Distributed Generation for Energy Harvesting in Distributed Systems using Hybrid Energy Storage

Prabha Ariyaratna
*University of Wollongong*

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Distributed Generation for Energy Harvesting in Distributed Systems using Hybrid Energy Storage

Prabha Ariyaratna, BSc.Eng (Hons)

Supervisors:
Professor Kashem Muttaqi, Professor Danny Sutanto

This thesis is presented as part of the requirement for the conferral of the degree:
Master of Philosophy

This research has been conducted with the support of the Australian Government
Research Training Program Scholarship

University of Wollongong
School of Electrical, Computer and Telecommunications Engineering

March 2019
Dedicated to,

My parents who taught me the value of education.

My husband who persuaded me for higher studies.

My daughter for understanding the hard working mom.
Abstract

The Solar Photovoltaic (PV) generation is one of the fastest growing types of renewable energy sources integrated into distribution systems worldwide and in Australia. Penetration levels of Solar PV systems are increasingly growing with the progressing development in the solar cell technology and the energy storage technology.

The installation of Solar PV at the proper location with its appropriate size is beneficial to the network operator. However, the installation of rooftop solar PV units by residential consumers completely changes the way distribution systems were designed and operated, and therefore it has various impacts on the distribution networks that need to be mitigated. The impact of the rooftop solar PV unit on the voltage profile in the connected distribution feeder is discussed in this thesis. Slow fluctuations (SF) in the voltage profile are caused by the variation of sun irradiation versus load demand. Fast fluctuations (FF) in the voltage profile are caused by the sudden cloud passing.

The rooftop solar PV systems gain the capability to supply electricity during grid outages and to provide ancillary services to the grid, such as voltage control, demand-side management and improvement of the power quality through the integration of energy storages (ES). Consequently, ES increases the capacity of the utility network to host more rooftop solar PV systems.

In this thesis, a low voltage distribution feeder consisting of residential households integrated with rooftop solar PV has been modelled and validated using practical network data.
Initially, a methodology for the simultaneous control of fast and slow voltage fluctuations using a battery energy storage system (BESS) is introduced. The fast voltage fluctuation control and the slow voltage fluctuation control are integrated to mitigate both SF and FF of the rooftop solar PV output using a BESS. The capacity of the BESS was determined based on its 24-hour availability and sufficient capacity to support simultaneous fast fluctuation control (FFC) and the slow fluctuation control (SFC). The methodology for simultaneous FFC and SFC has been validated using both, 24hr data and 7 day data considering the variations of the solar energy versus the residential demand.

At the second phase of the thesis, the sizing of the BESS integrated with solar PV unit to regulate voltage profile, when the system is undergoing both slow and fast fluctuations, was determined based on the solar PV output data and demand variations throughout 24-hour period. A suitable sizing of BESS was determined based on the ability to mitigate both fast and slow fluctuation in the voltage profile, the ability to maintain the charging/discharging rates of the BESS to be within the manufacturer specifications, the fully utilized capacity of BESS with a 10% margin to mitigate unexpected variations in voltage profile, and the ability to assure SoC of the BESS at the end of the day to be same as the initial SoC at the start of the next day.

In the final phase of the thesis, the methodology for the FFC and FFC simultaneously was implemented using a hybrid energy storage system (HESS). The slow fluctuations will be alleviated using BESS and the fast
fluctuations will be alleviated using super capacitor storage (SCS). The inclusion of SCS to the energy storage system provided better flexibility in FFC; however, on the other hand provision of undisrupted FFC became more challenging due to the characteristics of SCS. Accordingly, an improved SoC management control was introduced to ensure undisrupted supply of energy for both SFC and FFC throughout a 24-hour period. The results were validating the methodology for simultaneous SFC and FFC.

The study carried out in this thesis can be highly beneficial for the rising popularity of the rooftop solar PV units towards the cost of voltage regulation of the distribution network. The operational cost of the distribution network may be minimized while allowing more customers to connect to the grid.
Acknowledgments

It is my responsibility to extend sincere appreciation to all who rendered support in numerous ways to make my research project a success. Firstly, I wish to express my sincere gratitude to my supervisors Professor Kashem Muttaqi and Professor Danny Sutanto of the University of Wollongong. I highly appreciate all the time and effort you both invested on me, all the knowledge you shared with me. Secondly and more importantly, I wish to convey my everlasting gratefulness to my mentor Professor Sarath Perera of the University of Wollongong, for giving me the guidance to succeed in my research, career and life. Thirdly, I wish to express my sincere appreciation to Dr. Ashish Agalgaonkar of the University of Wollongong, for the clear and concise communication throughout the tough time. Everything, I learned throughout the journey at the University of Wollongong have strengthen me to be a better and an innovative Electrical Engineer for the Transport industry in NSW.

My heartiest appreciation goes to my mother, Nirosha Wickramasinghe and my farther, Ariyaratna Fernando for always giving me strength, courage and love to pursue in studies. I must thank my husband, Rajeev Gnanarathna for his ongoing support and love throughout my engineering career and life.

Lastly and specifically, my everlasting love goes to my brave strong daughter Felicia Natharie Gnanarathna, for enjoying every bit of this journey. I hope I have been a good example for you to have a look into the life in right direction.
Certification

I, Prabha Madhubhashinie Ariyaratna, declare that this thesis submitted in fulfilment of the requirements for the conferral of the degree of Master of Philosophy, from the University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

_________________________________________

Prabha Madhubhashinie Ariyaratna

13th March 2019
Publications Arising from This Thesis

Journal Publications:

Conference Publications:
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<tr>
<td>AEMO</td>
<td>Australian Energy Market Operator</td>
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<tr>
<td>AER</td>
<td>Australian Energy Regulator</td>
</tr>
<tr>
<td>AGC</td>
<td>Automatic Generation Control</td>
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<td>AMN</td>
<td>Active Management Networks</td>
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<tr>
<td>BESS</td>
<td>Battery Energy Storage System</td>
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<tr>
<td>BS</td>
<td>Battery Storage</td>
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<td>BS&lt;sub&gt;Ah&lt;/sub&gt;</td>
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<td>BS&lt;sub&gt;V&lt;/sub&gt;</td>
<td>Voltage in a battery cell array</td>
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<td>(\frac{dP_{BESS, SF}}{dt}(t))</td>
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<td>The rate of charge/discharge</td>
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<tr>
<td>DG</td>
<td>Distributed Generation</td>
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<td>DNO</td>
<td>Distribution Network Operator</td>
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\[ \frac{dP_{PV}(t)}{dt} \] Power fluctuation of the PV panel at time \( t \)

**DRR** Defined Ramp Rate

**\( E_{BESS} \)** Stored energy of BESS

**EDLC** Electric Double Layer Capacitor

**\( E_{FFC} \)** Required energy for the fast fluctuation control

**EMAP** Euler type Moving Average Prediction

**EMS** Energy Management System

**ES** Energy Storage

**\( E_{SSFC} \)** Required energy for the slow fluctuation control

**ESS** Energy Storage Systems

**EV** Electric Vehicle

**FF** Fast Fluctuations

**FFC** Fast Fluctuations Control

**\( FF_{PV} \)** Fast Fluctuations in Solar PV Output

**HESS** Hybrid Energy Storage System

**HEV** Hybrid Electric Vehicle

**ICCT** Communication and Control Technologies

**LTC** Load Tap Changer

**LV** Low Voltage

**MARR** Maximum defined Ramp Rate

**\( MARR_{\text{max}} \)** Maximum positive value of MARR

**\( MARR_{\text{min}} \)** Minimum negative value of MARR

**NEM** Australian National Electricity Market
OLTC  On-load tap changers
PCC  Point of Common Coupling
PEV  Plug-in electric vehicle
PV  Photo Voltaic
P_{BESS}  Output power of the BS
P_{ES}  Power injected by the ES
P_{inv}  Output of the PV inverter
P_{Grid}  Power obtained from the grid
P_{Load}  Power absorbed by the residential load
P_{PV}  Power generated by the solar PV
PVRR  Ramp Rate of PV
P_{PV} (t)  Power output of solar panel at time t
P_{PV} (t - \Delta t)  Power output of solar panel at previous time instance
SC  Super Capacitor
SCS  Super capacitor storage
SF  Slow Fluctuations
SFC  Slow Fluctuation Control
SF_{PCC}  Slow Fluctuations in the Voltage Level at PCC
SFVFC  Slow and Fast Voltage Fluctuation Control
V_{BS} (t)  Battery voltage
VR  Voltage Regulators
V_{DC-link}  Voltage level at DC link
\eta_{inv}  Inverter Efficiency
\alpha  Rate of charging of BS
| \( \beta \) | Rate of discharging of BS |
| \( \rho \) | Decision variable on the voltage range of \( V_{PCC} \) |
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Chapter 1

Introduction

1.1 Statement of the problem

Renewable energy has become a vital element in the search for solutions to reduce global warming and to combat the environmental issues caused by fossil-fuel consumption. The expansion and the development of renewable energy technology to compensate the fast transfer from fossil fuel will assure the sustainable energy supply for the industrialization and basic human needs. The photovoltaic (PV) generation at consumer premise has gained momentum recently and will become increasingly attractive for consumers as long as self-produced electricity and self-consumed load is not charged or taxed [1]. The percentage of solar generation is not yet considerably high in Australia, currently about 15% of the total renewable energy market [2]. However, it is expected to grow rapidly due to the wide spread installations of rooftop solar PV and solar farms of various scales (e.g. utility scale, medium scale, etc.).

Power distribution systems are traditionally designed to operate in a radial manner and therefore it is necessary to study the impacts of solar PV on the system and to plan to overcome these impacts. Depending on the penetration level, impact can be local (e.g. at the individual feeder, substation level) or system wide (e.g. affecting several feeders, sub-transmission network, etc.). The impacts of the solar PV generators can be either steady state or dynamic. The voltage profile of the power distribution feeder is determined by the combination of the centralized generation,
solar generation and the load. Voltage rise and reverse power flow occur when the
distribution network become more active with the power flows. The variations in the
voltage profile of the individual feeder, outside the operating voltage range cause
frequent operation of voltage control and voltage regulation devices such as load tap
changers (LTC), line voltage regulators (VR), etc. Moreover, the voltage rise and the
reverse power flow cause mal-operation in the overcurrent protection and the
overvoltage protection equipment. Depending on the penetration level of the solar
PV generation, the degree of the impact is varying. Reactive power fluctuations
occur as a result of the operation of switched capacitor banks in the distribution
networks, where the solar generators are connected. Also, the power output
fluctuations (specifically, fast fluctuations) cause frequent operation in the LTC and
the switched capacitor banks as they race to maintain the power quality [3-7].

Typically, due to frequent operation to overcome voltage rise and fluctuation issue,
depreciation of the instruments occur faster than manufacturer lifetime.

Rooftop solar PV generators supply a portion of the residential household load
demand which relieve the stress level of a distribution feeder. Having distributed
rooftop solar generators over the network improves the system performance by
generating energy to meet the load demand whilst reducing the feeder losses by
maintaining approximately steady voltage profile where feeder is not heavily loaded.

Generally, when there is no solar PV installed along the feeder, the voltages in the
distribution feeder reduce from the substation towards the remote end. However,
when the PV generation is higher around midday excess power might be present at
the point of common coupling (PCC) causing the current to flow back and hence
produces voltage rise along the feeder [4, 7-10]. Distribution feeders are expected to
operate within voltage limits stipulated by the local regulations and standards. The voltage rise in midday can cause such limits to be violated where the distribution feeder is heavily loaded and weak.

Solar PV generation can be highly intermittent due to variations in solar irradiation and insolation caused by sudden cloud passing. The effect of the intermittent behavior of the solar PV output lead to significant voltage fluctuations when the solar PV penetration is higher in weak radial distribution systems. This scenario exists when the variability of the intermittent PV generation is the dominant factor in deciding the need for substation, network or control upgrades compared to variability of load demand. The reduction in the solar irradiation and the insolation might cause sudden drop of PV generation by 60% within few seconds in some cases. Time taken for cloud passing is dependent on sun elevation, wind speed and distance to the cloud. The variability in the solar PV generation is considered insignificant on a cloudless day. On the contrary, the intermittency in solar PV generation is highly considerable during a cloudy sunny day due to drastic variations in solar insolation and irradiation [11].

Various mitigation techniques have been discussed in literature for the mitigation of voltage rise and voltage fluctuations. The control settings of capacitor banks can be modified to stay off during the periods of maximum PV generation to avoid unnecessary operation of the capacitor banks in the process to maintain the voltage profile of the specified local distribution network. Similarly, the settings of LTC can be modified. Also, the use fixed capacitor banks should be avoided if there is a high penetration of PV generation [3-4]. The operation of solar PV generators at non-unity leading power factor for the absorbance of reactive power have been discussed in [3-
5, 7, 12] to alleviate the voltage rise and voltage fluctuations. The reduction of the utility series impedance by using larger or multiple conductors, using more transformers or transformers with larger derating factor have been discussed as the most logical solution for the mitigation of voltage rise on electricity networks [4, 12]. PV inverter settings are modified to fold back the PV generation by using an energy management scheme that incorporate load shedding [4]. Forecasting of PV generation and the curtailment of PV generation are required for a stable operation of the power system when the penetration level of the PV generation becomes high [11]. The utilization of energy storages (ES) has become popular as the solution to mitigate voltage rise and voltage fluctuation in recent research activities [6, 8-10, 13-18].

The requirement to utilize an ES to allow the constant power production in a PV power plant is investigated in [8]. The utilization of distributed ES with the rooftop solar PV is reported in [14] to mitigate the voltage rise in the distribution feeder during midday. The excess energy is utilized to charge ES during midday and the stored energy is discharged in the evening peak load to reduce the burden on the grid. The power threshold to activate charge/discharge process of the ES has been identified based on the purpose to avoid violations of safe operational voltage range [9]. Voltage control strategies in the local feeder by using battery energy storages that are integrated to rooftop solar PV generators are discussed in [7, 15, 16].

The ramp Rate (RR) is the rate of change of solar PV output during an event of voltage fluctuation due to slow or fast intermittency. The ramp rate can be negative or positive and high or low depending on the PV output at the start of the ramp and the PV output at the end of the ramp. Battery energy storage system (BESS – note
that BESS and BS are interchangeably used throughout this thesis) has been suggested as a solution to mitigate some of the integration challenges of solar PV such as ramp rate, frequency by providing voltage stability through dynamic VAr support and frequency regulation through droop control [13]. A control strategy using a BESS for the alleviation of ramp rate of PV output is introduced for both ramping event and post ramping event using dynamic control [10]. The desired ramp rate is maintained by controlling the amount of energy charged or discharged based on an inverse relationship to mitigate the impact of fluctuation. If the ramping event is positive and increasing, energy to store/release is negative and decreasing. Voltage rise/dip problems are addressed by the coordinated use of PV inverters and BESS in [16] considering both rural and urban scenarios. The reactive capability of the PV inverter and the droop based BESS are also studied in [16]. Sudden ramping events can be controlled with the use of capacitors instead of using BESS. This can improve the lifetime of the battery storage (BS) and the total system. The use of electric double layer capacitor (EDLC), fuel cell and PV system is proposed in [17] to ensure the voltage stability and uninterruptible power supply to customers by employing modified Euler type moving average prediction (EMAP) model. The utilization of EDLC to limit the ramp rate of the solar PV output is proposed in [19-20]. A study on the sizing solar PV unit and an effective ES to control different ramp rates has been reported in [18] for specified AC power fluctuations.

The design of a hybrid energy storage system (HESS) that consist of two energy storages, typically one ES is dedicated for “high power” fluctuations in voltage profile, while second ES is dedicated for “high energy” requirements in load demand. The HESS technology for renewable energy applications [21-25] and for electric
vehicle applications is discussed in [25-29]. There are various HESS coupling architectures in literature. Various types of HESS architectures with different energy storage combinations of super-capacitor, li-ion battery, lead acid battery, hydrogen storage and hot water heat storage have been studied in [21]. HESS coupling topologies for battery and ultra-capacitor are discussed in [21-22], [29-31] while comparing advantages and disadvantages of economical operation. In [22], HESS topologies are compared based on internal losses that occur at the smoothing operation.

1.2 Aim of the Research Work

Modern day electricity consumers are driven by the strategy to reduce the energy bill by installing solar PV on the rooftop. Usually, the rooftop solar PV inverter exports excess energy generated during midday when generation is higher than the household demand; import deficient energy from grid during peak hours when generation is lower than the household demand. Also, the rooftop solar PV generators cause sudden fluctuations in the voltage profile due to cloud passing. These scenarios cause voltage rise and drop in the distribution network causing voltage regulation devices to operate more frequent than usual.

1.2.1 Ramp rate control of rooftop solar PV output while regulating voltage in the feeder and minimizing the Solar PV output curtailment

As mentioned earlier, many researchers have worked on slow fluctuations and fast fluctuations in the context of renewable energy generation. However, majority of the work is done on the wind generation. Moreover, most of the works have addressed either slow fluctuations or fast fluctuations problem only. In addition, the ramp rate
control mechanism has not been incorporated with the voltage regulation in the present research space. There should be a proper charge/discharge mechanism to control both slow fluctuations and fast fluctuations in the voltage profile of the distribution feeder. With the increasing demand for rooftop solar PV generators in Australia, penetration levels of grid connected solar PV are drastically growing. Hence, there is an urgent requirement for methodologies to mitigate slow fluctuations and fast fluctuations of solar PV output, to avoid unnecessary burden on electricity network. Majority of rooftop solar PV units are installed with BS in Australia due to cost savings in installation produced as a result of the introduction to government incentives and the continuing drastic drop in BS manufacturing cost. Therefore, it will be advantageous to use the already available BS for the control of slow and fast fluctuation. This feature adds the industrial value to the proposed methodology.

1.2.2 Effective sizing for energy storage to support the LV distribution grids

The effective sizing of the BS to facilitate the slow and fast fluctuation control is determined; based on the Solar PV generation, the residential load demand, the technical constraints of BS and the availability of BS for a non-disrupted energy transfer throughout entire day period. The selected time period for the study is 24 hours. Over-sizing or the under-sizing of the BS reduces the efficiency of the solar PV unit which is integrated with BS. The effective sizing of BS improves the cost effectiveness of the unit whilst improving the lifetime of the BS, increasing the energy efficiency of the system and enhancing the return on investment for solar PV unit integrated with BS.
1.2.3 Ramp rate control of rooftop solar PV output while regulating voltage in the feeder using HESS

The idea of using HESS is to incorporate the advantageous properties of two different types ESs to complement each other. Accordingly, high power ES and high energy ES usually combines to create a HESS. As mentioned above, both ramp rate control and voltage control in the distribution feeder will be performed using a BS. However, with the limited physical capability of BS, it might not be capable to support ramp rate control when the output of solar PV generator increases. As BS is not designed for high power operations, the lifetime of BS (number of operating cycles) can drastically go down causing a higher operational cost. Hence, with the increasing demand for rooftop solar PV generators and the increasing size of the generators, it is essential to design a HESS with the BS and the super capacitor (SC) to achieve both ramp rate control and voltage control in the connected distribution feeder.

1.2 Research Methodology and Specific Contribution

The research aims as mentioned above are planned to be achieved through the development of methodologies discussed below. The key contribution of this work is to develop methodologies to mitigate slow and fast fluctuations of the voltage and the power in the low voltage distribution feeder caused by the variations in the solar PV output and the residential load demand.

At the first stage, the voltage fluctuation problem is addressed using lead-acid BS. The methodology for the mitigation of fast fluctuations is based on the slope of raw solar PV output and the specified slope of the inverter output. Accordingly, the BS is
charged/discharged to mitigate fast fluctuations. Simultaneously, the mitigation of slow fluctuations is determined based on the voltage level at the PCC in the connected low voltage feeder. The voltage level at the PCC is used as the control variable. The BS is charged/discharged based on the level of voltage at the PCC in a given time instance. Both fast fluctuation control and slow fluctuation control are integrated to regulate voltage in the connected feeder while controlling the ramp rate.

At the second stage, the suitable size of the BS for the mitigation of simultaneous fast and slow fluctuation is explored. The sizing of BS is determined based on the varying solar PV output and the varying residential load demand, leading to fast and slow voltage fluctuations. The sizing of BS is based on the,

- Ability to mitigate both fast and slow fluctuations in the voltage profile
- Ability to maintain the charging/discharging rates of the BS to be within the manufacturer specification
- Ability to fully utilize the capacity of BS with a 10% margin to mitigate unexpected variations in voltage profile
- Ability to assure the state of charge (SoC) of the BESS at the end of the day is same as the initial SoC at the start of the same day.

At the last stage, the fluctuations in voltage and power output is addressed using HESS. The implementation of an energy management methodology to manage lead-acid battery and ultra-capacitor in HESS is explored while considering a required level of energy transfer at the PCC. In this thesis, HESS is developed and modelled incorporating SOC limits, charge/discharge current limits and voltage limits of both energy storage systems in HESS to mitigate fast and slow fluctuations at the PCC. The charge/discharge strategy for the BS is developed based on voltage control to
mitigate slow fluctuations while the charge/discharge strategy for SC is developed for the mitigation of fast fluctuations in voltage profile. Both charge/discharge strategies are coordinated for the effective control to mitigate fast and slow variations in voltage profile simultaneously.

