grid can be improved significantly by proper reference generation of inverter interfaced BESSs.

4. High droop coefficient can increase the exporting or importing power from inverter interfaced BESSs. It can have beneficial effect on the stability of islanded micro grid.

5. The state of charge of any storage battery in this system is to be maintained within specific limits. Implementation of the new droop line with SOC limits provides a smooth transition for other power generators in both the power export and import cases.

5.2 Scope of future work

Some areas for future work are listed below.

1. The angle drop control scheme can be modified to share power bi-directionally with multiple inverters interfaced BESSs in islanded micro grid consisting of inertia and non-inertia DGs, namely PV generator, wind generator.

2. Protection of inverters interfaced BESSs in case of fault in micro grid can be investigated.

3. Improvement can be achieved by selecting more appropriate input signals or controller gains.

4. A modified droop control can be derived for frequency dependent loads.
APPENDIX

CONVERTER STRUCTURE AND CONTROL

The single phase VSI structure and control used in this thesis from existing publication, thesis and book by other authors are presented in this appendix. This converter is connected to islanded micro grid with an output LCL filter. The converter control techniques implemented in this thesis are state feedback control method.

A.1 Converter Structure

The single phase VSI is shown in Fig. A.1. The converter is connected with Li-ion storage battery denoted by Vdc. The output of the converter is connected with R_lL_clR_1L_1 filter to reduce harmonics shown in fig.A.1.

![Single-phase VSI with state feedback control system](image)

Fig. A.1: Single-phase VSI with state feedback control system

A.2 Converter Control

In this study, inverter current, capacitor voltage and line current of VSI in the islanded micro grid is controlled by means of LQR method. This control is optimal with respect to operating cost of the system, as its objective is to maintain micro grid stability. For tuning the LQRs in a micro grid, fig A.1 is considered.

The LQR control method is chosen for a single phase inverter with an LCL-filter. This controller provides a multivariable proportional regulator. Based on the small signal model of the inverter, the optimal gain matrix of the LQR controller can be obtained by solving a related algebraic Riccati equation (ARE) [89-90]. The detailed design procedure of the LQR
controller is also included in this study. The performance of the inverter system is verified by the simulation results on the Matlab/Simulink platform.

A single-phase full bridge PWM inverter with LCL-filter to reduce harmonics, dc source, load are considered as islanded micro grid in this study. LQR controller is used to regulate the real power to control frequency in the proposed micro grid. A mathematical model describing the islanded operation mode of micro grid can be writing in the following form:

\[
L_f \frac{di_f}{dt} + R_f \times i_f + v_c = (\pm u) u_o ;
\]

(a.1)

\[
C_f \frac{dv_c}{dt} = i_c ;
\]

(a.2)

\[
i_c = i_f - i_1;
\]

(a.3)

\[
L_1 \frac{di_1}{dt} + R_1 \times i_1 + V_t = v_c ;
\]

(a.4)

Where,

- \(L_f\) inverter side inductance;
- \(L_1\) grid side inductance;
- \(R_f\) equivalent series resistor of \(L_f\);
- \(R_1\) equivalent series resistor of \(L_1\);
- \(i_f\) inverter output current;
- \(i_c\) capacitor output current;
- \(i_1\) microgrid side current;
- \(u_o\) inverter output voltage;
- \(v_c\) capacitor voltage;
- \(V_t\) grid side voltage.

Note that there are three state variables are \(i_f\), \(i_1\), and \(v_c\). Choose \(i_1\) as the system output, the state equation can be written as

\[
dx/dt = Ax + B u_o + CV_t;
\]

(a.5)

\[
x = \begin{bmatrix} i_f \\ i_1 \\ v_c \end{bmatrix} ;
\]
The output equation can be expressed as

\[ y = Dx; \]

where, \( y = i_1 \) and \( D = [0 \ 1 \ 0] \).

The above state-space model is valid for large-signal operation. In the steady-state condition, the state variables \( i_1 \), \( i_1 \), and \( V_c \) are all alternate variables, thus the state-space model cannot be used for the LQR controller design directly.

**A.3. LQR Controller Design**

Before designing the LQR controller, we must make sure that the state-space model is controllable and observable. Using the parameters list in the Table I, the state matrix \( A \) and control matrix \( B \) are expressed in Appendix A.2.

For a single-input case, the following linear quadratic cost function is chosen

\[ J = \frac{1}{2} \int_0^a (\Delta x^T Q \Delta x + \Delta u^T R \Delta u) \, dt \]  

(a.6)

Where, \( Q \) is a 3×3 constant, symmetric positive semi-define matrix and \( R > 0 \) is a scalar constant which puts a plenty on maximum control action, a 1×1 symmetric, positive definite matrix. The first item in (3.5) stands for the control accuracy, while the second one for cost of the control effort.

The optimal gain matrix \( K \) is given by

\[ K = R^{-1} B^T P \]  

(a.7)

where \( P \), the 3×3 constant, positive definite, symmetric matrix, is the solution of the matrix algebraic Riccati equation (ARE)
\[ A^T P + PA - P B^T R^{-1} B^T P + Q = 0 \]  \hspace{1cm} (a.8)

From (3.6) and (3.7), \( K \) can be expressed as

\[ K = [k_1 \; k_2 \; k_3] \]  \hspace{1cm} (a.9)

The optimal control law is given by

\[ u = -K\Delta x \]  \hspace{1cm} (A.10)

where, \( u \) is the switching function and is given by \( u = \pm 1 \). The main aim of the converter control is to generate \( u \) from a suitable state feedback control law such that the output voltage and current are tracked properly according to their references. The reference of output voltage and current are considered from power flow conditions.

To control the converter, a discrete time line quadratic regulator has the form

\[ u = -K[x(k) - x_{ref}(k)] \]

\[ =-[k_1k_2k_3] \text{(If I1 vc)} + V_{cref} \]  \hspace{1cm} (a.11)

The converter shown in Fig.A.1 is most suitable for tracking the output voltage, where the voltage reference \( V_{cref} \) can be pre-specified as \( V_t + j*\text{Iref}*wL_1 \) to track \( V_c \). However, it is rather difficult to find a reference (If and I1) for the converter filter current and output current, If and I1. One approach can be to set this reference to zero. This will however lead to incorrect control action. It should be noted that current, if and i1 should only contain lower frequency components, while its high frequency components should be zero. Therefore, if and i1 should pass through a high-pass filter to remove low frequency components.

In order to perform the state feedback control, inverter current(if), inverter line current (i1), and capacitor voltage (vc) are used to generate switching function(u) for battery power discharging and charging operation. To reduce the system cost and simplify design, capacitor reference voltage, \( V_{cref} \) is introduced to generate \( u \) as follows:

\[ u = V_{cref} - k_1*\text{HPF}(if) - k_2*\text{HPF}(i1) - k_3 (vc - v_{cref}) \]  \hspace{1cm} (a.12)
REFERENCE


[10] B.Idlbi,“Dynamic simulation of a PV-Diesel-Battery Hybrid plant for off-grid electrical supply.” A Masters of Engineering thesis submitted to the Faculty Of Electrical Engineering And Computer Science at the University Of Kassel And Faculty of Engineering, Cairo University, 2012.