MATLAB software tool is used for modelling of the network to test the research methodologies developed in this study.

1.3 Outline of the Thesis

A brief description of the remaining chapters is given below.

Chapter 2 is the literature review providing an overview of rooftop solar PV generation and the distributed solar PV generation on MV/LV distribution systems. Impacts and present limitations/challenges of the existing technologies are discussed. In addition, electricity tariff is also being briefly discussed. Furthermore, the energy storage systems for grid connected rooftop solar PV generation; specifically hybrid system with battery storage and ultra-capacitor storage system are discussed. Moreover, the operation of rooftop solar PV system at the PCC with and without ES is analyzed.

In Chapter 3, a methodology to mitigate both fast and slow fluctuations in the distribution feeder is discussed. In this methodology, the slope of the solar PV inverter output, as well as the voltage level at the PCC is controlled using a single BESS. The methodology is discussed in detail in this chapter including the slow and fast variations in PV output and the mitigation using BESS which are also demonstrated through case studies.

In Chapter 4, a methodology to determine a suitable size of BESS for the purpose
mentioned above is proposed. Accordingly, there are four criteria in consideration for the optimization of BESS; ability to mitigate both slow and fast fluctuations in the voltage profile without any disruption, ability to charge/discharge BS within manufacturer constraints, fully utilize BS with allowing 10% margin for unexpected fluctuations and ability restore SoC back to initial level at the end of 24hour period. Chapter consists of the proposed strategy for the sizing of the BESS to regulate voltage at the PCC and its validation through case studies.

Chapter 5 discusses the methodology to mitigate both fast and slow fluctuations using HESS. Accordingly, the fast fluctuations are mitigated using SC and the slow fluctuations are mitigated using BESS. The chapter consists of the system description and modelling, management of SoC levels of HESS to ensure undisrupted slow and fast fluctuation mitigation, and the implementation of the proposed method and its validation through several case studies.

Chapter 6 is the last chapter which summarizes the major outcomes and the prospective future work of the thesis.
Chapter 2

Literature Review

2.1 Introduction

This chapter presents a summary of the reviewed literature related to the distributed solar PV generation in MV/LV distribution networks and ES integration with solar PV. The major contributions produced by other researchers on ES and solar PV in MV/LV distribution networks are critically examined in order to identify the research gaps for further research. The operation of solar PV system at PCC with and without ES is also discussed in a later stage of this chapter.

2.2 Distributed Solar PV Generation in MV/LV distribution Systems

The solar PV generation is one of the fastest growing renewable energy sources worldwide. When compared to other renewable energy sources (wind energy, geothermal energy, ocean tidal energy, hydro energy, etc.) solar energy is cheaper and readily accessible by residential customers. A majority of solar PV systems in Australia are small-scale and used by residential customers. Moreover, the popularity for commercial rooftop installations is increasing too. With the costs continually decreasing and the efficiency continually increasing in solar PV systems, the penetration of solar PV systems is also increasing [32]. The total solar PV capacity in Australia has reached 6 GW and is expected to be double over the next few years. The rooftop solar PV capacity has now reached 5.6 GW and large-scale solar capacity is now 496 MW and growing very fast [34].
2.2.1 An Overview of Rooftop Solar PV Generation

Several advantages can be obtained by maintaining a grid connected solar system. Feed in tariff is decided by the retailers. The selection of solar PV unit for a suitable generation capacity depends on few variables such as the residential load demand, rooftop area, shading losses, etc. A typical layout of a grid connected rooftop solar PV generator system is shown in Fig. 2.1.

![Figure 2.1: A typical arrangement of a grid connected rooftop solar PV system](image)

The solar PV energy is energy converted from sunlight to electricity. Solar panels convert the energy of sunlight into DC electricity. The main building block of a solar panel is PV cells where a conventional PV cell is made of semiconductor materials such as silicon that has a photovoltaic effect [33]. The solar panels interface with the grid through an inverter, an inverter mainly converts the DC electricity into AC electricity. Through the main switch box, AC energy is distributed to the consumer loads such as appliances and lighting, or other devices where needed. The power meter measures the energy absorbed from the grid and the energy injected into the grid.
In general, the active power balance of the grid connected rooftop solar PV system can be described by (2.1).

\[ P_{\text{Grid}} = P_{\text{Load}} + P_{\text{PV}} \]  \hspace{1cm} (2.1)

Where \( P_{\text{Grid}} \) is the Power obtained from the grid, \( P_{\text{Load}} \) is the power absorbed by the residential load, and \( P_{\text{PV}} \) is the power generated by the solar PV.

Accordingly, when power generation from solar PV is higher than the residential load demand the excess energy will be added to the distribution system. Inversely, when the residential load is greater than the power generation from solar PV, the energy will be supplied from the distribution grid.

**2.2.2 Impact of Rooftop Solar PV Generation on MV/LV distribution networks**

Electricity distribution systems in the utility industry are traditionally designed to operate in radial feeding arrangements. Therefore, grid connected intermittent energy sources such as rooftop solar PV generation may cause impacts that need to be studied and planned for [34]. The installation of DG with a proper size in the proper location is beneficial to the DNO, especially for improvement of the voltage profile, reduction in losses, removal of the need to transmit bulk power, etc. [32]. However, the installation of rooftop solar PV units in the distribution network may not necessarily be providing benefits only; there are various impacts on the networks that need to be mitigated [3, 11, 13, 20, 32-39]. Also, the grid connected rooftop solar PV units add additional challenges to the distribution system design and operation.
2.2.2.1 Impacts on Voltage Profile

The voltage profile of the electricity distribution network is a vital criterion to ensure the safety and the sustainability of the operation of consumer equipment connected to the grid. Voltage rise and voltage drop [3, 32, 37, 38] can occur in the connected distribution feeder depending on the penetration level of the grid connected rooftop solar PV units. Voltage rise condition occurs when the solar PV generation is higher than the load demand of the specific feeder. This condition can be severe enough to trigger reverse power flow to the grid causing costly damages to protection equipment. Voltage drop conditions occur when the effective load is high (PV output power becomes zero at the evening when the residential load demand increases). Voltage rise and drop problem could be severe in highly loaded feeders.

The power output from solar-PV units has significant impact on system voltage profiles. The intermittent power output form solar-PV unit causes voltage fluctuations which complicates the Volt/VAr control and subsequent operation of the distribution systems. This is one of the major challenges for distribution system operators (DNOs) in the presence of increasing penetration of solar-PV in the distribution systems. The variations in solar-PV power output are mainly caused by stochastic phenomenon such as solar irradiation and insolation patterns, passing clouds, and dust contamination on solar-PV cells. The associated solar-PV power output variations can be categorised as slow-variations and rapid-variations. The slow variations are mainly caused by daily movement in sun leading to sun-rise and sun-set. The rapid variations are mainly caused by passing clouds. It is evidenced that clear and dark sky conditions have less effect than that of partly cloudy days where irradiance rapidly fluctuates almost instantaneously [11]. However, distributed
solar-PV units with similar capacity may have less effect [37]. Hence, the impact of solar-PV, especially on voltage profiles of the distribution systems, can be significant in urban or semi-urban areas in the presence of highly dense solar-PV penetration.

Detailed study to determine the acceptable penetration level of solar PV has been conducted in [39] for some selected feeders taking voltage level as one parameter. Study has been mainly undertaken in two parts; first, without solar PV generation and second, with solar PV generation. Hosting capacities of the grid for certain penetration levels have been identified for the selected area.

2.2.2.2 Impacts on voltage-control and regulation devices

Regulating the service voltage at the point of common coupling (PCC) is important, for the safety and sustainability of customer equipment. However, customer may provide sufficient immunity to the equipment through taking proper precautions against storms, lightning and partial loss of supply. The service voltage at PCC is expected to be within the ‘standard voltages’ according to AS60038; however the DNO has the freedom to specify it differently based on their specific circumstances. Table 2.1 contains the typical low voltage supply range in NSW.

Table 2.1: Typical Low Voltage Supply Range in NSW

<table>
<thead>
<tr>
<th>Percentage of Time</th>
<th>Voltage Range (Percent)</th>
<th>Voltage Range (Phase to Neutral)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99%</td>
<td>+10% to -6%</td>
<td>253V to 216 V</td>
</tr>
</tbody>
</table>
Automatic generation control (AGC) is used for voltage regulation during the generation process. AGC is capable to quickly change the generation output (MW/min) by tracking the momentary fluctuations in customer loads. Therefore, AGC ensures to avoid against unexpected fluctuations in generation up to certain accuracy. Equipment such as voltage regulators and capacitor banks are used at some feeders to improve the voltage profile by stepping up or stepping down the voltage level. Voltage regulation and voltage control devices usually permit the modification of distribution feeder operating conditions via automated monitoring systems. However, due to increased operation for voltage control and regulation in highly penetrated feeders with rooftop solar PV, this equipment could experience significant reduction of the lifetime due to the mechanical stress associated with each operation [36].

2.2.2.3 Impacts on Losses and Line Loading

The losses are an important issue in distribution networks. The network components are heated up by losses causing the reduction in their design life, and hence the energy loss has to be reduced. Essentially, the energy due to active power losses need to be supplied by the energy sources by generating more power. Hence losses should be maintained as low as possible.

Distributed rooftop solar PV generators in the distribution networks alter the structure of power flows from being radial to bidirectional. The current flowing in the feeder and the resistance in the line are the decision parameters of the magnitude of line losses. Therefore, the reduction of either line current or resistance or even both can reduce line losses. The increase or decrease in losses is depending on the capacity of distributed rooftop solar PV generators, their locations, the load variation
and the network structure [40]. Moreover, the effect of distributed rooftop solar PV generator capacity proportionally varies with the penetration level of generators. The higher the penetration levels results in a higher effect and vice versa.

2.2.2.4 Impacts on overcurrent and overvoltage protection

The sensitivity and selectivity are the major factors to be considered when considering the impact of solar-PV power output on over current and over voltage protection. The power output fluctuations in distributed solar-PV units have definitive impact on the sensitivity and selectivity of the protections to be applied; and thereby dynamic adjustment of control settings of adequate protection devices will be required for safer operation of the distribution systems. In this context, adaptation of smart grid infrastructure will help DNO many ways.

Hence, distribution network limits the amount of rooftop solar PV connected to the network. The maximum allowable penetration level or the hosting capacity is determined by the overvoltage and over current limits in the distribution network [41].

2.2.2.5 Impacts on Steady State Voltage Stability

Most urban and semi-urban distribution networks are weaker in terms of demand management, network arrangement with light/heavy loading conditions and with low short-circuit capacity. Therefore, the amount of power that can be injected/absorbed to the system is restricted to ensure the stability of the system is not compromised. Hence, the installation of rooftop solar PV unit has significant impacts on the electricity network in terms of the system reliability. Accordingly, the increasing
penetration levels of rooftop solar PV unit installations may create stability problems in the electricity network.

DNOs have introduced “hosting capacity” to avoid unnecessary stability issues due to uncontrolled installations of rooftop solar PV units. Hosting capacity is the capacity of specific distribution system to host intermittent sources such as rooftop solar, energy storage and electric vehicles.

2.2.3 Present Limitations and Future Directions to Overcome Challenges

It is very clear that technical, economical and regulatory barriers need to be observed for effective deployment of rooftop solar-PV units in the distribution systems assuring smooth migration. In literature, there are solutions proposed for addressing those issues. In [3, 34, 35], in-depth analyses have been carried out considering the impact of small scale solar-PV penetration levels in the distribution systems concluding some feasible solutions to the adverse problems. In [3, 34, 35], the importance of adaptive control systems in synchronous generators [41, 32, 38] is highlighted. The use of artificial intelligence and cloud computing systems are proposed in [42, 43]. Moreover, in [44, 45] novel controls and algorithms are proposed for distribution systems embedded with high penetration of solar-PV. Adaptive optimisation is one of the viable options for the tuning of controller parameters of inverters of solar-PV units, Volt/VAr control devices and the protection devices [46, 47]. The challenges for regulators to maintain a fostering balance between innovation and customers’ satisfaction have been analysed in [48, 49] to highlight the requirement for a new technical and regulatory framework. However, still there is an urging requirement of a global strategy.
Accordingly, the necessity of further technical development in the operation of solar-PV inverters is emphasised. In this context, integrated energy storage (ES) with PV and its optimal control are promising outcomes. The optimisation can also aid to overcome technical and economic barriers. However, as it is known, the optimisation methods do have their own barriers, such as computational burdens depending on the adopted optimisation, and complexities in modelling and simulations depending on the power system and its controls. Moreover, in the context of system protection, the challenges associated with bi-directional power flows especially in radial topologies, grid connected and islanded modes of operations, intermittent power generation and associated topological changes yet to be addressed. Furthermore, the installation of rooftop solar-PV generator units lead to increased losses and costs, complications in Volt/VAr controls, and poor system reliability and stability. The proposed heuristics and optimization techniques are formulated considering economic, technical and environmental factors. However, in reality, the model based approaches have their own limitations. In practice, the main challenges are caused by complexity and inherently varying characteristics of the power systems. Therefore, most researchers have considered scenarios, and proposed solutions to reduce the associated computational and modelling barriers. In the context of system controls, as a remedy, active management networks (AMN) is dominantly proposed and they are supported by decentralised (or centralised) control, and information, communication and control technologies (ICCT). However, AMN possesses many challenges, as it is still in its infancy. The key question is the level of required change to the present market to support AMN. In the longer term, a price-based approach will benefit both industry operators and consumers for the promotion of rooftop solar-PV integration.
In this context, in summary, ES will unquestionably have strategic importance in future electrical power systems. Hence, ES will provide added value to non-controllable renewable energy sources, in this study, rooftop solar-PV generation. ES will allow the DNO to accommodate larger penetration of rooftop solar-PV, and thereby improve flexibility to meet the demand and system operational requirements resulting higher reliability and hosting capacity of solar-PV.

2.4 Energy Storage Systems for Grid Connected Rooftop Solar PV Generation

The integration of ES to the rooftop solar PV systems adds value by providing the capability to supply undisrupted electricity during power outages caused by severe weather conditions such as storms or other emergency stability issues situations. Moreover, the integration of ES adds the advantage in the provision of:

- Ancillary services, specifically voltage control
- Management of the demand
- Improvement of the power quality.

Simultaneously, ES increases the capacity of the utility network to host more rooftop solar PV systems.
2.4.1 An Overview

Numerous research works have been carried out during recent years based on grid connected solar PV generation and ES systems. ES is mainly used to mitigate issues in the connected network due to intermittency of the solar PV output. The solar PV output can be categorised into two types of intermittencies as below:

Slow intermittency (low frequency): Slow intermittency of the solar PV output occurs due to slow movement of the sun from the sun rise to sun set. The solar PV output in a given time instance is based on the sun insolation and sun irradiation, which follows a predictable pattern of 24 hour duration. The pattern of sun insolation and sun irradiation vary with the season in Australia. Figure 2.2 depicts the variation in sun irradiation throughout a selected day in summer and winter for the area of Wagga Wagga in NSW, Australia.

![Figure 2.2: Difference in solar radiation levels across the day between summer and winter for Wagga Wagga, NSW][50]

Accordingly, the pattern is similar with the difference in the span of the duration and the strength of the irradiation.
Fast intermittency (high frequency): Fast intermittency of the solar PV output occurs due to sudden variation of sun insolation and irradiation due to cloud passing. The number of occasions and the severity of intermittencies within a selected period depend on how frequent the clouds interrupt the sun. In fact, a fully rainy/cloudy day will have less fast intermittencies than a sunny but intermittently cloudy day. Fast intermittency profile varies significantly for each day and each instance and hence is not predictable. Figure 2.3 illustrates solar PV output for five consecutive days. Accordingly, the PV generator has been generating highly intermittent solar PV output in Day 1 to Day 3, caused by the presence of intermittent clouds. The PV generator has been generating smooth (visibly) solar PV output in Day 4, as it was a clear sunny day. The PV generator has less intermittent solar PV output in Day 5 due to presence of fewer amounts of clouds and also the day has been sunny.

![Graph showing solar PV output across five days](image)

Figure 2.3: Difference in solar PV output levels across cloudy and sunny days

There are many challenges attached with the mitigation of fast intermittencies specifically due to unpredictability.
The ES system used to mitigate slow and fast intermittencies depends on the characteristics and the physical capability of the ES, which will be discussed in the next sections.

2.4.2 Battery Storage Systems

BS systems are widely used and well-suited storage technology for rooftop solar PV applications. The majority of the research work and the practical application of the BS in the context of rooftop solar PV generation focus on energy management through peak generation and peak demand periods [51, 14, 52]. Different techniques such as reference power output [51, 14] and reference voltage level [52] have been used to charge/discharge BS to manage energy for the grid support to avoid voltage rise/drop in the connected feeder.

In this work, Lead Acid BS will be used. The initial cost of Lead Acid battery technology is less than most other battery technologies. Moreover, the cost per Ah is less in lead acid battery compared to other battery technologies which is the key reason for lead acid batteries to be widely used in renewable systems where larger storage capacities are required.

Battery Voltmeter

Battery voltameters are inexpensive and easy to install. Battery voltmeter readings can be turned into a reliable assessment of the battery state of charge (SoC). Battery voltmeter readings must be tracking small details to extrapolate information through those details [50]. Battery voltage is affected by SOC, current and temperature. Every electrochemical cell in the battery has an internal resistance. The cell voltage varies with the internal resistance as the current flows through the cell. The cell
voltage increases faster if the charging current flow is higher, the cell voltage decreases faster if the discharging current flow is higher.

During this work, we have used the characteristics generated for 350 Ampere-hour (Ah) lead acid cells. The voltage of a single cell is 2V. Hence, 6 numbers of cells are connected in series to make 12V lead acid battery of 350 Ah.

2.4.3 Super Capacitor Storage Systems

Super capacitors (SC) are also known as an Ultra capacitor or Electric Double Layer Capacitors. The super capacitor storage (SCS) are devices with large capacitance; the capacitances might be several thousand farads, for example 12000 farads. Conventional capacitors are considered as high power density devices where battery storages are considered as high energy density devices. However, SCS consist of characteristics of both conventional capacitors and battery storages and therefore, fills the vacuum of missing devices to meet both energy and power density requirement. This is comprehended in Table 2.2 with facts. In addition, SCS have a higher cycle life compared to batteries which makes them economically attractive due to low maintenance/replacement cost.
Table 2.2: Battery, Super Capacitor and Conventional Capacitor characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lead Acid Battery</th>
<th>Super Capacitor</th>
<th>Conventional Capacitors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy (Wh/Kg)</td>
<td>10-100</td>
<td>1-10</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Specific Power(W/Kg)</td>
<td>&lt; 1000</td>
<td>&lt; 10000</td>
<td>&lt;100000</td>
</tr>
<tr>
<td>Cycle Life (cycles)</td>
<td>1000</td>
<td>&gt;500000</td>
<td>&gt;500000</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.7 - 0.85</td>
<td>0.85-0.98</td>
<td>&gt;0.95</td>
</tr>
<tr>
<td>Discharge time</td>
<td>0.3-3 hrs</td>
<td>0.3 - 30s</td>
<td>10^{-3} to 10^{-6} s</td>
</tr>
<tr>
<td>Charge time</td>
<td>1-5 hrs</td>
<td>0.3-30s</td>
<td>10^{-3} to 10^{-6} s</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-120 to 100 C</td>
<td>-40 to 65 C</td>
<td>-20 to 65 C</td>
</tr>
</tbody>
</table>

The high power density and low energy density of SCS cause the application of SCS to obtain pulsed loads. In addition, SCS are the most effective device to obtain energy for a duration in the range of $10^{-2} < t < 10^2$ s [53]. Otherwise, it will require batteries and traditional capacitors to be oversized to provide energy within such duration. A few potential applications of super capacitors are mentioned below:

- UPS applications where power during short duration interruptions is provided using SC.
- Power conditioning applications where voltage sags on the system are filtered using SC.
- Pulsed power output for applications with intermittent renewable sources such as solar and wind.
- Pulsed power output for applications such as Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) during acceleration and regenerative braking.

During this work, SC will be used to provide power bursts during intermittencies in rooftop solar PV systems. Maxwell K2 series 3400F (Farad) SC is used in [54]. The voltage of a single SC is 2.85V. Typical stored energy in a single SC is 3.95 Wh (Watt hours).

2.4.4 Hybrid Battery and Super Capacitor Storage System

During the latter stage of this thesis (Chapter 5), Hybrid Energy Storage System (HESS) is used to mitigate both slow and fast intermittencies of the voltage profile in connected LV feeder. BS can be used with both slow and fast intermittencies when the highest possible fast intermittency is within the technically capable limit of the BS, which does not affect life time of BS (Chapter 4). However, this cannot be guaranteed, especially with the boom in the solar PV industry, household rooftop solar PV capacity tends to get higher with the advancement in PV cell technologies. Hence, the SC capability of handling fast intermittencies must incorporate in to the ES.

Three main categories of topologies for HESS have been discussed in literature [55-56]. Each category consists of several sub categories of HESS topology. There are
advantages and disadvantages and each topology. Main points of advantages and disadvantages of each topology are discussed below as a guide line for the selection of topology used in Chapter 5.

Figure 2.4: Difference HESS topologies discussed in literature
2.4.4.1 Direct connected topology of Battery Storage (BS) and SCS

Figure 2.4 (a) depicts the illustration of this topology; which is the most basic way of connecting two different ESs. Advantages and disadvantages are discussed below:

Advantages:

• Only small and slow voltage fluctuations present.
• The control system is significantly simple.
• Simple and least cost construction.

Disadvantages:

• Fast deterioration of the operation and the lifetime of the battery due to exposure to extremely large sudden fluctuations in discharge/charge currents.
• Lack of overall efficiency due to limited functionality of SCS.
• System optimization is not achievable due to the absence of a power management mechanism between BS and SC.

2.4.4.2 Partially decoupled topology of BS and SCS

In partially decoupled topology, DC/DC converter is used to decouple BS or SCS from the DC link; topology I in Figure 2.4 (b) and topology II in Figure 2.4(c) offer the following major advantages compared to the topology in Figure 2.4 (a).

Topology I illustrated the direct connection of the SCS, and BS connection via DC-DC converter to the DC link.
Advantages:

• Improved immunity of BS to face heavily fluctuating charge/discharge currents.
• Improved controllability of the BS power output.
• Ability of SCS to charge/discharge to mitigate sudden fast fluctuations.

Disadvantages:

• Heavy losses at the DC/AC converter due to large voltage fluctuations caused by direct connection with SCS.

Topology II illustrated the direct connection of the BS, and SCS connection via DC/DC converter to the DC link.

Advantages:

• The improved controllability of SCS due to connection via DC/DC converter.

Disadvantages:

• Reduced life time of BS due to exposure with high fluctuations in charge/discharge current.
• Higher overall cost due to higher power rating of the DC/DC converter to address comparatively higher power requirements of SCS.
2.4.4.3 Fully decoupled topology of BS and SCS

In this topology, both BS and SCS are decoupled and power requirement is shared. This topology facilitates the full control, and therefore, the overall performance of the system is improved. More importantly, the life time of BS will be enhanced. However, the construction cost is significantly higher and the losses are increased due to the use of large number of semiconductor devices and passive elements.

There are several categories of fully decoupled topologies which are shown in Figure 2.4(d) to Figure 2.4(g). Advantages and disadvantages can be summarised as below,

The topology illustrated in Figure 2.4 (d) is the Parallel BS and the SCS decoupled using a DC/DC converter.

Advantages:

- Higher controllability of the power output

Disadvantages:

- Inefficient operations of SCS
- Shorter battery life time

The topology illustrated in Figure 2.4 (e) is using Cascade DC/DC converters to decouple BS and SCS.

Disadvantages:

- Potential stability issues due to constant power output
- Higher losses [55]
The topology illustrated in Figure 2.4 (f) is using Cascade DC/DC converters to decouple BS and SCS which is a slightly different topology to the one in Figure 2.4 (d).

Disadvantages:

- Higher BS voltage is cause difficulty in balancing cell voltage [56]
- Increased cost due to requirement of a DC/DC converter with a larger capacity

The topology illustrated in Figure 2.4 (g) is the Parallel DC/DC converter topology.

Advantages:

- Less stability issue
- Less cost compared to cascade topologies

The parallel DC/DC converter topology is a favourable and commonly used. The stability problems and the converter costs have been taken care of when compared with cascaded configurations. Hence, in the work in Chapter 5, topology illustrated in Figure 2.4(g) is used for HESS.
2.5 Operation of rooftop Solar PV System at PCC with and without Energy Storage

The power flow in a traditional power network flows from the power plant to the transmission network and then to the load through the distribution network. However, the traditional power flow might be affected by distributed rooftop solar PV generators, which are connected to the distribution feeders. Reverse Power Flow might occur when there is a higher solar PV generation during mid-day while fewer loads are present in the distribution feeder where rooftop PV generators are connected. Generally, the voltage level along the feeder is reducing from the source to the far end of the feeder. Even though the rooftop solar PV generators are connected along the feeder; voltage level along the feeder reduces when generation from rooftop PV is lower than the load demand. The voltage along the feeder remains constant when generation from rooftop PV is equal to the load demand of the feeder. The voltage along the feeder increases when generation from rooftop PV is higher than the load demand. This scenario generally occurs during mid-day when solar irradiation is higher.

![Diagram of Power Flow along the feeder](image_url)

Figure 2.5: The Power Flow along the feeder
Considering a single node of the simple feeder illustrated at Figure 2.5, active (P) and reactive (Q) power injected or absorbed at the node is decided by the generated active (P<sub>PV</sub>), reactive (Q<sub>PV</sub>) power through the solar PV and the active (P<sub>L</sub>), reactive (Q<sub>L</sub>) load consumed by the household at any given instance. Hence, the net injection at any node can be obtained by,

\[
P + jQ = (P_{pv} + jQ_{pv}) - (P_L + jQ_L) = (P_{pv} - P_L) + j(Q_{pv} - Q_L)
\]  

(2.2)

Voltage rise/drop problem can be mitigated by controlling the net injection. Strategies such as active power curtailment, reactive power support and integrating ES with rooftop solar PV can be used as a solution.

During this study, the active power transfer was considered to analyse the voltage level at PCC. Power factor is considered as unity throughout the study. First, rooftop solar PV system without ES and second, rooftop solar PV system with ES is considered for comparison.

2.5.1 Rooftop solar PV systems without ES

Generally, during mid-day when solar PV generation is higher than demand; the voltage level of the feeder reaches the upper limit of safe operating voltage. During the evening peak hours solar PV generation is null and the demand is higher; the voltage level of the feeder reaches the lower limit of safe operating voltage.

\[
P = P_{pv} - P_L
\]  

(2.3)

Active power injected or absorbed by the selected node is equivalent to the difference between generated power output of solar panel and the load demand of the
household. Accordingly, the rooftop solar PV system will have to curtail active power \( (P_{PV}) \) injection to maintain the voltage level within the operational range of voltage.

### 2.5.2 Rooftop solar PV systems with ES

The energy loss occurring due to active power curtailment as above; can be avoided by integrating ES with the rooftop solar PV system. The excess energy generated during mid-day will be stored into the BS to utilize during the evening peak load period to avoid voltage drop across the feeder.

\[
P_{GRID} = P_{PV} - P_{LOAD} - P_{ES} \tag{2.4}
\]

Where, \( P_{ES} \) is the power injected by the ES.

However, the cost of rooftop solar PV system increases with integration of ES. Oversizing of the ES reduces the cost effectiveness of the system. Hence, the appropriate size of ES should be carefully selected. The SOC should be maintained considering lifetime of ES and the voltage level at PCC to assure the mitigation of voltage rise/drop problem.

### 2.6 Summary

This chapter has provided general information on the operation and control of grid-connected distributed rooftop solar PV systems in highly penetrated feeder environment. Initially, an overview about grid connected rooftop solar PV is done. Next, impacts of Rooftop solar PV generation on MV/LV distribution networks are discussed in detail. Present limitations in the available technologies and future
directions to overcome challenges in the distribution network caused by grid connected rooftop solar are discussed thereafter. At the next stage, energy storage systems as a solution for above challenges are discussed. BS, SC and HESS have been discussed in detail considering recent literature. Accordingly, advantages and disadvantages of each ES category have been explained in relation to the process of selecting the HESS in active parallel DC/DC converter topology which is the topology used in Chapter 5. Lastly, the operation of rooftop solar PV systems at PCC with and without ES is explained, and the basic equation for the modelling of solar PV system is discussed.
Chapter 3

Slow and Fast Voltage Fluctuations Mitigation using Battery Storage integrated to the Rooftop Solar PV

3.1 Introduction

The deployment of rooftop solar PV units in household and commercial customers has been accelerated during past few years. The introduction of the government and the retailer incentive schemes has caused the increase in the popularity. A high penetration of the rooftop solar PV units in weak power distribution networks can cause voltage drop during the peak demand period and voltage rise during the peak generation period in the voltage profile of the connected distribution feeder. In addition, the events of cloud passing over the rooftop solar PV unit may cause sudden voltage fluctuation in the voltage profile at the connected power distribution feeder. Therefore, the limit of operating voltage may be violated which is variable based on the penetration level of solar PV units. As a result, the distribution network operators (DNO) have enforced limitations on the penetration levels of rooftop solar PV units connected to the distribution feeder as a precaution to avoid/delay expensive grid upgrades [57]. Therefore, it is essential to exploit the limitation on penetration levels by introducing appropriate control mechanism/s to maintain the operating voltage limits in the power distribution feeder.

In general, slow fluctuations (SF) in the voltage profile are caused by the variation of sun irradiation versus load demand. Fast fluctuations (FF) in the voltage profile are caused by the sudden cloud passing. A case study to show the advantage of having
residential rooftop solar PV units integrated with Battery Energy Storage System (BESS) over industrial scale solar farms has been discussed in [58], while highlighting economic and environmental benefits of the rooftop solar PV units. Strategies for voltage regulation and peak shaving with BESS is discussed in [57], with one of the objectives to reduce the annual cost. The peak shaving with BESS significantly based on load data is discussed in [59], which need further improvement to consider voltage level of the distribution feeder as a minimum requirement to activate peak shaving. A dynamic state analysis on the subject of the voltage regulation was carried out in [60]; however, the State of Charge (SoC) of the BESS has not been measured as a limiting factor. Also, the voltage level at PCC has oscillated around the nominated voltage (1 pu) for the voltage control during the events of sudden cloud passing. The active and reactive power control to alleviate the over-voltage limit violation is studied in [61] using the most recent previous 15 second PV output to forecast the curtailment threshold. The proposed control strategy has been shown to be unsuccessful in the presence of sudden large fluctuations in the PV output. A mechanism to control the BESS SoC while controlling the slow and fast fluctuation in the voltage profile is proposed in [51, 62], however the results are showing that the reverse power flow is minimized rather than avoided. A droop based control mechanism on distributed BESS SoC is discussed for a slow voltage fluctuation control in the distribution feeder in [63, 64], specifically to avoid the violation of the limit of SoC. However, both references discuss the requirement of the establishment of prior communication between all the distributed BESS to accomplish the application of the control strategy. A multi-level inverter that is integrated with a solar PV generator and BESS is discussed in [65], showing the successful results for a short time period, and has suggested that the
studies could be extended further by analyzing results for a longer time (24 hour) period. An ESS control mechanism to alleviate the sudden fluctuations in the voltage profile is discussed in [66, 67]. However, candidate has not considered avoiding/reducing the reverse power flow to the grid and controlling the voltage in the feeder. These have been the shortfalls of the proposed mechanisms.

The necessity to investigate a smart way to mitigate both slow and first voltage fluctuations mitigation that considers practical issues such as the limited BESS capacity, the sudden fluctuations in the PV generation with high ramp rate, and the SoC limits motivates us to carry out the research in [68]. The methodology will be simulated on a hypothetical distribution feeder system based on 24 hour and 7 day data in 1 second intervals. Both controls for SF and FF will be integrated using a single BESS. The size and the capacity of the BESS is determined by candidate in [69] based on the 24-hour availability of BESS to achieve the simultaneous SFVFC.

In this thesis, the simultaneous operation of the slow and fast voltage fluctuations control (SFVFC) will be explored in the context of solar PV units in LV distribution feeders. The proposed approach utilizes a single battery energy storage system (BESS) to be integrated with the PV unit for this purpose, which will be dynamically charged during mid-day to alleviate the voltage rise and discharged during the evening peak hours to alleviate the voltage drop, while simultaneously controlling the fluctuations of the PV output. This also controls the voltage levels during both FF and SF by using a BESS whilst managing BESS SoC dynamically to provide necessary control throughout the day. The methodology will be simulated on a hypothetical distribution feeder system based on 24 hour and 7 day data in 1 second intervals.
3.2 An insight into Available Control Techniques to Control Rate of Change of Solar PV Inverter Output

The various techniques to control the rate of change of solar PV inverter output based on the input or sequential inputs of the solar PV generator, have been discussed in the literature [10, 13, 70-74]. A comparison of the reported techniques in the literature is shown in Table 3.1.

The rate of change of the inverter output is maintained at a specified rate in [10]. Few variables are required determination to avoid the energy loss of PV generation caused by the BESS output which always depends on the previous BESS output. The ramp rate control in [71] is based on the percentage change of ramp rate with respect to the PV generation; which makes the method inefficient. The moving average method and its adaptations such as the lagging moving average, the cantered moving average, etc. have been discussed in [71, 73-74], and the results vary based on the selection of the time window, which deliver less desirable results due to higher dependency on previous generation data.

The low pass filter method has been studied in [72- 73]. When the ramp rate is limited to less than 5%/min, the requirement for the capacity of the storage system drastically increases [72]. The lagging and double moving average methods produce different results based on the size of window and the solar PV output data [73-74]. The double moving average method produces a smoother output compared with other moving average methods.
Table 3.1: Comparison of Control Techniques in literature

<table>
<thead>
<tr>
<th>Method</th>
<th>Ref.</th>
<th>Effectiveness of storage time</th>
<th>Losses in storage system</th>
<th>SOC level</th>
<th>Cycling degradation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp rate control</td>
<td>[10], [71]</td>
<td>Very Good</td>
<td>Average</td>
<td>Maintain 40-60% often</td>
<td>Less than 2% always</td>
</tr>
<tr>
<td>Moving Average</td>
<td>[71], [73], [74]</td>
<td>Bad</td>
<td>High</td>
<td>Vary between 0-100% letting 0-10% frequent</td>
<td>Approximately 10% for 0W-40kW solar panels</td>
</tr>
<tr>
<td>Step Control</td>
<td>[71]</td>
<td>Good</td>
<td>Low</td>
<td>Maintain 40-60% often</td>
<td>Less than 1% always</td>
</tr>
<tr>
<td>Low pass filter</td>
<td>[72], [73]</td>
<td>Bad</td>
<td>Low</td>
<td>Maintain 60-90% often</td>
<td>Very low as 0.5% always</td>
</tr>
<tr>
<td>Moving median</td>
<td>[73]</td>
<td>Bad</td>
<td>High</td>
<td>Vary between 0-100%, including rapid</td>
<td>Approximately 10%</td>
</tr>
</tbody>
</table>
The methodology proposed in this research for the mitigation of FF in the voltage profile does not depend on a time window. Therefore, it can have the ability to control the output based on the present power output of the PV generator and a specified maximum rate of change; a novel technique which has not discussed in literature.

### 3.3 The Proposed Methodology to Alleviate the Slow and Fast Fluctuation in Voltage Profile Using BESS

The proposed simultaneous voltage control proposes to mitigate both the slow and the fast fluctuations caused by the mismatch between the solar PV output and the residential load will be achieved. The conceptual block diagram of a typical BS integrated with a rooftop solar PV system, which will be studied in this work, is presented in Fig. 3.1.

![Conceptual Diagram of the solar PV unit with BESS](image)

Figure 3.1: Conceptual Diagram of the solar PV unit with BESS

The BS will be charged/discharged faster to mitigate the fast fluctuations in the solar PV output (FFPV) and charged/discharged slower to mitigate the slow fluctuations in the voltage level at the PCC (SF_PCC). Both controller mechanisms will be integrated
to operate using a single BS within its technical limitations. As per Fig. 3.1, the solar PV unit and the BS are connected through an inverter to the residential load and the grid. Firstly, the BS power output to mitigate $FF_{PV}$ will be calculated. The BS power output to compensate $SF_{PCC}$ will be calculated next and then the BS will be operated to mitigate both fast and slow fluctuations simultaneously. It is assumed that the communication within the Energy Management System (EMS) does not experience any delay in the response time.

The proposed SFVFC methodology was published in [13].

The power output from the solar panel ($P_{PV}$) and the power injection/absorption to/from grid ($P_{Grid}$) must be equal to the power output of the BESS ($P_{BESS}$) and the load demand ($P_{Load}$); as shown as (3.1) below,

$$P_{PV} + P_{Grid} = P_{Load} + P_{BESS} \quad (3.1)$$

The regulation of $P_{Grid}$ by controlling $P_{BESS}$ is essential to maintain the voltage profile within the standard operating limit of the connected power distribution feeder. However, it is assumed the BESS has a sufficient capacity to deal with the power requirement ($P_{BESS}$) for the proposed SFVFC.

An illustration of the (3.1) is depicted in Fig.3.2, which contains a hypothetical data (in watts) for analysis.
The power absorption from the grid; \( P_{\text{Grid}} \), is considered unchanged for the ease of analysis. At the 1\textsuperscript{st} instance, \( P_{\text{PV}} \) is null, \( P_{\text{BESS}} \) is null, load demand is supplied by the grid and hence, \( P_{\text{Grid}} \) is equivalent to \( P_{\text{Load}} \). During 2\textsuperscript{nd} and 3\textsuperscript{rd} instances, \( P_{\text{PV}} \) is 10W and 25W respectively, \( P_{\text{BESS}} \) is 5W and 20W, \( P_{\text{Load}} \) is 10W in both instances, required 5W (\( P_{\text{Grid}} \)) is supplied by the grid. At the 4\textsuperscript{th} instance, \( P_{\text{PV}} \) is 10W, \( P_{\text{Load}} \) is 15W, \( P_{\text{BESS}} \) is null and \( P_{\text{Grid}} \) is 5W. In the 5\textsuperscript{th} instance, \( P_{\text{PV}} \) is null, \( P_{\text{Load}} \) is 20W, \( P_{\text{BESS}} \) is discharging 15W and \( P_{\text{Grid}} \) is 5W.
3.3.1 Alleviation of the Fast Fluctuations (FF) in the voltage profile

The FF in the voltage profile is caused by the cloud passing over the solar PV unit. The maximum allowable rapid voltage change of LV network is 5% under normal circumstances and 10% if it is infrequent, based on the EN50160 standard for voltage disturbances [70].

The output of the integrated BESS and the PV inverter; $P_{inv}$, can be obtained as an expression of the PV panel output power; $P_{PV}$, the inverter efficiency; $\eta_{inv}$ and the battery output power; $P_{BESS}$, as given below [13]:

$$P_{inv} = \eta_{inv} \times (P_{PV} + P_{BESS})$$  \hspace{1cm} (3.2)

After differentiating all the terms in (3.2), and rearranging; we obtain (3.3),

$$\frac{dP_{BESS}}{dt} = \frac{1}{\eta_{inv}} \left[ \frac{dP_{inv}}{dt} |_{def} - \eta_{inv} \times \frac{dP_{PV}}{dt} \right]$$  \hspace{1cm} (3.3)

The rate of change of the solar PV output; $\frac{dP_{PV}}{dt}$, is referred to as the solar PV ramp rate (PVRR). The solar PV inverter efficiency; $\eta_{inv}$, can be obtained from the manufacturer data sheet. However, for the calculation here after $\eta_{inv}$ is considered as unity in value.

The rate of change of the solar PV inverter output is fixed to a specified value; and referred as Maximum Applicable Ramp Rate (MARR). The specified ramp rate is set as negative (MARR$_{min}$) when the PVRR is negative and set as positive (MARR$_{max}$) when the PVRR is positive; otherwise, it is set as zero (when PVRR is null), as shown in (3.4) [13]:
The rate of change of the BESS power output, \( \frac{dP_{BESS}}{dt}(t) \) can be calculated, after the selection of MARR based on the PVRR of the PV. The rate of change of BESS consists of two parts: the rate of change of BESS during the FF control and the rate of change of BESS during the SF control. This relationship can be shown in (3.5).

\[
\frac{dP_{BESS}}{dt}(t) = \frac{dP_{BESS,FF}}{dt}(t) + \frac{dP_{BESS,SF}}{dt}(t)
\]  

(3.5)

Where, \( \frac{dP_{BESS,FF}}{dt}(t) \) is the rate of change of BESS for the FF control; \( \frac{dP_{BESS,SF}}{dt}(t) \) is the rate of change of BESS for the SF control.

The rate of change of the power output of BESS, \( \frac{dP_{BESS,FF}}{dt}(t) \) can be obtained as below:

\[
\frac{dP_{BESS,FF}}{dt}(t) = \begin{cases} 
0, & \text{if } |PVRR| \leq |MARR| \\
MARR - PVRR, & \text{otherwise} 
\end{cases}
\]  

(3.6)

As seen in (3.6), \( \frac{dP_{BESS,FF}}{dt}(t) \) is zero when the absolute value of the current PVRR is equal or lower than the absolute value of the specified MARR. Otherwise, \( \frac{dP_{BESS,FF}}{dt}(t) \) is the gap between MARR and PVRR.

Calculation of \( \frac{dP_{BESS,FF}}{dt}(t) \) based on MARR and PVRR is illustrated in Fig.3.3 below using fictitious data,
Figure 3.3 (I): Solar PV data and Battery power output to mitigate fluctuations

The specified MARR during the illustration was 5W/s. During instance 1 - 2, the solar PV output increased from zero to 2W and hence, the calculated PVRR is 2W/s. However, the PVRR is less than specified MARR; hence, $\frac{dP_{BESS, FF}}{dt}(t)$ is zero for the duration. During instances 2 - 3 and 3 - 4, the solar PV output increased from 2W to 5W and 5W to 10W respectively. Hence, the calculated PVRR are 3W/s and 5W/s.
However, the PVRR is less than specified MARR in both instances and hence, \( \frac{dP_{BESS,FF}}{dt}(t) \) is zero. During instance 4 - 5, the solar PV output decreased from 10W to 4W, the calculated PVRR is -6W/s; which is larger (note that only the absolute values of both PVRR and MARR are compared in (3.6)) than the specified MARR is -5W/s; hence, the MARR is -5W/s during the duration. Accordingly, \( \frac{dP_{BESS,FF}}{dt}(t) \) is 1W/s. During instance 5 - 6, the solar PV output is stable, and the calculated PVRR is zero. \( \frac{dP_{BESS,FF}}{dt}(t) \) is zero for whole duration, since the PVRR is less than the MARR. During instances 6 - 7 and 7 - 8, the solar PV output decreased from 4W to 2W and 2W to zero respectively. Hence, the calculated PVRR is -2W/s for both instances. \( \frac{dP_{BESS,FF}}{dt}(t) \) is zero since the PVRR is less than the MARR.

This methodology will be used to calculate \( \frac{dP_{BESS,FF}}{dt}(t) \) for the alleviation of the FF.

### 3.3.2 Alleviation of Slow Fluctuations (SF) in the Voltage Profile

The SF in the voltage profile is caused by the changing sun irradiation and insolation against the varying residential load demand. The solar PV generation starts at sunrise and ends at sunset. The imbalance in generation and demand can be balanced using the BESS with a sufficient charge/discharge capacity in BESS.

The ac voltage of the rooftop solar PV should be 230V at the Point of Common Coupling (PCC) in single phase line-to-neutral and 400V in the three phase line-to-line with a tolerance of +10% and -6% [3], according to the Australian Standard AS 60038 for Standard Voltages.
The proposed SF control method dynamically measures the voltage level at PCC to determine the rate of change of charge/discharge rate \( \frac{di_{BESS\_SF}}{dt}(t) \) of BESS. During the methodology to control the SF, several sets of pre-defined voltage levels of PCC is used to determine the rate of change of charge/discharge rate \( \frac{di_{BESS\_SF}}{dt}(t) \) of BESS which is again pre-defined to suit the loading of the feeder. Table 3.2; Contains pre-defined voltage levels and \( \frac{di_{BESS\_SF}}{dt}(t) \) for the specific feeder.

Table 3.2: Method to determine rate of change of charge/discharge rate of BESS for SF

<table>
<thead>
<tr>
<th>Lowest reference ( V_{PCC} ) (P.U)</th>
<th>Highest reference ( V_{PCC}(P.U) )</th>
<th>( \frac{di_{BESS_SF}}{dt}(t) ) (A/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.94</td>
<td>1.1</td>
<td>0</td>
</tr>
<tr>
<td>BESS Charging to regulate voltage profile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>1.104</td>
<td>C/20</td>
</tr>
<tr>
<td>1.104</td>
<td>1.108</td>
<td>C/10</td>
</tr>
<tr>
<td>1.104</td>
<td>-</td>
<td>C/5</td>
</tr>
<tr>
<td>BESS discharging to regulate voltage profile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.93</td>
<td>0.94</td>
<td>C/10</td>
</tr>
<tr>
<td>-</td>
<td>0.92</td>
<td>C/5</td>
</tr>
</tbody>
</table>

The rate of change of charge/discharge rate of BESS is lower when the voltage at PCC deviates less from the operating voltage range. Similarly, the rate of
charge/discharge of BESS is higher when the voltage at PCC deviates more from the operating voltage range.

A BESS with the capacity of 500Ah is used for the simulations, the rate of change of charge/discharge rate \( \frac{dI_{BESS \_SF}}{dt}(t) \); are 12.5, 25 and 50 A/h respectively. The rate of change of discharging rates \( \frac{dI_{BESS \_SF}}{dt}(t) \); W1 and W2 are based on C/10 and C/5 respectively; valued as 25 and 50A/h.

Once, \( \frac{dI_{BESS \_SF}}{dt}(t) \) is determined; the rate of change of BESS power output;

\[
\frac{dP_{BESS \_SF}}{dt}(t) \]

\( = \frac{dI_{BESS \_SF}}{dt}(t) \times \frac{1}{3600} \times V_{BESS} \)  \( (3.7) \)

The rate of charge/discharge in A/h is obtained as per Table 3.2. The SoC value is the calculated SoC for the previous instance. Both \( \frac{dI_{BESS \_SF}}{dt}(t) \) value and the SoC value are then used with the battery characteristic curves (Fig.3.4) (for 12V lead acid battery curve) [50] to obtain the BESS operating voltage \( V_{BESS} \) using interpolation. Next, the rate of change of BESS power output; \( \frac{dP_{BESS \_SF}}{dt}(t) \) is determined.
3.3.3 The Tuning of the rate of change of BESS for the alleviation of simultaneous SFVFC

The rate of change of BESS output for FF ($\frac{dP_{BESS,FF}}{dt}(t)$) and the rate of change of BESS output for SF ($\frac{dP_{BESS,SF}}{dt}(t)$) are calculated as per Section 3.3.1 and 3.3.2. Therefore, according to (3.5), we have obtained the cumulative rate of change of BESS ($\frac{dP_{BESS}}{dt}(t)$). Results of calculations are used in (3.8) for the calculation of the rate of change the inverter output, $\frac{dP_{inv}}{dt}(t)$.

$$\frac{dP_{inv}}{dt}(t) = \frac{dP_{BESS,FF}}{dt}(t) + \frac{dP_{BESS,SF}}{dt}(t) + \frac{dP_{PV}}{dt}(t)$$

(3.8)
The calculated $\frac{dP_{\text{inv}}}{dt}(t)$ in (3.8) may exceed the specified MARR value since the cumulative result of the $(\frac{dP_{\text{BESS FF}}}{dt}(t))$ and the $(\frac{dP_{\text{BESS SF}}}{dt}(t))$ is used as the rate of change of BESS $(\frac{dP_{\text{BESS}}}{dt}(t))$. The rate of change of BESS $(\frac{dP_{\text{BESS}}}{dt}(t))$ should be tuned as shown in (3.9); if $\frac{dP_{\text{inv}}}{dt}(t)$ exceeds the specified MARR value. Otherwise, the control process shall be continued to next step.

$$\frac{dP_{\text{BESS}}}{dt}(t) = \frac{dP_{\text{BESS FF}}}{dt}(t) + \frac{dP_{\text{BESS SF}}}{dt}(t) = \begin{cases} MARR_{\text{max}} - PVRR, & \text{if } \frac{dP_{\text{inv}}}{dt}(t) > MARR_{\text{max}} \\ MARR_{\text{min}} - PVRR, & \text{if } \frac{dP_{\text{inv}}}{dt}(t) < MARR_{\text{min}} \end{cases}$$ (3.9)

The rate of change of the inverter output can be regulated within the specified range of MARR ($MARR_{\text{min}} < \text{MARR} < MARR_{\text{max}}$) by tuning the rate of change of BESS $(\frac{dP_{\text{BESS}}}{dt}(t))$ according to (3.9).

If the rate of change of $\frac{dP_{\text{inv}}}{dt}$ is higher than $MARR_{\text{max}}$ based on the calculation in (3.8); the rate of change of BESS should be tuned as to lower $\frac{dP_{\text{inv}}}{dt}$ by increasing the rate of change of charging of BESS $(\frac{dP_{\text{BESS}}}{dt}(t))$ from the previously calculated value. Accordingly, BESS starts charging at a higher rate and hence the rate of change of inverter output, $\frac{dP_{\text{inv}}}{dt}$ is maintained below $MARR_{\text{max}}$. If the rate of change of $\frac{dP_{\text{inv}}}{dt}$ is lower than $MARR_{\text{min}}$ based on the calculation in (3.8); the rate of change of BESS should be tuned as to increase $\frac{dP_{\text{inv}}}{dt}$ by increasing the rate of change of discharging of BESS $(\frac{dP_{\text{BESS}}}{dt}(t))$ from the previously calculated value. Accordingly, BESS starts
discharging at a higher rate and hence the rate of change of inverter output, \( \frac{dP_{inv}}{dt} \) is maintained above \( MARR_{min} \). If the rate of change of \( \frac{dP_{inv}}{dt} \) is higher than \( MARR_{min} \) and less than \( MARR_{max} \) based on the calculation in (3.8), the rate of change of BESS output does not need to be tuned. Hence, the BESS continues to charge/discharge/idle in similar rate as the previous time instance. The significance of the proposed tuning methodology is the capability to conserve energy throughout the SFVFC to utilize solar energy in the optimum manner.

The command signal is sent to BESS for the generation of the required BESS output, following the calculation of the cumulative rate of charge/discharge of the BESS \( \left( \frac{dP_{BESS}}{dt} (t) \right) \) by tuning.

The power output of BESS for SFVFC; \( P_{BESS}(t) \) is calculated based on the cumulative rate of change of charge/discharge of the BESS for the present instance and the power output of BESS for SFVFC in the previous instance which is expressed in (3.10):

\[
P_{BESS}(t) = P_{BESS,FF}(t) + P_{BESS,SE}(t) =
\begin{cases}
0, & \text{if } |PVRR| \leq |MARR| \\
P_{BESS}(t - T) + \left[ \frac{dP_{BESS,FF}}{dt}(t) + \frac{dP_{BESS,SE}}{dt}(t) \right] \ast (t - (t - T)), & \text{otherwise}
\end{cases}
\]

\( (3.10) \)

The power output of BESS for SFVFC (\( P_{BESS}(t) \)) is zero when the rate of change of PV (PVRR) is smaller than the specified MARR. In other words; the BESS remain idle when the rate of change of PV (PVRR) is acceptable since PVRR is lower than
the maximum acceptable rate of change (MARR). Otherwise, the power output of BESS for SFVFC; \( P_{BESS}(t) \) is calculated by applying the amount of change during the selected time duration to the initial \( P_{BESS}(t) \) for the previous instance.

### 3.3.4 Calculation of the SoC of the BESS

The accumulated Energy of BESS (\( E_{BESS} \)) is calculated by intergrating the charged/discharged energy during each time period as in (3.11),

\[
E_{BESS} = \sum_{t=0}^{N} \frac{P_n + P_{n-1}}{2} \times (t_n - t_{n-1})
\]  

(3.11)

Where, \( E_{BESS} \) is the accumulated energy of BESS, \( N \) is the total time duration, \( P_n \) is the BESS power output in the present time, \( P_{n-1} \) is the BESS power output in the previous time and \( t_n - t_{n-1} \) the duration of the selected period.

The SoC of the BESS can be calculated using (3.12).

\[
SoC = \frac{E_{BESS}}{C} \times 100\%
\]  

(3.12)

Where, SoC is the State of Charge of BESS as a percentage, \( E_{BESS} \) is the accumulated energy of BESS and \( C \) is the energy capacity of BESS (must be in same units as \( E_{BESS} \)).

### 3.3.5 Ensuring Undisrupted BESS Availability

Advanced techniques are required to ensure the undisrupted BESS availability to support the SFVFC. The following SoC management techniques are proposed to ensure undisrupted BESS availability throughout the entire duration that require SFVFC. Accordingly, the BESS SoC is enhanced during time periods that BESS is
not expected to perform SFVFC. Consequently, the BESS acquires a sufficient capacity to provide support during upcoming SF and FF in the voltage profile during period that there is no SF or/and FF present in the voltage profile.

Table 3.3 Method to determine rate of change of charge/discharge rate of BESS for SoC Management

<table>
<thead>
<tr>
<th>Lowest reference $V_{PCC}$ (P.U)</th>
<th>Highest reference $V_{PCC}$ (P.U)</th>
<th>$\frac{d}{dt}BESS_SOC(t)$ (A/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS Charging for SoC Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.05</td>
<td>1.1</td>
<td>C/20</td>
</tr>
<tr>
<td>BESS discharging for SoC Management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.945</td>
<td>0.94</td>
<td>C/20</td>
</tr>
</tbody>
</table>

More importantly, the BESS is charged/discharged for SoC management during instances that there is no presence of the SF or/and FF. In addition, if the BESS SoC level is lower than 30% and the $V_{PCC}$ within the lowest and highest reference values for BESS charging as per Table 3.3; BESS will charge to enhance the SoC. On the other hand, if the BESS SoC level is higher than 90% and the $V_{PCC}$ within the lowest and highest reference values for BESS discharging as per Table 3.2; BESS will discharge to enhance the SoC. The rate of change of charge/discharge rate $\frac{d}{dt}BESS\_SOC(t)$ depends on the feeder loading and MARR. In this scenario, $\frac{d}{dt}BESS\_SOC(t)$ will be 12.5 A/h (BESS with 500Ah amphere capacity is used during this work) is for both charging and discharging events to manage SoC.
Once, rate of change of charge/discharge rate; \( \frac{di_{\text{BESS-SOC}}}{dt}(t) \) for SoC management is determined; the rate of change of charge/discharge of BESS; \( \frac{dP_{\text{BESS-SOC}}}{dt}(t) \) can be calculated as in (3.13).

\[
\frac{dP_{\text{BESS-SOC}}}{dt}(t) = \frac{di_{\text{BESS-SOC}}(t)}{3600} \times V_{\text{BESS}}
\]

(3.13)

The rate of charge/discharge in A/h is obtained as per Table 3.3 and the SoC is calculated as per (3.12). Both \( \frac{di_{\text{BESS-SOC}}}{dt}(t) \) value and SoC value are then used with the battery characteristic curves (12V lead acid battery curve) [50] to the BESS operating voltage \( V_{\text{BESS}} \) using interpolation. Next, the rate of change of charge/discharge of BESS; \( \frac{dP_{\text{BESS-SOC}}}{dt}(t) \) is determined as in (3.13) for the SoC management.

The controller process should again go through the process to calculate the rate of change of the solar PV output as per section 3.3.3

3.3.6. Implementation of the Simultaneous Slow and Fast Voltage Fluctuation Control

The detailed methodology of the simultaneous voltage control for the alleviation for slow fluctuations and fast fluctuations in the connected feeder is illustrated in Fig.3.5 and elaborated in this section. The methodology is built-in into the BESS which is integrated with the solar PV system.

Initially, the specified MARR value is determined based on the (3.4) following the determination of rate of change of solar PV output. Next, the rate of change of BESS
output for the control of FF \( \frac{dP_{BESS,FF}}{dt}(t) \) in voltage profile is determined using (3.6).

![Flow chart for the SFVFC](image)

Figure.3.5: Flow chart for the SFVFC

Thereafter, the voltage at the PCC is determined by applying the load, the BESS output for FF control and the PV output in a quasi-steady-state power flow. Depending on the voltage level at the PCC; the rate of change of charge/discharge rate of BESS \( \frac{di_{BESS,SE}}{dt}(t) \) is determined using Table 3.2. Next, the rate of change of BESS power output; \( \frac{dP_{BESS,SE}}{dt}(t) \) is determined using the SoC value from the previous instance and the \( \frac{di_{BESS,SE}}{dt}(t) \) value obtained from the Table 3.2. The BESS operating voltage \( \text{V}_{\text{BESS}} \) is found by the interpolation of BESS characteristics curves to be used in (3.7). After the calculation of both \( \frac{dP_{BESS,FF}}{dt}(t) \) and \( \frac{dP_{BESS,SE}}{dt}(t) \),
the obtained values are used to tune the BESS output to maintain the rate of change of the solar PV inverter output within the specifies MARR range; which is performed using (3.8) and (3.9). The tuned BESS output, \( \frac{dP_{BESS}}{dt}(t) \) is used to calculate the BESS power output \( P_{BESS}(t) \) using (3.10). Accordingly, the BESS power output for the present time instance is calculated using BESS power output of the previous instance and the rate of change of BESS power output for the present instance. However, if the calculated BESS power output is zero, the BESS SoC management may occur depending on the SoC level of the BESS. Accordingly, if the BESS SoC is less than 30% and the voltage at PCC is within range as per Table 3.2; BESS is charged to increase the SoC above 30%. On the other hand, if the BESS SOC is higher than 90% and the voltage at PCC is within range as per Table 3.2; BESS is discharged to decrease SoC below 90%. The simultaneous voltage control for slow fluctuations and fast fluctuations is performed; if the calculated BESS power output is not zero and the BESS SoC is within 20-100% SOC range. Finally, the entire operation proceeds to the next time instance.
3.4 Case Studies

The practical MV/LV system consisting 16 LV buses in the distribution feeder is used to demonstrate the effectiveness of the proposed method described in Section 3.3. The feeder data for a section of the practical MV/LV network (Fig. 3.6) in NSW is used. Each bus includes a household with a 5kW rooftop solar PV installed with an integrated 500Ah BESS.

![Diagram of MV/LV Network and the selected LV feeder for simulations](image)

Figure 3.6: MV/LV Network and the selected LV feeder for simulations

The results will be discussed separately for fast fluctuation control initially and simultaneous slow-fast fluctuation control separately for the advantage of comparison of results to validate the proposed methodology.

Fig. 3.7, shows the solar PV generation, the BESS power output for FF control and the inverter power output considering the FF control only. The sudden fast
fluctuation occurs from 7.30am to 8.15 am and 12.30 pm to 3.30 pm more frequently and vigorously. The fluctuation with the highest rate of change occurs around 12.30 pm which is roughly 550 Watts/ second.

Figure 3.7: Solar PV generation, BESS power and Inverter power output

Fig. 3.8 and Fig. 3.9 show the comparison of the PVRR value with MARR value. Fig. 3.9 shows the zoomed 50-second duration of Fig. 3.8 starting at 12.58.45 hr of the day.
Fig. 3.10 shows the battery SoC variation; and approximately 18% of SoC is used for the ramp rate control using a battery with 500Ah capacity. The occurrence of the fast fluctuation events caused the BESS to charge/discharge to maintain MARR.
Figure 3.10: SoC variation considering FF control

Fig 3.7 shows the activity level of BESS increases during the passing cloud events resulting in a drop/rise in the SoC level of BESS as shown in Fig. 3.10 during the same period. With the FF control, the rate of change of the inverter output has been reduced from 550 watts/sec to 5 watts/sec during the highest fluctuation. Similarly, the entire FF with the magnitude over specified MARR have been controlled successfully.

The simulation results for the simultaneous voltage control for both slow fluctuations and fast fluctuations are presented in Fig 3.11-Fig 3.14 that show the inverter output after the SF control, load data, net power at PCC, BESS SOC variation and voltage profiles for LV bus 16 in the MV/LV network.
Figure 3.11: Inverter output, load demand, net power with/without BESS for FF control

Fig. 3.11 depicts the inverter output after the simultaneous control, the load demand, the BESS power output for voltage control and the net power with/without BESS for voltage control. The BESS is charged in three different charging rates depending on the voltage at PCC during mid-day. As a result, the voltage profile is maintained stable close to the operating voltage limit. The BESS is discharged in three different charging rates during the evening. The BESS starts charging from 10am until 3 pm, and discharges from around 7pm until 9pm for voltage control.
Fig. 3.12 depicts the variation of the BESS SoC for the integrated control. The BESS SoC has started from 60% SoC and ended to be 42% SoC by the end of the day after carrying out the simultaneous SFVFC.

Fig. 3.13 shows the voltage profile without any control at PCC of the 16th LV bus in the test feeder. Fig. 3.14 depicts the voltage profile with FF control and voltage profile with SFVFC. Accordingly, sudden fast fluctuations in the Fig. 3.13 have been successfully alleviated as per the illustration in Fig. 3.14 with the proposed SFVFC technique. Moreover, voltage profile has been successfully controlled within the operating voltage range with the suggested voltage control mechanism.
Moreover, the proposed simultaneous SFVFC was tested together with the SoC management technique on the same feeder considering 7 day data set to validate the hypothesis comprehensively. Fig.3.15- Fig.3.18 illustrates the inverter output, BESS power output, SoC variation, voltage improvement with FF control and with simultaneous SFVFC for a week starting from Monday.
Fig. 3.15 depicts the raw solar PV output, BESS output and inverter output with FF control for week duration. Accordingly, Day 1 and 2 have the highest PV generation and variation articulates that these are sunny days with few clouds in the sky. Day 3 and 4 have largely varying PV generation and variation says that these are cloudy days. Day 5 and 6 have good PV generation and these are less sunny days than Day 1 and 2 but very few clouds in the sky. The pattern of the Day 7 shows that it has been a sunny day with more clouds until mid-day which turned to be an extremely cloudy afternoon. Fig. 3.15 proves that the proposed FF control has been able to control the FF throughout the entire period with the integration of BESS.
Figure 3.16: Inverter power with FF control, load demand, net power with/without BESS for FF control

Fig. 3.16 illustrates the inverter power output with FF control, the load demand, the net power with/without BESS for FF control. Accordingly, the BESS has been charged during mid-day for SF control during all the days except Day 3. Significantly less PV generation in the Day 3 caused no excess generation in the mid-day. The BESS has been discharged during evening peak period during all the days except Day 6 and 7; as a result of the fewer loads in weekend evenings. According to Fig. 3.16, the proposed methodology for voltage control has been able to control the voltage profile to lie within the operating voltage limits. Hence, the integrated controller for FF controller and the SF controller can be successfully implemented to alleviate fast and slow fluctuations in the voltage profile by integrating a BESS with the solar PV unit.
Figure 3.17: Overall variation of BESS SOC

Fig. 3.17 illustrates the SoC variation during entire duration (week) for SFVFC. Initial SoC is 60% and at the end of Day 1 SoC level has become 42%. SoC value had been 48%, 40%, 38%, 29%, 66% and 80% at the end of Day 2-7 respectively. The SoC management mechanism activates when the SoC become less than 30% or higher than 90% while the voltage at PCC meets the voltage requirement as per Table 3.3.
Figure 3.18: Voltage profile with FF control and with SFVFC

Fig. 3.18 shows the voltage profile in LV bus 16 with the FF controller only and with the proposed SFVFC. Accordingly, the voltage profile has been controlled within the operating voltage range while maintaining the rate of change of the solar PV inverter output at 5 watts/second maximum. Moreover, the simulations for the 7-day period strongly validate the successful implementation of the proposed integrated controller for SFVFC using a 500Ah lead acid BESS.

3.5 Summary

The application of a single BESS to alleviate the slow and fast fluctuations of solar PV output has been presented. The management of the battery SoC is included to ensure an undisturbed BESS support during the control. The SF has been alleviated by charging the BESS during mid-day; when the solar PV output is higher than the load demand and discharging the BESS during evening; when the solar PV output is absence and the load demand is high. The charging/discharging rate of BESS for the voltage control has been determined based on the voltage level at the PCC; which
has been a novel hypothesis that has not been reported in literature previously. Simultaneously, the FF control of the connected feeder has been achieved using the same BESS. The FF control mechanism proposed in this work is an original idea which has not been addressed in literature. The control methodology presented in this work contributes to the industry through,

- Providing voltage control to mitigate both SF and FF simultaneously by dynamically calculating BESS output for every 1 second duration.

- Providing charge/discharge control methods to suit the power flow and BESS SoC.

- Opening up the discussion to provide incentives and tariff benefits to customers for supporting the grid.

- Introducing the variable charge/discharge methods to be implemented by the residential solar PV generator to conserve energy without curtailing the output power of the PV via inverter control, etc.

The proposed method is validated using a practical MV/LV network in NSW. The simulation results show that the proposed method can alleviate the slow (due to intermittency of solar PV) and the fast (due to passing cloud) fluctuations of the PV output. Initially, the specified rate of change of the inverter output (MARR), the operating voltage range and the severity levels are set, the method is not dependent on any simulation parameter thereafter. The proposed controller mechanism is tested using the same network for a 1 week period. The results show that the proposed methodology has effectively controlled the ramp rate of change of the inverter output.
while maintaining the voltage profile within the operating voltage range using a 500Ah lead acid BESS.

The charging/discharging mechanism incorporated with the BS to control SoC will be extended in Chapter 5.
Chapter 4

The Sizing of Battery Energy Storage for the Mitigation of Slow and Fast Fluctuations in Rooftop Solar PV Output

4.1 Introduction

The residential rooftop PV units which are connected to the power grid have gained lot of attention within last few decades in Australia. The grid-connected PV units certainly cause various problems in the power system due to the uncertainty of the power generation and the dynamic nature of load.

The integration of Energy Storage Systems (ESS) with the solar PV units can ensure that the effect of the changing behaviour of the generation on power system is minimized or eliminated. The addition of ESS allows the intermittent PV generation to provide supply and demand balance despite the varying nature of the sun irradiation and the load demand. In addition, the integration of ESS with the rooftop PV units provide value added benefits by being able to reduce energy costs, improving power quality and increasing reliability [75,76].

A strategy for peak load shaving to utilize the available capacity of a plug-in electric vehicle (PEV) is discussed in [77]; which mainly focuses on utilizing the balanced energy stored in the BESS of PEV to improve the voltage profile. However, the methodology does not prioritize the voltage regulation. The sizing of BESS based on peak load shaving has been investigated in [78, 79]; where the reduction in the energy bill has been the main criteria to determine the sizing. The sizing of BESS based on load shifting while considering energy cost has been explored in [80, 81].
However, none of above literature [77-81] discusses about the voltage regulation by utilising BESS during simultaneous SF and FF.

The work presented in this chapter focuses on the sizing of BESS integrated with the solar PV unit for regulation of the voltage profile in the connected power distribution feeder, when the system is undergoing both SF and FF. The sizing of BESS will be determined based on the real time varying solar PV output and the varying residential load demand, leading to fast (due to cloud passing causing high ramp rate PV output) and slow voltage variations (due to varying sun irradiation during the day).

The sizing of BESS will be determined based on the;

(i) Ability to mitigate both fast and slow fluctuation in the voltage profile,

(ii) Ability to maintain the charging/discharging rates of the BESS to be within the manufacturer specification,

(iii) Fully utilize the capacity of BESS with a 10% margin to mitigate unexpected variations in voltage profile,

(iv) Ability to assure SoC of the BESS at the end of the day is same as the initial SoC at the start of the same day.

As per the Australian Standard AS 60038 for Standard Voltages, the rooftop solar PV output should be at 230V at the Point of Common Coupling (PCC) in single phase line-to-neutral with a tolerance of +10% and -6% [3]. Maximum charge/discharge rate of the BESS based on physical limitations of lead acid BESS is C/3 (Capacity hour rate) according to manufacturer specifications. Assurance of the SoC of the BESS at the end of the day is same as the initial SoC at the start of the same day is important for the sustainability of the charging/discharging of the battery
for the mitigation of both fast and slow fluctuation without incurring charging/discharging to restore the BESS SoC level within 24 hr period.

Trial simulations on a practical distribution feeder in NSW have been carried out with various BESS sizes to validate the proposed strategy.

### 4.2 The Proposed Strategy for Sizing of BESS to Regulate Voltage at PCC

The conceptual block diagram of a typical BESS integrated with a rooftop solar PV system is presented in Fig. 4.1; is studied during this work.

![Diagram](image)

**Fig. 4.1: Conceptual Diagram of the solar PV unit with BESS**

Without the BESS, when the inverter output (P\text{INV}) is higher than the residential load (around noon time), the excess energy will flow into the power system leading to voltage rise, which may cause the voltage to exceed the upper limit of the Australian standard 60038. However, with the BESS, the excess energy can be stored temporarily in the BESS for use in the evening to support the voltage (to avoid voltage at PCC eluding the lower limit of the Australian standard 60038) during the evening peak load period.
4.2.1 Modelling Solar PV Inverter

Fig. 4.1 shows that the power output of the solar PV inverter, $P_{INV}$ is a combination of the raw power output of solar PV, $P_{PV}$ and the power output of BESS, $P_{BESS}$. Therefore, the rooftop solar PV system used in this work can be modeled as Eq.3.2 in Chapter 3.

$\eta_{INV}$ is usually provided in the manufacturer datasheet for the specific inverter. For simplicity, in this study, the inverter efficiency $\eta_{INV}$ will be considered to be at unity.

4.2.2 Modelling Battery Energy Storage System (BESS)

The mitigation of both FF and slow SF in the power output of solar PV inverter ($P_{INV}$) will be taken into consideration for the modeling of the BESS. The lead acid BESS is utilized during this work.

1) Modeling of BESS to mitigate fast fluctuations in solar inverter output

The FF in the solar PV inverter output occur due to the events of sudden cloud passing over the rooftop solar PV unit causing sudden drops in the solar PV output leading to fast fluctuations in the voltage profile.

Eq. 3.1 to Eq. 3.6 in Chapter 3, illustrates the calculation steps in the modelling process of BESS for the mitigation of fast fluctuations. The rate of change of the BESS power output ($\frac{dP_{BESS, FF}}{dt}$) is zero when the absolute value of the rate of change of the raw solar PV output ($\frac{dP_{PV}}{dt}$) is equal or lower than the absolute value of the specified MARR. Accordingly, the BESS is idle at such moments; it is not charged.
or discharged. Otherwise, the rate of change of the BESS power output \( \frac{dP_{\text{BESS,FF}}}{dt}(t) \), will be the difference between the MARR and \( \frac{dP_{\text{PV}}}{dt} \), to mitigate the fast fluctuations.

2) **Modeling of BESS to mitigate the slow fluctuations in solar inverter output**

Slow fluctuations in the solar PV inverter output are caused by the relatively slow variations of the solar PV generation (due to the variation in the sun irradiation) versus variations in the load demand. As a result, the slow fluctuations in the voltage profile of the connected power distribution feeder are occurred.

To address the above problem, BESS will be charged in the mid-day when there is excess solar PV generation, and discharged in the evening when there is no solar PV generation but higher residential load. The real time selection of the rate of change of charge/discharge current \( \frac{di_{\text{BESS}}}{dt}(t) \) of the BESS is crucial for the voltage control as the use of the limited storage needs to be maximized.

The improvement in the voltage \( \Delta V \) is related to the rate of change of charge/discharge current of the BESS \( \frac{di_{\text{BESS}}}{dt}(t) \). For example, if the improvement in voltage is 0.1 pu when \( \frac{di_{\text{BESS}}}{dt}(t) \) is 20 A/h, it will be higher when \( \frac{di_{\text{BESS}}}{dt}(t) \) is 30 A/h, and it will be lower when \( \frac{di_{\text{BESS}}}{dt}(t) \) is 10 A/h.

Similarly, the time \( T \) it takes to fully charge or discharge the battery capacity, C, (within its specified depth of discharge) is inversely related to \( \frac{di_{\text{BESS}}}{dt}(t) \). The higher \( \frac{di_{\text{BESS}}}{dt}(t) \), the faster it takes to charge or discharge the battery capacity (within its specified depth of discharge) and vice versa.
Because of the limited capacity of the battery, it is desirable to ensure that the full capacity of the battery is used during charging/discharging. For example, if the rate of change of battery charging is too high, the battery will be fully charged to its full capacity while there is still excess PV generation, and therefore the voltage rise will still occur. Similarly, if the rate of battery charging is too low, at the end of the duration of the voltage rise, the battery is not fully charged and hence we have not maximized the use of the battery capacity.

In our proposal, the selection of $\frac{d\text{exit}}{dt}(t)$, is based on the voltage at the point of common coupling (PCC). When the voltage at PCC deviates more from the operating voltage boundary, the rate of change of charge/discharge is higher, and when it deviates less from the operating voltage boundary, the rate of change of charge/discharge is lower. This has been expressed in Table 3.1 in Chapter 3.

Fig. 4.2 illustrates the methodology for the selection of parameters.
The voltage severity level decision parameters $Y_1$, $Y_2$ and $Z_1$, $Z_2$ are determined based on the initial voltage profile. The voltage profile, which lies outside the operating voltage range, is divided into sections based on the deviation from operating voltage range. However, the number of sections and the size of a section can be different for each case study. During our work, we have divided the voltage profile into three sections for charging and three sections for discharging. Once $Y_1$, $Y_2$ and $Z_1$, $Z_2$ are determined, parameter values $X_1$, $X_2$, $X_3$, $W_1$, $W_2$ and $W_3$ can be determined as the energy stored during charging to be discharged totally at the end of discharging period of BESS (4.1).

\[
(X_1 \times \Delta T_1) + (X_2 \times \Delta T_2) + (X_3 \times \Delta T_3) \\
= (W_1 \times \Delta t_1) + (W_2 \times \Delta t_2) + (W_3 \times \Delta t_3)
\]

(4.1)
Where, $\Delta T_1, \Delta T_2, \Delta T_3$ are charging durations with the rates change of charging $X_1, X_2, X_3$ respectively and $\Delta t_1, \Delta t_2, \Delta t_3$ are discharging durations with the rates of change of discharging $W_1, W_2, W_3$ respectively. Initially, the simulation will be performed with $X_1$ as the lowest rate of change of charging and $X_3$ as the highest rate of change of charging; $W_1$ as the lowest rate of change of discharging and $W_3$ as the highest rate of change of discharging within the physical constraints of the BESS. During the simulations, the results will be analysed if the voltage profile is maintained within the operating voltage range after applying the proposed voltage control method. The BESS capacity will be increased if the highest rate of change of charging ($X_3$) or the highest rate of change of discharging ($W_3$) is not capable to support the voltage control. Also, the BESS capacity will be decreased if the lowest rate of change of charging ($X_1$) or the lowest rate of change of discharging ($W_1$) is capable of supporting voltage, but the utilization of the BESS capacity is less.

The rate of change of the charge/discharge power output of BESS for the voltage control ($\frac{dP_{BESS\_SF}}{dt}(t)$) can be calculated as per Eq. (3.8)
3) Modeling of BESS to mitigate both fast and slow fluctuations in voltage profile

Even though \( \frac{dP_{\text{BESS}_F}}{dt}(t) \) and \( \frac{dP_{\text{BESS}_S}}{dt}(t) \) are determined separately for the mitigation of the fast and slow fluctuations, both can be integrated to form \( P_{\text{BESS}}(t) \) to charge or discharge the BESS for voltage control. In this thesis, we have separated the two, to show more clearly the outcome of each of the proposed strategy.

The power output of the BESS, \( P_{\text{BESS}}(t) \) for voltage control is determined based on the BESS power output at the previous instance \( P_{\text{BESS}}(t-T) \) and the rate of change of charge or discharge of the BESS power output for the current instance as Eq.(3.10) in Chapter 3.

Proper measures should be taken to avoid overcharging the BESS during the charging/discharging periods. Hence, the BESS State of Charge (SoC) will be maintained between 20-100% during the entire control operation. The initial SoC of the BESS must be sufficient to mitigate the fast fluctuations that occur prior to the start of BESS charging for the slow fluctuations in mid-day. In addition, the capacity of the BESS must be sufficient to control voltage during the entire period.
4.3 Case Studies

The feeder data for a section of the practical MV/LV network (Fig. 3.6) in NSW, Australia is used to demonstrate the effectiveness of the proposed method described in Section 4.2.

Fig. 3.6 in Chapter 3, shows a small low-voltage feeder connected to MV/LV network, which is derived from a practical system in New South Wales, Australia. The system consists of a 11kV/400V transformer and 16 LV buses. Each LV bus is connected to a household with a 5kW rooftop solar PV and a BESS installed.

Various BESS capacities are considered during the initial simulations to identify the optimum capacity and the optimum operation. The voltage control strategy associated with the fast fluctuations is to maintain the magnitude of the maximum rate of change of the solar PV inverter output \( \frac{dP_{INV}}{dt} \) at 5 Watts/s. The voltage control strategy associated with slow fluctuations is to select the optimum parameter values for \( X_1, X_2, X_3, W_1, W_2, Y_1, Y_2, Y_3, Z_1 \) and \( Z_2 \) on the initial voltage level. The minimum value of SoC used was 20% and the maximum value of the SoC used was 100% for all the trial simulations. Also for the test feeder used in this study, the lower voltage limit, \( V_L \) and the higher voltage limit, \( V_H \) are set according to the Australian Standard, AS60038 as 0.94 pu and 1.1 pu, respectively.
Initialy, 250 Ah BESS was considered for simulations. The initial SoC level was assumed as 30% of the full BESS capacity.

Fig. 4.3 illustrates the variation of the raw solar PV output, the BESS power output for fast fluctuation control and the inverter output with fast fluctuation control over the selected 24hr time duration. The fast fluctuations with high ramp rates occur between 10am to noon due to cloud passing. Moreover, fairly large isolated ramping events have occurred from 12.30 pm to 4 pm. The compensation provided by the BESS for the mitigation of fast fluctuations has successfully softened the solar PV inverter output.
Figure. 4.4: Variation of BESS SOC in 22-31% SoC range

Fig. 4.4 illustrates the SoC variation during the mitigation of fast fluctuations in the solar PV output. A solar PV output drop of 2.77kW occurs around 11:30 am lasting for 20 sec. The mitigation of this event lasts around 800 sec. with the BESS losing 4.74% of its SoC. Fig 4(b) shows that about 8% of the full capacity of BESS is used for the fast fluctuation control during entire 24hr period. Few frequent but smaller fluctuations occur around 12.30 pm to 4:30 pm, which have caused continuous drop in the SoC level of the BESS. With sufficient initial storage available in the 250Ah battery, fast fluctuations can be mitigated without any interruption.
4.3.1 Comparison on the mitigation of fast fluctuations in the solar PV output using various BESS sizes

The initial SoC level must assure that sufficient energy is stored in the BESS to facilitate the mitigation of fast fluctuations which can occur anytime without reaching the minimum allowed SoC level (which is 20%) of BESS. Based on the results with a 250 Ah BESS, the initial SoC level of 35% was used for simulations with 200Ah and 150 Ah BESS, 40% with 120 Ah BESS to ensure that there is sufficient capacity available for the mitigation of the fast fluctuations. Fig. 4.5 illustrates the SoC variation for different BESS capacities for the mitigation of fast fluctuations in the solar PV output.

Figure. 4.5: Variation of Different BESS SOC in 22-40% SoC range

Accordingly, the variation of the SoC is apparently similar in its behavior but different in how much the percentage of the SoC is used. The BESS with 120 Ah used 16% of SoC when the BESS with 250 Ah used only 7.5% of SoC for fast fluctuation control. The BESS with 150 Ah and 200 Ah used 13% and 10% of SoC.
respectively. Accordingly, all the BESS capacities have reached 22-25% minimum SoC for fast fluctuation control within 24hr period which avoids the undercharging of the BESS without any interruption.

Next, the optimum sizing of the BESS will be decided based on the ability to provide the slow fluctuation control to comply with Australian Standard, AS60038 having selected initial SoC levels in this section.

4.3.2 **Comparison on the mitigation of slow fluctuations in the voltage profile using various BESS sizes**

The mitigation of the slow fluctuations in the voltage profile is performed as the methodology explained in Section 4.2.2 2). The parameters used for slow fluctuation control with different BESS capacities are given in Table 4.1 for charging and Table 4.2 for discharging.

**Table 4.1: Parameter Selection for Slow Fluctuation Control during Charging**

<table>
<thead>
<tr>
<th>Capacity</th>
<th>$Y_1$(P.U)</th>
<th>$Y_2$(P.U)</th>
<th>$X_1$(A/h)</th>
<th>$X_2$(A/h)</th>
<th>$X_3$(A/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 Ah</td>
<td>0.004</td>
<td>0.004</td>
<td>12.5</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>200 Ah</td>
<td>0.004</td>
<td>0.004</td>
<td>12.5</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>150 Ah</td>
<td>0.004</td>
<td>0.004</td>
<td>12.5</td>
<td>25</td>
<td>46</td>
</tr>
<tr>
<td>120 Ah</td>
<td>0.004</td>
<td>0.004</td>
<td>12</td>
<td>24</td>
<td>40</td>
</tr>
</tbody>
</table>
Table 4.2: Parameter Selection for Slow Fluctuation Control during discharging

<table>
<thead>
<tr>
<th>Capacity</th>
<th>$Z_1$ (P. U)</th>
<th>$W_1$ (A/h)</th>
<th>$W_2$ (A/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 Ah</td>
<td>0.01</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>200 Ah</td>
<td>0.01</td>
<td>25</td>
<td>55</td>
</tr>
<tr>
<td>150 Ah</td>
<td>0.01</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td>120 Ah</td>
<td>0.01</td>
<td>26</td>
<td>40</td>
</tr>
</tbody>
</table>

Several trial simulations were run for each BESS capacity to identify the optimum set of parameters to provide voltage control with the available capacity. Fig. 4.6 to Fig.4.9 illustrates the improvement in the voltage profile with the utilization of different BESS sizes. The selection of parameters $X_1 - X_3$ and $W_1 - W_2$ was based on the ability to maintain voltage profile within the operating voltage limit without overcharging or undercharging the BESS within the physical constraints of BESS.
Figure. 4.6: Improvement in voltage profile with different BESS capacities

Figure. 4.7: (Left) Zoomed plot of (Fig.4.6) during charging 250 sec. period

Figure. 4.8: (Right) Zoomed plot of (Fig.4.6) during discharging 250 sec. period
The selection of the charge/discharge rates for all the BESS capacities were based on Eq. (4.1). Also, the maximum charging/discharging rate did not exceed the C/3 (capacity hour) rate to comply with the manufacturer specification of the lead acid BESS. According to Table 4.2, BESS with 120 Ah charge and discharge at C/3 rate (40A/h) for voltage control, which is illustrated in Fig. 4.5 to Fig.4.8. However, the 120 Ah BESS is not capable of maintaining the voltage profile within the operating limit according to the Australian Standard, AS60038. 150 Ah BESS discharge at C/3 rate (50A/h) and charge at C/3.26 rate (46A/h which is lesser than C/3) to maintain the voltage profile within the operating limits. Moreover, 200 Ah BESS discharge at C/3.64 rate (55A/h), charge at C/5 (50A/h) and 250 Ah BESS discharge, and charge at C/5 (50A/h) to maintain the voltage profile within operating limits. Accordingly, 150 Ah is the BESS to achieve voltage control according to Australian Standard, AS60038 while charging and/or discharging at the highest rate as per the manufacturer specification.

Figure. 4.9: The overall SoC variation with different BESS capacities
Fig. 4.9 illustrates the overall variation of SoC with the utilization of the different BESS sizes. Accordingly, 250 Ah, 200 Ah, 150 Ah and 120 Ah BESS have reached 62%, 77%, 90% and 99% of SoC at the end of charging period. However, the optimum sizing of BESS is the capacity which has the ability to maintain voltage profile within the operating voltage limit without overcharging or undercharging the BESS. Moreover, 10% margin of SoC will be allowed to meet any unexpected variations in voltage which can occur anytime.

Hence, 150 Ah BESS is the optimum size of the BESS to provide voltage control at Bus 16 in the system illustrated in Fig. 3 for the selected data set. The 150 Ah BESS can be charged up to 90% of SoC during charging with the maximum rate of C/3.26 (46 A/h) and will reach 35% of SoC (which is the initial SoC level as well) at the end of discharging period with the maximum discharging rate of C/3 (50 A/h). Accordingly, at the end of discharging period the BESS returns the SoC to its initial value for use in the next day.

4.4 Summary

The optimum sizing and the optimum operating parameters for voltage control for BESS to mitigate the slow and fast fluctuations of solar PV output has been presented. Sufficient capacities for the mitigation of slow and fast voltage fluctuations have been determined through simulations using different BESS capacities. The fast voltage fluctuations have been mitigated by charging/discharging the BESS to maintain the rate of change of the inverter output at a specified level. Slow fluctuations have been mitigated by charging the BESS during mid-day and by discharging during the evening peak time. In addition, three charging/discharging
rates for voltage control based on the severity level of voltage at PCC have been proposed. The sizing and the optimum operating parameters for the proposed method have been determined using a practical network in NSW. A BESS with a capacity of 150 Ah was identified as the optimum size for the voltage control strategy to mitigate the fast and slow voltage fluctuations. The sizing of the BESS is based on the minimum capacity to support voltage control during the 24hr period to maintain voltage profile within operating limit without exceeding physical limitations of the BESS while achieving the SoC at the end of the day similar to initial SoC.
Chapter 5

Slow and Fast Fluctuations of the Voltage of Rooftop Solar PV using an integrated Hybrid Energy Storage System

5.1 Introduction

In 2016, the rooftop solar PV generation was providing approximately 16.0 per cent of Australia's clean energy generation. In fact, the solar PV generation was 2.8 per cent of the country's total electricity requirement [80]. Specifically, the rooftop solar PV has become popular within the country during last 2 decades. There were suburbs with more than forty per cent of the rooftop solar PV installations in Australia by July, 2017 [81].

The energy storage system technologies available at present are not capable to satisfy the wide frequency spectrum of generated renewable energy using a single energy storage technology. Therefore, the Hybrid Energy Storage System (HESS) technology has been introduced where two types of ES’s are complimenting each other to achieve power and energy requirement in overall. The HESS combination with an ES with high energy density and an ES with high power density is commonly utilised. However, the HESS technology is still in its infancy and requires further advancement.

The HESS, consisting of battery-super capacitor combination, has been discussed in [83-86] that is integrated with wind energy generation. A coordination methodology between the battery and the super-capacitor is discussed in [84] to manage the active and the reactive power flow among remote area power supply systems (off-grid).
However, the study is based on a dynamic simulations where each storage responds to the demand - generation mismatch based on the frequency component. A design of a least cost battery - super capacitor energy storage system with the concern of various storage capacities to meet the power dispatch requirement for a hypothetical wind farm has been discussed in [85]. However, the work did not discuss an exact method to obtain the power output of the integrated system. The sizing of a HESS with a battery and a super-capacitor for power balancing in an isolated system with wind power is studied in [86]. A frequency based approach is studied to maintain the grid frequency stability. The HESS has been mostly investigated in the context of wind energy within the literature.

However, there is a recent tendency for the HESS studies related to the area of solar energy [87-88]. An inverter (residential and large scale solar systems) is developed to inject the active power to the grid in 15 min intervals in [87] in which the power is shared to maintain the system output constant during 15 min interval. The main drawback of the discussed method is the power output requirement which has to be met though the ES through continuous operation. The reference power output tends to differ from the original output always urging the HESS to operate; this might increase the operational cost of the system. A method to suppress the power fluctuation of the solar power generation in a large scale system during the radiation change was studied in [88]; several methods have been compared for power sharing between the BS and SCS.

There is an urging requirement for novel power sharing methodology/methodologies related to the residential solar PV systems integrated with HESS at present. Where the cost related to ES manufacturing is drastically dropping; the limitations in the
penetration level of the residential rooftop solar PV units in a distribution feeder can be eliminated by developing proper energy management techniques.

This chapter will present the application of hybrid energy storage for the control of slow and fast fluctuations of voltage profile in the connected LV distribution feeder. The slow fluctuations (due to the variations of sun irradiation and load demand) will be alleviated using the BS and the fast fluctuations (due to the ramping events caused by passing cloud) will be alleviated using the super capacitor storage (SCS). The capacity (sizing) of the BS and the SCS will be decided based on the HESS topology and the 24-hour availability of energy for the simultaneous control of SF and FF. Next sections of this work will be organized as Section 5.2: System Description and Modelling Section 5.3: The Proposed Method HESS to Mitigate the Slow and Fast Variations in PV output, Section 5.4: Case Studies, Section 5.5: Conclusion and Section.

**5.2 System Description and Modelling**

Fig.5.1. illustrates the energy density (Wh/kg) vs the power density (W/kg) for different electrochemical energy storages. Accordingly, Lead-Acid battery has high energy density but very low power density. Ultra-capacitor has less energy density but high power density. Hence, during this work Lead-Acid BS and Ultra-capacitor storage will be combined to produce HESS.
The HESS has a better performance compared with the BS only systems. The lifetime of the BS is extended as the integrated SCS causes reduction in the discharge rate of BS [90]. The BS will be providing the long term stable power, while the SCS provides short term power fluctuations.

5.2.1 Parallel Active topology for HESS

The introduction of HESS creates whole new set of problems such as, the challenges of power division among the BS and the super-capacitor and the identification of appropriate coordination to satisfy the exact requirement [55]. Different HESS topologies and different EMS for HESS have been reported in literature. The parallel DC/DC converter topology provides each storage device the capability to be controlled independently giving the flexibility to the control algorithm [55-56]. Fig. 5.2. shows the parallel DC/DC converter topology used during this work.
Figure 5.2: Parallel DC/DC converter topology for the connection of Battery and Ultra-capacitor with PV system

The BS and the SCS are connected in parallel through bidirectional DC/DC converters. This topology allows the SOC of both the BS and the SCS to be controlled independently during the charging and discharging process [55]. Moreover, the DC-link voltage is not directly affected by the SOC of the ES’s. A bidirectional DC/DC converter is used after the solar PV panels to connect to the DC link. The DC link voltage must be in a certain voltage range to properly generate the AC side voltage [94-95]. An inverter is used to maintain the AC side $230V_{\text{rms}}/50\text{Hz}$ voltage.
5.2.2. Modelling HESS

The main objective of using the HESS is to divide the power variations of the system into two parts based on the rate of charge/discharge required to alleviate SF and FF.

Figure 5.3: Parallel DC/DC converter connections of BS and SCS with Energy Management System (EMS)

The slow charge/discharge component will be injected/absorbed by the BS and the fast charge/discharge component will be injected/absorbed by the SCS.

5.2.2.1 Voltage level at DC link ($V_{DC\text{-}link}$)

The bi-directional DC/DC converters connecting the ES’s with the DC link provide the independent control of each ES with a greater flexibility for energy management through the EMS. The efficiency of the bi-directional DC/DC converters is important for the performance of the EMS. A DC/AC converter (inverter) is used to convert the DC voltage to the AC voltage. A typical rooftop solar PV inverter efficiency can vary depending on the inverter load. The high quality sine wave inverter efficiency lies between 90-95% [93]. The general inverter efficiency ($\eta$) formula is given by Eq. (5.1).
\[ \eta = \frac{P_{AC}}{P_{DC}} \]  

(5.1)

Where, \( \eta \) is the inverter efficiency, \( P_{AC} \) is the power output in the AC side of the inverter, \( P_{DC} \) is the power output in the DC side of the inverter. The power output of the DC side and the AC side can be elaborated using the current \( i \) and the voltage \( V \) in each side as below,

\[ \eta = \frac{i_{AC} \times V_{AC}}{i_{DC} \times V_{DC}} \]

The inverter is used to generate the AC side 230V <sup>rms</sup>/50Hz voltage as shown in Fig.5.3. Therefore, the DC link voltage, \( V_{DC\text{-link}} \), must satisfy Eq. (5.2) assuming the inverter efficiency is between 90-95% and the rms value of AC side current (\( i_{AC} \)) is equivalent to the peak value of the DC side current (\( i_{DC} \)).

\[ 342V < V_{DC\text{-link}} < 361V \]  

(5.2)

Accordingly, the DC link voltage, \( V_{DC\text{-link}} \), within the range of 342V to 361V will be considered during designing process of HESS.

5.2.2.2 The Voltage level at the Energy Storage (\( V_{BS} \) and \( V_{SCS} \))

The objective of using the DC/DC converters in parallel is to maintain the BS current as constant as possible with the slow transition from low to high current during fast and high fluctuations to limit the battery stress. On the other hand, the SCS ought to charge/discharge as fast as possible without exceeding the maximum operating current due to fast fluctuations caused by sudden cloud passing over the rooftop solar PV generator [94].
The bidirectional DC-DC converters used during this work is connected in series with the BS and the SCS; that exchanges power between the DC link and the energy storage system (BS/SCS). The voltage ratio of the DC link to the energy storage side is approximately 6 to 1. The conversion efficiency decreases with the increase of the ratio [95]. However, bidirectional DC-DC converters used in this work have realized with the conversion efficiency of 94% or higher during both charging and discharging [95]. According to the datasheet [96], the high voltage side DC voltage can vary from 300V to 380V, and the low voltage side DC voltage can vary from 36V to 60V. Accordingly, to meet the $V_{DC\text{-link}}$ voltage requirement in (5.2),

$$41V < V_{ES} < 57V \quad (5.3)$$

Where, $V_{ES}$ is equivalent to the DC voltage at the energy storage. Accordingly, the $V_{ES}$ ought to vary from 41V to 57V.

5.2.2.3 Sizing BS to meet the DC voltage requirement

The BS voltage is usually the cell voltage multiplied by the number of cells in series. The ampere-hour capacity of the BS is the same as the ampere-hour capacity of a single cell [97]. The DC voltage at the BS is assumed to be 48V for modelling in this section. The cell voltage is approximately 2V [50], hence 24 cells are needed to connect in series to make 48V BS.

As per simulations, the required energy ($E_{SFC}$) for the slow fluctuation control (SFC) during the selected 24hr period for the selected dataset,

$$E_{SFC} = 10800 \text{ kJ} \quad (5.4)$$
The required energy ($E_{SFC}$) for the SFC, can be as below,

$$E_{SFC} = \frac{BS_{Ah} \times BS_{V} \times 3600}{1000}$$  

(5.5)

Where, $BS_{Ah}$ is the capacity of the Battery cell, $BS_{V}$ is the voltage in a battery cell array. Accordingly, after solving both Eq. (5.4) and (5.5); the BS capacity of 62.5 Ah with 48V DC voltage will be required for the modelling of the HESS.

5.2.2.4 Sizing SCS to meet the DC voltage requirement

The DC voltage at the SCS is assumed to be 48V for modelling in this section. The cell voltage is approximately 3V [98], hence 16 cells are needed to connect in series to make 48V SCS.

As per simulations, the required energy ($E_{FFC}$) for the fast fluctuation control (FFC) during the selected 24hr period for the selected dataset,

$$E_{FFC} = 6912 \text{ kJ}$$  

(5.6)

The required energy ($E_{VC}$) for the FFC, can be as below,

$$E_{FFC} = \frac{1}{2} \frac{c \times v^2}{1000}$$  

(5.7)

Where, $c$ is the capacity of the super-capacitor cell, $v$ is voltage in the super-capacitor cell array. Accordingly, after solving both Eq. (5.6) and (5.7); the super-capacitor equivalent capacitance of 6000F with 48V DC voltage will be required for the modelling of HESS. Accordingly, 16 cells with 3000F [98] capacity will be connected in series [99], with a total capacitance of 187.5F in an array. An equivalent
32 arrays will be connected in series to form the required super-capacitor capacity of 40Ah with 48V DC voltage for the modelling of HESS.

5.3 The Proposed Method to Mitigate the Slow and Fast Fluctuations in PV output Using HESS

The slow fluctuations in the rooftop solar PV output is caused by the geographical movement of the sun starting at sun rise to sun set. The sun irradiation and insolation variation due to the movement of sun affect the solar PV output. The fast fluctuations in the rooftop solar PV are caused by the sudden cloud passing. The severity (magnitude of the rate of ramp) in the fast fluctuations increases with the sudden variation in the clouds. The objective of this work is to propose an energy management technique to mitigate both the slow and the fast fluctuations at the PCC of the residence with rooftop solar PV unit integrated with HESS [100].

The HESS will be used to balance the supply and demand. Accordingly, in its simplest term, the power output from the solar panel ($P_{PV}$) plus the power output of HESS, $P_{HESS}$ should be equal to the load demand ($P_{Load}$), assuming that the HESS has infinite capacity:

$$P_{PV} + P_{HESS} = P_{Load} \quad (5.8)$$

Eq. (5.8) shows that the supply and the demand can be balanced, irrespective whether $P_{PV}$ is larger or smaller than $P_{Load}$ as long as there is sufficient $P_{HESS}$ from the HESS to meet the difference. However, practically there will be power injection/absorption to/from the grid depending on the physical capability of HESS. Hence, power balancing equation will be like below:
\[ P_{PV} + P_{HESS} = P_{Load} + P_{Grid} \] (5.9)

Eq. (5.9) shows that any imbalance between supply and the demand can be injected/absorbed to/from the grid, \( P_{Grid} \).

### 5.3.1 Mitigation of Fast Fluctuations in voltage profile using Super-capacitor storage

The SCS will be used to control the fast fluctuations in the solar PV inverter output. The slope of the power fluctuation of a PV solar panel at a given instance can be calculated as in Eq. (3.1).

The output of the integrated HESS and the PV inverter, \( P_{inv} \), can be obtained as an expression of the PV panel output power \( P_{PV} \), the inverter efficiency \( \eta_{inv} \) and the HESS output power \( P_{HESS} \), as given below:

\[ P_{inv} = \eta_{inv} \times (P_{PV} + P_{HESS}) \] (5.10)

Differentiating all the terms in (5.10) and rearranging them we obtain (5.11),

\[ \frac{dP_{HESS}}{dt} = \frac{1}{\eta_{inv}} \left[ \left. \frac{dP_{inv}}{dt} \right|_{def} - \eta_{inv} \times \frac{dP_{PV}}{dt} \right] \] (5.11)

The slope of the PV output \( \frac{dP_{PV}}{dt} \) is referred to as the PV slope (PVRR). PVRR is calculated based on Eq.(3.1). The inverter efficiency \( \eta_{inv} \) represents the efficiency of the inverter. The actual value of \( \eta_{inv} \) can be obtained from the manufacturer data sheet.

In our proposed method, the slope of the inverter output is fixed to a defined value, which is referred to as the Maximum defined slope (MARR). The defined slope is set
as negative \((MARR_{\text{min}})\) when the slope of PV output is negative, and set as positive \((MARR_{\text{max}})\) when the slope of the PV output is positive; otherwise, it is set as zero (when there is no slope in the PV output).

After the selection of the MARR based on the slope of the solar PV output; the slope of the HESS output, \(\frac{dP_{\text{NESS}}}{dt}(t)\) can be calculated. The slope of the HESS consists of two parts: the slope of SCS during FFC and the slope of BS during SFC. This relationship can be shown in (5.12) below:

\[
\frac{dP_{\text{NESS}}}{dt}(t) = \frac{dP_{\text{BS}}}{dt}(t) + \frac{dP_{\text{SCS}}}{dt}(t)
\]

(5.12)

Where, \(\frac{dP_{\text{SCS}}}{dt}(t)\) is the slope of SCS for the FFC; \(\frac{dP_{\text{BS}}}{dt}(t)\) is the slope of BS for the SFC.

The slope of the SCS output, \(\frac{dP_{\text{SCS}}}{dt}(t)\) can be obtained as below:

\[
\frac{dP_{\text{SCS}}}{dt}(t) = \begin{cases} 
0, & \text{if } |PVRR| \leq |MARR| \\
MARR - PVRR, & \text{otherwise}
\end{cases}
\]

(5.13)

\(\frac{dP_{\text{SCS}}}{dt}(t)\) is zero when the absolute value of the current PVRR is equal or lower to the absolute value of the specified MARR. \(\frac{dP_{\text{SCS}}}{dt}(t)\) is the difference between the absolute value of the current PVRR and the specified MARR, otherwise.

5.3.2. Mitigation of Slow Fluctuations in voltage profile using Battery Storage

During the day time, the load demand is lower than the solar PV generation (in a regular sunny day. However, the grid support is needed, when there is no or less solar PV generation in the evening peak hours. This imbalance in generation and
demand can be compensated using the BS to charge during the day-time and discharge during the evening peak hours.

During the day-time, both the FFC and the SFC are in operation. However, only the SFC is in operation during the evening peak hours, as the solar PV generation becomes zero at that time.

\[
\frac{d_i}{dt}(t) = \begin{cases} 
0, & \text{if } V_{\text{Ref,L}} < V_{\text{PCC}} < V_{\text{Ref,H}} \\
X_1(1 + \Delta V'), & \text{if } (V_{\text{Ref,H}}) < V_{\text{PCC}} < (V_{\text{Ref,H}} + Y_1) \\
X_2(1 + \Delta V''), & \text{if } (V_{\text{Ref,L}} - Z_1) < V_{\text{PCC}} < (V_{\text{Ref,L}}) \\
W_1(1 + \Delta V^*), & \text{if } V_{\text{PCC}} < (V_{\text{Ref,L}} - Z_1) \\
W_2(1 + \Delta V^{**}), & \text{if } (V_{\text{Ref,H}} + Y_1) < V_{\text{PCC}} < (V_{\text{Ref,H}} + Y_1) \\
\end{cases}
\] (5.14)

Our proposed method uses multiple sets of voltage levels of measured voltage at PCC for the determination of the rate of charge/discharge \((\frac{d_i}{dt}(t))\). The rate of charge/discharge is higher when the voltage at PCC deviates more from the operating voltage range; the rate of charge/discharge is lower when the voltage at PCC deviates less from the operating voltage range (Eq.5.14).

Where, \(\Delta V', \Delta V'', \Delta V^*, \text{and } \Delta V^{**}\) are the voltage difference from the selected boundary. \(X_1 < X_2\) and \(W_1 < W_2\) are decided based on maintaining the voltage profile at PCC within the operational range in the optimum manner. Accordingly, the parameters will be selected as the BS is not exhaustively being charged or discharged. \(Y_1 \text{ and } Z_1\) are decided to maintain the voltage profile closer to the boundaries of operational voltage limits, which avoid exhaustive operation of BS. The suitable set of parameters in (5.14) is found through running simulations for the specific PCC.
Further details about the selection of above parameters can be found in Chapter 4.

The current rate of charge/discharge in A/h obtained in (5.14) and the current SoC obtained [89]) are then used with the battery characteristic curves [50] to obtain the correct battery voltage \( V_{BS}(t) \) using interpolation.

The rate of charge/discharge of the power output of BS for the voltage control \( \frac{dP_{Bar_VC}}{dt}(t) \) can be calculated as in (5.15).

\[
\frac{dP_{BS}}{dt}(t) = \frac{dS_{BS}(t)}{3600} \times 4 \times V_{BS}
\]  

(5.15)

Where, \( \frac{dS_{BS}(t)}{dt} \) is the current charge/discharge rate of the 12V lead acid battery in A/h, and \( V_{BS}(t) \) is the Battery Voltage in V obtained by interpolation using the battery characteristic curves. Battery voltage obtained through the interpolations should be times by 4 as we use 48 V lead acid BS during this study.

The power output \( P_{BS}(t) \) is calculated based on the BS power output at the previous instance and slope of the BS power output determined in (16).

\[
P_{BS}(t) = P_{BS}(t - T) + \left[ \frac{dP_{BS}}{dt}(t) \right] \times \left( t - (t - T) \right)
\]  

(5.16)

Accordingly, \( P_{BS}(t) \) will be calculated using the BS power output in the previous instance, \( P_{BS}(t - T) \) and the slope of the BS power output in the present instance, \( \frac{dP_{BS}}{dt}(t) \).

5.3.3. Tuning the charge/discharge rate of SCS for FFC

Once the \( \frac{dP_{SCS}}{dt}(t) \) and \( \frac{dP_{BS}}{dt}(t) \) are obtained as per Section 5.3.1 and 5.3.2, they are used in (5.17) to calculate the slope of the inverter output, \( \frac{dP_{inv}}{dt}(t) \).
\[
\frac{dP_{\text{inv}}}{dt}(t) = \frac{dP_{\text{BS}}}{dt}(t) + \frac{dP_{\text{SCS}}}{dt}(t) + \frac{dP_{\text{solar}}}{dt}(t) \tag{5.17}
\]

The slope of BS, \(\frac{dP_{\text{BS}}}{dt}(t)\) is the value calculated in (5.15) above. Calculated \(\frac{dP_{\text{inv}}}{dt}(t)\) in (5.17) may exceed MARR in certain situations where tuning is required. Hence, \(\frac{dP_{\text{inv}}}{dt}(t)\) will be tuned as below:

\[
\frac{dP_{\text{inv}}}{dt}(t) = \begin{cases} 
MARR_{\text{max}} - PVRR, & \text{if } \frac{dP_{\text{inv}}}{dt}(t) > MARR_{\text{max}} \\
MARR_{\text{min}} - PVRR, & \text{if } \frac{dP_{\text{inv}}}{dt}(t) < MARR_{\text{min}}
\end{cases}
\tag{5.18}
\]

Accordingly, the slope of the inverter output is always maintained to be within the defined range \((MARR_{\text{min}} < \text{MARR} < MARR_{\text{max}})\).

The above procedure of tuning the slope of the inverter output using (5.17) and (5.18) can be explained using (5.4).

Fig. 5.4 depicts a situation where \(\frac{dP_{\text{inv}}}{dt}\) was higher than \(MARR_{\text{max}}\) after the calculation in (5.17). PVRR is larger than MARR (which is \(MARR_{\text{max}}\) since PVRR is positive) at the time instance \(T_1\); HESS start charging and hence the slope of the inverter output, \(\frac{dP_{\text{inv}}}{dt}\) is maintained below MARR. The PVRR at the time instance \(T_2\) is even larger than PVRR at \(T_1\); SCS starts charging at a higher rate and hence \(\frac{dP_{\text{inv}}}{dt}\) is maintained at MARR. The PVRR drops to zero at the time instance \(T_3\) and hence MARR is zero. HESS charging rate become zero (depicts as ‘c’ in \(\frac{dP_{\text{HESS}}}{dt}\) plot) and hence \(\frac{dP_{\text{inv}}}{dt}\) goes higher (depicts as ‘a’ in \(\frac{dP_{\text{inv}}}{dt}\) plot) than \(MARR_{\text{max}}\) which is not desirable for FFC. This phenomenon occurs due to already achieved power output of
HESS which is ought to be controlled in a favourable manner to maintain \( \frac{dP_{inv}}{dt} \) within the expected range \( MARR_{min} < MARR < MARR_{max} \)

Figure 5.4: Tuning of the slope inverter output at the defined value MARR

Accordingly, initial result of Eq. 5.17 will be higher than \( MARR_{max} \) for the time instance \( T_3 \). Hence, new value for \( \frac{dP_{HESS}}{dt} \) (which is equivalent to \( \frac{dP_{inv}}{dt}(t) + \frac{dP_{SCS}}{dt}(t) \)) will be obtained by (5.17). Accordingly, \( \frac{dP_{HESS}}{dt} \) to be implemented on HESS as per Fig. 5.4 depicts as ‘d’ and the relevant value of \( \frac{dP_{inv}}{dt} \) which is maintained at \( MARR_{max} \) depicts as ‘b’.

Once \( \frac{dP_{HESS}}{dt} \) have been calculated during tuning of the slope of inverter output, the signal is given to SCS to generate the power output for FFC. The power output \( P_{SCS}(t) \) is calculated based on the SCS power output at the previous instance and slope of the SCS power output determined in (5.17).
\[
P_{SCS}(t) = \begin{cases} 
0, & \text{if } |P_{VRR}| \leq |MARR| \\
P_{SCS}(t-T) + \frac{dP_{BS}}{dt}(t-T) + \left[\frac{dP_{SCS}}{dt}(t)\right] \ast (t - (t - T)), & \text{otherwise}
\end{cases}
\]

(5.19)

The slope of BS, \(\frac{dP_{BS}}{dt}(t-T)\) is the value calculated in (5.15) above. The voltage level at the PCC is maintained at an approximately constant voltage during mid-day and also in the period of evening peak load by following the above strategy for simultaneous FFC and SFC.

5.3.4. Management of HESS SoC to Ensure Undisrupted Slow and Fast Fluctuation Mitigation

The provision of undisrupted voltage control during both slow and fast fluctuations must be assured by managing the SoC of the BS and the SCS during the entire operation. Hence, the BS and the SCS are charged or discharged depending on the present SoC level to facilitate undisrupted supply considering following scenarios.

1) Scenario 1

The management of the BS SoC will be executed only during situations where there are no fast or slow fluctuations. Accordingly, the BS will be charged or discharged to manage SoC when there is no action required to mitigate slow fluctuations. The methodology is shown in (5.19);
\[
\frac{d\text{BS}}{dt}(t) = \alpha, \text{if} \ (V_{\text{Ref},H}) < V_{\text{PCC}} < (V_{\text{Ref},H} - \rho) \\
\text{and} \ (\text{SoC} < 30\%) \\
\frac{d\text{BS}}{dt}(t) = \beta, \text{if} \ (V_{\text{Ref},L} + \rho) < V_{\text{PCC}} < (V_{\text{Ref},L}) \\
\text{and} \ (\text{SoC} > 90\%) \\
0, \text{Otherwise} \\
\] (5.19)

Where, \(\alpha\) is the rate of charging of BS, \(\beta\) is the rate of discharging of the BS, \(\rho\) is the decision variable on the voltage range of \(V_{\text{PCC}}\). Accordingly, the BS is charged to manage SoC; if the SoC level is lower than 30\% while voltage at \(V_{\text{PCC}}\) lie within the standard operating range but not less than \(\rho\) amount (in P.U) from the upper limit. Moreover, the BS is discharged to manage SoC; if the SoC level is higher than 90\% while voltage at \(V_{\text{PCC}}\) lie within the standard operating range but not higher than \(\rho\) amount (in P.U) from the lower limit. In this study, \(\alpha\) and \(\rho\) values are selected as 0.05 P.U.

After, the determination of \(\frac{d\text{BS}}{dt}(t)\) to manage SoC; the rate of charge/discharge of the power output of the BS for the voltage control \(\frac{d\text{BS}}{dt}(t)\) can be calculated as in (5.15) and continue with the rest of the controller operation for the same time instance.

2) Scenario 2

The SCS will be charged during the dawn period if there is no sufficient energy stored to mitigate fast fluctuations in the next day. The required minimum SoC (stored energy) is determined through simulations. It is essential to assure the SoC of SCS is sufficient for FFC until the dawn, until it charges to prepare for the next day.
3) Scenario 3

In addition, a special feature is integrated with the HESS to utilize BS during extreme weather conditions, where SCS is over utilized for FFC. This feature will be activated mostly during extremely varying cloudy days. Accordingly, BS will be charged or discharged to provide FFC only unless SCS has sufficient SoC to mitigate fast fluctuations.

5.3.5. Implementation of the Simultaneous FFC and SFC using HESS to mitigate fluctuations in solar PV output

The proposed strategies for FFC and SFC have been incorporated into an integrated HESS and the solar PV system (Fig.5.2).

Fig.5.5 illustrates the flow chart for the integration of both methods and SoC management techniques. Initially, the slope of the solar PV output is calculated using Eq.(3.1); then the value of MARR is defined and the sign of MARR is determined ($MARR_{\text{max}}$ or $MARR_{\text{min}}$) based on whether PVRR is negative or positive. Then the slope of SCS is determined using Eq.(5.13). Second, the rate of change of current of BS is determined using Eq.(5.14). Next, the slope of BS power output and the BS power output for the SFC is calculated using Eq.(5.15) and Eq.(5.16) respectively.
At the next stage, the slope of the SCS is tuned using the calculated slope of BS, the slope of PV output (PVRR) and the defined PV inverter output (MARR). Next, the power output of the SCS for FFC is calculated using the tuned slope of SCS output and the SCS power output in the previous instance. The SoC management mechanisms for both SCS and BS are functioning in parallel with the FFC and SFC control mechanism. The SCS is charged only during the dawn period (1AM to 5AM), if the SoC level is less than 80% SCS will be charged. If the SoC of the SCS (including the intended charge/discharge of the present instance) is within 0% and 100%, SCS will be instructed to charge/discharge for FFC. Otherwise, the power output will be transferred to BS to handle FFC. Simultaneously, if the calculated BS power output for SFC is zero, the SoC of the BS will be charged/discharged if the SoC level is less than 30% /higher than 80% respectively. However, charge/discharge mechanism will be only function if the voltage at PCC follows the criteria explained in section 5.3.4. Otherwise, if the calculated power output of BS
has a value, the BS will be instructed to be charged/discharged for SFC if the SoC level of BS is within the range of 20% and 100%. Finally, both SFC and FFC will be implemented if all the conditions are satisfied. Then, the voltage level at PCC will be determined using quasi-steady-state power flow and the controller will move in to the next time step.

5.4 Case Studies

The proposed methodology was tested on a section of the practical MV/LV network (Fig.3.6) in NSW.

The tested practical MV/LV feeder consists of a 11kV/400V substation and 16 LV buses. Each bus includes a household with a 5kW rooftop solar PV installed with an integrated 62.5 Ah BS and 40 Ah SCS. Residential load demand is varying up to 3.5 kW during peak hours.

The following results will verify the validity of the proposed methodology through steady state analysis. Fig. 5.6 to Fig.5.9 shows the raw PV output, PVRR and MARR, SCS power and the inverter power output with FFC respectively.
Fig. 5.6 shows the raw solar PV generation for a selected day. The ramping events occur from 7.30 am to 8.15 am and 12.30 pm to 3.30 pm more frequently and vigorously. It has been smooth and only varies with the sun insolation/irradiation during most other time. The proposed methodology for FFC will be tested to mitigate fast fluctuations in raw solar PV output.

Figure.5.7: PVRR based on raw PV output and MARR
Fig. 5.7 illustrates the PVRR and the MARR of inverter output for FFC strategy proposed in this work. Zoomed section in Fig. 5.7 shows a 100-second duration starting at 27375 Second which clearly depicts the comparison of the PVRR and the MARR for each time instance. The magnitude of the highest MARR is used as 0.005 kW/second for this work. Accordingly, Fig. 5.7 illustrates the amount of control provided using BS to mitigate fast fluctuations.

![Graph showing PV inverter output and SCS output](image)

**Figure.5.8: SCS power and Inverter power output**

Fig. 5.8 shows the SCS power for FFC and the inverter power output after FFC. A 48V SCS with a 40Ah capacity is used for this study. The fast fluctuations have caused the SCS to charge/discharge to maintain the MARR of the inverter output.
Figure 5.9: SCS SoC variation

Fig. 5.9 depicts the SoC variation for fast fluctuation during 24hr period. Initial SoC level is 90% and the final SoC level in the end of 24 hr period is 7%. Accordingly, the mechanism to charge SCS during dawn period as discussed in section 5.3.4 must be activated prior to sun rise in the next day. With the proposed FFC, the magnitude of the slope of inverter output has been reduced from 0.55 kW/second to 0.005kW/second even during the highest ramping event (Fig.5.6 to 5.9). Similarly, all the fast fluctuations due to the passing cloud have been controlled successfully with the proposed FFC strategy.

The simulation results using the proposed approach for the simultaneous FFC and SFC is presented in Fig. 5.10 to Fig.5.13, which illustrates the net load at PCC with FFC, the net load at PCC with simultaneous SFC and FFC, BS power output for SFC, BS SOC variation for SFC and the voltage profiles for LV bus 16 in the MV/LV network.
Figure 5.10: The net load at PCC with FFC, the net load at PCC with simultaneous SFC and FFC, BS power output for SFC

Fig. 5.10 shows the net load at PCC with FFC, the net load at PCC with simultaneous SFC and FFC, BS power output for SFC. The BS is charged during mid-day using three different charging rates depending on the voltage at PCC. The BS is discharged with three different charging rates in the evening. Accordingly, the BS starts charging from 10am until 3 pm, and starts discharging from around 7pm until 9pm for SFC. Moreover, the BS is discharged around 5.30pm-5.45pm according to the BS SoC management criteria mentioned in Section 5.3.4. The power output of the BS during discharge is shown in Fig.5.10 while the voltage profile during this charge is shown in Fig.5.13 during the BS SoC management.
Fig. 5.11 depicts the variation of the BS SoC for SFC. The SoC of the BS started from 60% SoC and ended to be 52% of the SoC at the end of the day after carrying out SFC. A charging/discharging mechanism will be incorporated with the BS, during idle situations of the BS to assure the SoC is not too high (90% of SoC) or too low (30% of SoC). Accordingly, the SoC management mechanism has been operated around 5.30 pm-6.45pm. The BS starts to discharge when the SoC is about 96% and the voltage profile is within the operating range (specific range is mentioned in section 5.3.4, up to around 89% SoC. The variation of voltage profile is about 0.025 P.U during the SoC management period according to Fig.5.13.
Fig. 5.12 and Fig. 5.13 show the voltage profiles at PCC of the 16th LV bus in the test feeder. Fig. 5.12 depicts the voltage profile without any control. Fig. 5.13 depicts the voltage profile with simultaneous FFC and SFC. Fig. 5.12 shows that the fast and
slow fluctuations in the voltage profile which have been successfully mitigated with the proposed simultaneous FFC and SFC technique as illustrated in Fig. 5.13. The voltage profile is maintained stable close to the operating voltage limit using the proposed method (0.94 P.U<V<1.1 P.U).

The quasi-steady-state load flow analysis is performed at each instant to ensure that the operating limits are not exceeded. The obtained results have validated that the simultaneous FFC and SFC can successfully mitigate fast and slow fluctuations while maintaining SoCs of SCS and BS with the proposed integrated controller mechanism.

5.5 Conclusion

The application of a HESS for the simultaneous slow and fast fluctuation control to mitigate the slow and fast fluctuations of solar PV output has been presented. The fast fluctuations have been mitigated by controlling the solar inverter ramp rate to follow a defined value using SCS without depending on the power output of previous instance. The slow fluctuations have been mitigated by charging the BS when the solar PV output is higher than the load demand and discharging the BS when the solar PV output is lower than the load demand or when it is not available such as at night time. The charging/discharging rate for the voltage control has been based on the severity level of the voltage at the PCC. The SoC management techniques have been introduced to maintain control through the entire period. The proposed method is validated using a practical Australian distribution network and the simulation results show that the proposed method can mitigate slow (due to intermittency of solar PV) and fast (due to passing cloud) fluctuations of the PV output.
Chapter 6

Conclusion and Recommendation for Future Work

6.1 Conclusion

The impacts of the rooftop solar PV on the MV/LV distribution network and the existing control technologies were discussed through the comprehensive literature review. The urging requirement to develop technologies in the context of the rooftop solar PV generators, particularly the ES and the DG control, such as the ES integration and the optimal generation control is demonstrated. The integration of ES’s with the rooftop solar PV has been discussed in the literature review for the provision of,

- Ancillary services to the grid, such as voltage control.
- Demand-side management.
- Improvement of the power quality.

An extensive literature review on the available studies to alleviate fast and the slow fluctuations in the voltage profile has been done. Accordingly, the mitigation of both fast and the slow fluctuations has been given less consideration. However, the mitigation of both fast and the slow fluctuations in context of rooftop solar PV has not been done by previous researchers.

Chapter 3 elaborates the proposed methodology to mitigate both the fast and the slow fluctuations in the voltage profile due to grid connected solar PV systems using a single battery storage system. Fast fluctuations are mitigated through the ramp rate
control method to limit the slope of the solar PV output to a specified value. The slow fluctuations are mitigated by maintaining the voltage level at PCC. In both situations, the BS is charged/discharged to absorb/inject the active power into the connected distribution feeder. The novelty and the advantage of the technique/techniques introduced/used in Chapter 3 can be summarized as below,

- The Utilization of a single BS.
- The control of the fast fluctuations together with the slow fluctuations.
- The voltage of connected distribution feeder is maintained within the operating voltage range without putting a burden on the DNO auxiliary devices.
- The ability to use more solar PV generators (renewable energy sources) to connect to distribution feeder without causing extra operating expenses.

The disadvantages can be summarized as below,

- The BS is may not be capable of mitigating fast fluctuations (depending on the defined highest ramp rate and the practically largest ramp) where the solar PV capacity is higher than 5kW.
- The coordination between both the fast and the slow fluctuation control may be impossible due to the insufficiency of the BS capacity.
- Considerably larger BS would be needed in worst scenarios, such as an extremely cloudy sunny day.
Chapter 4 elaborates the sizing methodology of the BS for the control techniques introduced in Chapter 3. The sizing of the BS was based on,

- The ability to mitigate both fast and slow fluctuation in the voltage profile.
- The ability to maintain the charging/discharging rates of the BS to be within the manufacturer specification.
- A full utilization of the capacity of the BESS with a 10% margin to mitigate the unexpected variations in the voltage profile.
- The ability to assure the SoC of the BESS at the end of the day is the same as the initial SoC at the start of the same day.

Chapter 3 and Chapter 4 together validate the methodology and the effective BS size to mitigate both fast and slow fluctuations in the voltage profile caused by the intermittency of grid connected rooftop solar PV generation. The mitigation of fast fluctuations has limited the ramp rate of the solar inverter output to match a defined value with the BS. The ramp rate of the solar inverter output has not depended on the power output of the previous instance or the present instance of the BS. The mitigation of slow fluctuations was achieved by charging BS when the solar PV output is higher than the load demand and discharging BS when the solar PV output is lower than the load demand. The charging/discharging rates for the slow fluctuation control were based on the severity level of the voltage at PCC. Chapter 4 presented the optimum sizing and the optimum operating parameters for the voltage control using a single BS. Sufficient capacities for the mitigation of slow and fast voltage fluctuations have been determined through simulations using different BS capacities. Moreover, three charging/discharging rates for the voltage control based on the severity level of voltage at PCC have been proposed.
The proposed method/methods were validated using a practical Australian distribution network and the simulation results show that the proposed method can mitigate the slow (due to the intermittency of solar PV) and the fast (due to passing cloud) fluctuations of the PV output. A BS with a capacity of 150 Ah was identified as the optimum size for the voltage control strategy to mitigate the simultaneous fast and slow voltage fluctuations. The sizing of the BS was based on the minimum capacity to support voltage control during the 24hr period to maintain the voltage profile within the operating limits without exceeding the physical limitations of the BS while achieving the SoC at the end of the day similar to initial SoC.

Chapter 5 elaborates, the utilization of HESS technology consisting of a BS and a SC to mitigate both fast and slow fluctuations in the voltage profile of the connected distribution feeder due to intermittent generation of the rooftop solar PV. Accordingly, the disadvantages of using single BS for the above purpose can be omitted or minimized by using a HESS. The advantages of using HESS over a single BS are:

- The ability to mitigate the fast fluctuations of the solar PV output up to the defined largest ramp rate value despite the capacity of the solar PV unit.
- The convenience in coordination between both controlling functions (the slow and the fast fluctuation mitigation).
- The convenience in sizing the ESs to ensure undisrupted fast and slow fluctuation mitigation throughout the entire duration.

The selection of the ESs for the HESS was based on the Ragone plot (Figure. 5.1). Moreover, the parallel active topology was used to connect both the ESs to allow
more flexibility in operation and also due to the high efficiency of the connection. The sizing of ESs was achieved by considering the voltage levels within the parallel active topology. The HESS was used to balance the supply and demand. The SCS was used to control the fast fluctuations in the solar PV inverter output. This imbalance in generation and demand was compensated using the BS to charge during day-time and discharge during evening peak hours. At the same time BS was used to ensure the voltage level at PCC is maintained within the standard operating voltage limits.

Moreover, three scenarios were used to ensure undisrupted availability of HESS throughout the operation.

- **Scenario 1** - Management of BS SoC executed only during situations where there are no fast or slow fluctuations in presence.
- **Scenario 2** - The SCS was charged during the dawn period if there is no sufficient energy stored to mitigate fast fluctuations in the next day.
- **Scenario 3** - This feature activated mostly during extremely varying cloudy days. Accordingly, the BS will be charged or discharged to provide FFC only unless the SCS has sufficient SoC to mitigate fast fluctuations.

Accordingly, the fast fluctuations have been mitigated by controlling the ramp rate of the solar PV inverter to follow a defined value using the SCS without depending on the power output of the previous instance. The slow fluctuations have been mitigated by charging/discharging the BS. The charging/discharging rate for the voltage control has been based on the severity level of the voltage at PCC. More importantly, the SoC management techniques have been introduced to maintain disrupted control
through entire period. The proposed methods have been validated using a practical Australian distribution network.

6.2 Future Work and Recommendations

Research work carried out during this work can be reinforced into the industrial environment through the following suggestions.

6.2.1 Laboratory test set up with ESS, rooftop Solar PV generator and load simulator

The proposed methods to mitigate both slow and fast fluctuations using single BS and HESS can be practically tested in the laboratory environment. Accordingly, the reaction time of the ESS can be monitored and hence the simulated results in Chapter 3 to Chapter 5 may be validated in laboratory to introduce the methodologies into the industrial environment.

6.2.2 Comparison of BESS and HESS

The proposed methods to mitigate both slow and fast fluctuations with BESS and HESS were simulated for the same data set. According to Chapter 04, the optimum BESS size was 500Ah (12VDC). According to Chapter 5, the sizing of BS and SCS were 62.5 Ah (48VDC) and 40Ah (48VDC) respectively. These results can be extended to study the economic analysis between both BESS and HESS on the basis of overall voltage support, manufacture cost and operational cost. The technical capability of BESS (lead acid battery on this case- based on the manufacturer data sheet) limits the maximum FF that BESS can control. During the work of this thesis, the solar PV generator size was limited to 5kW/s to facilitate BESS to function
within its’ capabilities to allow undisrupted FFC. This can be extended to compare the performance of BESS and HESS.

6.2.3 **Expand methodologies with the coordination between ESS**

Depending on the feeder loading and the location of the residential rooftop solar PV unit in the feeder, the amount of charge/discharge of ESS to mitigate the slow and the fast fluctuations vary. Hence, the amount of charge/discharge of the ESS along the distribution feeder can be balanced through coordination arrangements.

6.2.4 **Introduce a mix of charge/discharge mechanisms throughout the feeder**

Various factors such as the distance to the transformer, the load profile, the SoC level of ESS and the voltage profile at the PCC suggest different charge/discharge mechanism. For example, the general charge/discharge arrangement considering the slow intermittency due to sun movement is preferred at PCC’s within proximity to the transformer. However, the charge/discharge mechanism considering the slow intermittency might be preferred at PCC’s within proximity to the further end of the feeder. Hence, the introductions of a mix of charge/discharging mechanisms along the feeder could be beneficial for effective energy harvesting.

At present, the cost of ESS can be high compared to the revenue of rooftop solar PV of the home owner. However, with the fast decline in the ESS cost due to the fast advancement in the ESS technology, the popularity of the ESS installation will be elevated. Accordingly, the study described in this thesis was a timely topic and an
essential innovation. As the proposer of the methodologies, it will be a privilege to take necessary actions to bring the innovation into the industry to make it useful for human kind.
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Appendices

Appendix 1

MATLAB CODE FOR FFC WITH BESS

% DEFINING MINIMUM AND MAXIMUM SOC
SOC_max=100;SOC_min=20;

% DEFINING MINIMUM AND MAXIMUM MARR
MARR_max=0.005;MARR_min=-0.005;

% DEFINING ARRAYS AND INITIALIZATION OF VARIABLES
iPVRR=[];iMARR=[];iRR_comp=[];
Energy_total=0;count1=0;count2=0;

% Abstract PV data
PV= 0.01 * xlsread ('Solar_week.xlsx'); %5kW solar panel

% INITIALIZATION OF MATRICES
for nn=16:16 % 16 BUS SYSTEM
for tt=1:604800 % NUMBER OF SECONDS FOR 24HR PERIOD
V3_time=zeros(nn,tt);
V1_time=zeros(nn,tt);
V2_time=zeros(nn,tt);
SOC_time=zeros(nn,tt);
SOC_RR_time=zeros(nn,tt); % SOC AFTER FFC
Energy_RR_time=zeros(nn,tt); % STORED ENERGY AFTER FFC FOR SPECIFIC SECOND
SOC_total_time=zeros(nn,tt); % STORED ENERGY AFTER FFC FOR ENTIRE DURATION
P_bat_time=zeros(nn,tt); % POWER OUTPUT OF BESS FOR FFC
P_bat_VC_time=zeros(nn,tt); % POWER OUTPUT OF BESS FOR FFC STORED SEPERATELY
P_inv=zeros(nn,tt); % INVERTER POWER OUTPUT OF BESS FOR FFC
P_inv_new=zeros(nn,tt); % INVERTER POWER OUTPUT OF BESS FOR FFC STORED SEPERATELY
end
end

% CONTROLLER ALGORITHM
for t=1:604800

    for n=16:16

        if(t==1)
            PVRR=0;
            P_bat=0;
            MARR=0;
        
Description of the code goes here...
SOC=60;
RR_P_bat=0;
Energy=0;
else

%calculate PVRR, SOC and BESS power output for previous second
PVRR=PV(t)-PV(t-1);
SOC=SOC_RR_time(n,t-1);
battery=P_bat_time(n,t-1);

%Setting up MARR value
if(PVRR<0)
    MARR=MARR_min;
else
    if(PVRR>0)
        MARR=MARR_max;
    else
        MARR=0;
    end
end

% calculate rate of change of BESS CHARGE/DISCHARGE RATE and BESS POWER OUTPUT based on PVRR and MARR
if(abs(PVRR)<=abs(MARR))
    RR_P_bat=0;
P_bat=0;
else
    RR_P_bat=MARR-PVRR;
P_bat= battery+RR_P_bat;
end

%modification to CONTROL post ramping event based on above BESS power OUTPUT
Inverter_RR=PVRR+P_bat-battery;

%Inverter_RR is used as reference to check accuracy of FF control. if Inverter_RR is higher than MARR_max-->Battery power will be forced to adopt to control inverter_RR than it was originally in above calculation
if(Inverter_RR>MARR_max)
    MARR=MARR_max;
    RR_P_bat=MARR-PVRR;
P_bat= battery+RR_P_bat;
else
    if(Inverter_RR<MARR_min)
        MARR=MARR_min;
        RR_P_bat=MARR-PVRR;
P_bat= battery+RR_P_bat;
    end
end

%check for SOC, if it is minimum then don't allow it to is charge further, if it is maximum, then don't let it to charge further.
if \( P_{bat} \leq 0 \land SOC \geq SOC_{max} \) \lor \( P_{bat} \geq 0 \land SOC \leq SOC_{min} \) 
    \( RR_{P_{bat}} = 0 \);
    \( P_{bat} = 0 \);
end

\% Calculate Energy and SOC
    Energy = (bat + P_{bat})/2;
    Energy\_total = Energy\_total + Energy;
    SOC = 60 - (Energy\_total/216);
end

end

\% store value as previous values
    iP_{VRR}(t) = P_{VRR};
    iMARR(t) = MARR;
    iRR\_comp(t) = RR_{P_{bat}};
    SOC\_RR\_time(n,t) = SOC;
    Energy\_RR\_time(n,t) = Energy\_total; \% energy stored within specific 1 second period
    P\_bat\_time(n,t) = P_{bat};
    P_{inv}(n,t) = P_{V}(t) + P_{bat};
end
Appendix 2

MATLAB CODE FOR SFC WITH BESS

% INITIALIZATION

Energy2_total=0;

%least-square method should be used to solve polynomial DYNAMIC BATTERY
MODELING OF LEAD-ACID BATTERIES USING MANUFACTURERS DATA

SOC1=10:10:120;
SOC_charging=10:1:120;

V_charging_C5=[12.6 12.75 12.95 13.2 13.38 13.39 13.52 14.02 15.2 15.95 16.32 16.48];
V_charging_C10=[12.36 12.58 12.82 13.05 13.2 13.3 13.62 14.08 15.25 15.75 15.92];
V_charging_C20=[12.05 12.44 12.7 13.0 13.12 13.15 13.38 14.12 15.15 15.55];

%interpolating
V_charging_C5=interp1(SOC1,V_charging_C5,SOC_charging,'spline');
V_charging_C10=interp1(SOC1,V_charging_C10,SOC_charging,'spline');
V_charging_C20=interp1(SOC1,V_charging_C20,SOC_charging,'spline');
V_charging_C40=interp1(SOC1,V_charging_C40,SOC_charging,'spline');

SOC2= 0:10:100; %0:0.1:1;
SOC_discharging=0:1:100; %0:0.01:1;

V_discharging_C40=[11.6 11.8 12.0 12.15 12.3 12.4 12.5 12.55 12.615 12.62 12.625];
V_discharging_C10=[10.98 11.28 11.49 11.7 11.9 12.0 12.15 12.25 12.35 12.42 12.49];
V_discharging_C5=[10.2 10.62 10.92 11.15 11.35 11.55 11.68 11.8 11.9 12.0 12.05];

%interpolating
V_discharging_C5=interp1(SOC2,V_discharging_C5,SOC_discharging,'spline');
V_discharging_C10=interp1(SOC2,V_discharging_C10,SOC_discharging,'spline');
V_discharging_C20=interp1(SOC2,V_discharging_C20,SOC_discharging,'spline');
V_discharging_C40=interp1(SOC2,V_discharging_C40,SOC_discharging,'spline');

for ttt=1:604800

for n=16:16

%transfer previously stored SOC for the next step

if(ttt>1)
SOC_VC=SOC_time(n,(ttt-1));
SOC_TOTAL=SOC_total_time(n,(ttt-1));
P_bat_VC1=P_bat_VC_time(n,(ttt-1));
P_inv_ramp=P_inv(n,ttt)-P_inv(n,ttt-1);

%INITIALIZE THE FIRST SECOND
else
SOC_VC=60;
SOC_TOTAL=60;
P_bat_VC1=0;
P_bat_VC=0;
P_inv_ramp=0;

end
end

end
end
Energy3_total=0;
end

%CALCULATE RATE OF CHANGE OF CHARGE RATE BASED ON THE VOLTAGE AT PCC
if(V1_time(n,ttt)>1.1) && (V1_time(n,ttt)<1.11)
    if (SOC_TOTAL<SOC_max)
        V_bat=V_charging_C20(round(SOC_TOTAL));
        P_bat_VC= -(V_bat * 25)/1000;
    else
        P_bat_VC=0;
    end
elseif(V1_time(n,ttt)>1.11) && (V1_time(n,ttt)<1.12)
    V_bat=V_charging_C10(round(SOC_TOTAL));
    P_bat_VC= -(V_bat * 50)/1000;
else
    P_bat_VC=0;
end

elseif(V1_time(n,ttt)>1.11) && (V1_time(n,ttt)<1.12) %1.095
    if(SOC_TOTAL<SOC_max)
        V_bat=V_charging_C10(round(SOC_TOTAL));
        P_bat_VC= -(V_bat * 100)/1000;
    else
        P_bat_VC=0;
    end

%CALCULATE RATE OF CHANGE OF DISCHARGE RATE BASED ON THE VOLTAGE AT PCC
elseif(V1_time(n,ttt)<0.94) && (V1_time(n,ttt)>0.93)
    if (SOC_TOTAL>SOC_min)
        V_bat=V_discharging_C20(round(SOC_TOTAL));
        P_bat_VC= (V_bat * 25)/1000;
    else
        P_bat_VC=0;
    end
elseif(V1_time(n,ttt)<0.93) && (V1_time(n,ttt)>0.92)
    if (SOC_TOTAL>SOC_min)
        V_bat=V_discharging_C10(round(SOC_TOTAL));
        P_bat_VC= (V_bat * 50)/1000;
    else
        P_bat_VC=0;
    end
elseif(V1_time(n,ttt)<0.92) && (SOC_TOTAL>SOC_min)
    V_bat=V_discharging_C5(round(SOC_TOTAL));
    P_bat_VC= (V_bat * 100)/1000;
elseif(V1_time(n,ttt)<1.1) 
	if (SOC_TOTAL<30) 
		V_bat=V_charging_C5(round(SOC_TOTAL)); 
		p_bat_VC= -(V_bat * 100)/1000; 
	else 
		P_bat_VC=0; 
	en 
elseif(V1_time(n,ttt)<0.99) 
	%1.095 
	if (SOC_TOTAL>80) 
		V_bat=V_discharging_C10(round(SOC_TOTAL)); 
		p_bat_VC= (V_bat * 100)/1000; 
	else 
		P_bat_VC=0; 
	en 
else 
		P_bat_VC=0; 
end 

%CALCULATE THE POTENTIAL RATE OF CHANGE OF INVERTER OUTPUT WITH OBTAINED RESULTS 

ramp=P_inv_ramp+P_bat_VC-P_bat_VC1; 

%CALCULATE THE INTENDED RATE OF CHANGE OF INVERTER OUTPUT OF THE CONTROLLER 

if(ramp>MARR_max) 
	P_bat_VC=P_bat_VC1+MARR_max-P_inv_ramp; 
elseif(ramp<MARR_min) 
	P_bat_VC=P_bat_VC1+MARR_min-P_inv_ramp; 
else 
end 

%STORE RESULTS IN MATRICES 

Energy2=(P_bat_VC1+P_bat_VC)/2; 
Energy2_total=Energy2_total+Energy2; 
Energy3_total=Energy2_total+Energy_RR_time(n,ttt); 
SOC_VC=60-(Energy2_total/216); 
SOC_TOTAL=60-(Energy3_total/216); 

end 

%STORE RESULTS IN MATRICES 
SOC_time(n,ttt)=SOC_VC; 
SOC_total_time(n,ttt)=SOC_TOTAL; 
P_bat_VC_time(n,ttt)=P_bat_VC; 
P_inv_new(n,ttt)=P_bat_VC+P_inv(n,ttt); 

end
Appendix 3

MATLAB CODE FOR FFC WITH HESS

% DEFINING MINIMUM AND MAXIMUM SOC
SOC_max_UC=100;SOC_min_UC=0;
SOC_max_bat=100;SOC_min_bat=20;

% DEFINING MINIMUM AND MAXIMUM MARR
MARR_max=0.005;MARR_min=-0.005;

% DEFINING ARRAYS AND INITIALIZATION OF VARIABLES
iPVRR=[];iMARR=[];iRR_comp=[];P_inv_RR=[];
Energy_total_UC=0;Energy_total_bat=0;
count=0;

% Abstract PV data
PV= 0.01 * xlsread ('Solar_week.xlsx');

% INITIALIZATION OF MATRICES
for nn=16:16
    for tt=1:604800
        V3_time=zeros(nn,tt);
        V1_time=zeros(nn,tt);
        V2_time=zeros(nn,tt);
        SOC_time_UC=zeros(nn,tt);
        SOC_time_bat=zeros(nn,tt);
        Energy_time_UC=zeros(nn,tt);
        Energy_time_bat=zeros(nn,tt);
        P_UC_time=zeros(nn,tt);
        P_bat_time=zeros(nn,tt);
        P_inv=zeros(nn,tt);
    end
end

% CONTROLLER ALGORITHM
for t=1:604800
    for n=16:16

        if(t==1)
            PVRR=0;
            P_UC=0;
            P_bat=0;
            MARR=0;
            SOC_UC=90;
            SOC_bat=60;
            RR_P_ES=0;
            Energy_UC=0;
            Energy_bat=0;
        else

            % calculate PVRR, SOC and SUPER CAPACITOR power output for previous SECOND
            PVRR=PV(t)-PV(t-1);
SOC_UC=SOC_time_UC(n,t-1);
SOC_bat=SOC_time_bat(n,t-1);
UC=P_UC_time(n,t-1);
bat=P_bat_time(n,t-1);

% Setting up MARR value
if(PVRR<0)
    MARR=MARR_min;
else
    if(PVRR>0)
        MARR=MARR_max;
    else
        MARR=0;
    end
end

% calculate rate of change of SUPERCAPACITOR CHARGE/DISCHARGE RATE and BESS POWER OUTPUT based on PVRR and MARR
if(abs(PVRR)<=abs(MARR))
    RR_P_ES=0;
P_UC= UC+RR_P_ES+bat;
P_bat=0;
else
    RR_P_ES=MARR-PVRR;
P_UC= UC+RR_P_ES+bat;
P_bat=0;
end

% CHARGING SUPERCAPACITOR IN THE DAWN PERIOD-UC
if mod(t,86400)>0 && mod(t,86400)<18000
    if (SOC_UC<30) && (SOC_UC<80)
        count=count+1;
P_UC= -1;
P_bat=0;
    else
        P_UC= 0;
P_bat=0;
    end
else
end

% END CHARGING IN THE DAWN PERIOD-UC

% modification to CONTROL post ramping event based on above SUPERCAPACITOR power OUTPUT

Inverter_RR=PVRR+P_bat+P_UC-UC-bat;

if(Inverter_RR>MARR_max)
MARR=MARR_max;
RR_P_ES=MARR-PVRR;
P_UC= UC+RR_P_ES+bat-P_bat;

elseif(Inverter_RR<MARR_min)
    MARR=MARR_min;
    RR_P_ES=MARR-PVRR;
    P_UC= UC+RR_P_ES+bat-P_bat;
else
    end

%check for SOC, if it is minimum then don't allow it to Discharge further, if it is maximum, then don't let it to charge further
if(P_UC<=0 && SOC_UC>=SOC_max_UC)
P_bat=P_UC;
P_UC=0;
elseif (P_UC>=0 && SOC_UC<=SOC_min_UC)
P_bat=P_UC;
P_UC=0;
else
end

if(P_bat<=0 && SOC_bat>=SOC_max_bat) || (P_bat>=0 && SOC_bat<=SOC_min_bat)
    RR_P_ES=0;
P_bat=0;
end

%Calculate Energy and SOC of UC
Energy_UC=(UC+P_UC)/2;
Energy_total_UC=Energy_total_UC+Energy_UC;
SOC_UC=90-((Energy_total_UC/34.56)); %20Ah Supercapacitor

%Calculate Energy and SOC of Battery
Energy_bat=(bat+P_bat)/2;
Energy_total_bat=Energy_total_bat+Energy_bat;
SOC_bat=60-(Energy_total_bat/216); %62.5Ah Battery lead acid

end

%store value as previous values
iPVRR(t)=PVRR;
iMARR(t)=MARR;
iRR_comp(t)=RR_P_ES;
SOC_time_UC(n,t)=SOC_UC;
Energy_time_UC(n,t)=Energy_total_UC; %energy stored within specific 1 second period
P_UC_time(n,t)=P_UC;
SOC_time_bat(n,t)=SOC_bat;
Energy_time_bat(n,t)=Energy_total_bat; %energy stored within specific 1 second period
\[ P_{\text{bat}\_time}(n,t) = P_{\text{bat}}; \]
\[ P_{\text{inv}}(n,t) = PV(t) + P_{\text{UC}} + P_{\text{bat}}; \]
end
Appendix 4

MATLAB CODE FOR SFC WITH HESS

% INITIALIZATION

Energy_total_bat_VC=0;
%least-square method should be used to solve polynomial DYNAMIC BATTERY
MODELING OF LEAD-ACID BATTERIES USING MANUFACTURERS DATA

SOC1=10:10:120; SOC_charging=10:1:120;
SOC2= 0:10:100; SOC_discharging=0:1:100;

V_charging_C5= 4*[12.6 12.75 12.95 13.2 13.38 13.39 13.52 14.02 15.2 15.95 16.32 16.48];
V_charging_C10=4*[12.36 12.58 12.82 13.05 13.2 13.4 13.62 14.08 15.25 15.75 15.92];
V_charging_C20=4*[12.05 12.44 12.7 12.9 13.0 13.12 13.15 13.3 13.58 14.12 15.15 15.55];
V_charging_C40=4*[11.8 12.25 12.55 12.22 12.32 12.42 12.45 13.0 13.15 13.5 14.5 15.1];
%interpolating
V_charging_C5=interp1(SOC1,V_charging_C5,SOC_charging,'spline');
V_charging_C10=interp1(SOC1,V_charging_C10,SOC_charging,'spline');
V_charging_C20=interp1(SOC1,V_charging_C20,SOC_charging,'spline');
V_charging_C40=interp1(SOC1,V_charging_C40,SOC_charging,'spline');

V_discharging_C20=4*[11.45 11.68 11.92 12.1 12.2 12.32 12.42 12.5 12.55 12.6 12.62];
V_discharging_C40=4*[11.6 11.8 12.0 12.15 12.3 12.4 12.5 12.55 12.615 12.62 12.625];
V_discharging_C10=4*[10.98 11.28 11.49 11.7 12.0 12.15 12.25 12.35 12.42 12.49];
V_discharging_C5=4*[10.2 10.62 10.92 11.15 11.35 11.55 11.68 11.8 11.9 12.0 12.05];
%interpolating
V_discharging_C5=interp1(SOC2,V_discharging_C5,SOC_discharging,'spline');
V_discharging_C10=interp1(SOC2,V_discharging_C10,SOC_discharging,'spline');
V_discharging_C20=interp1(SOC2,V_discharging_C20,SOC_discharging,'spline');
V_discharging_C40=interp1(SOC2,V_discharging_C40,SOC_discharging,'spline');
%Interpolating obtained data in Distributed energy storage for mitigation of voltage-rise
impact caused by rooftop solar PV

for ttt=1:604800

for n=16:16

%transfer previously stored SOC for the next step

if(ttt>1)
SOC_bat=SOC_time_bat(n,ttt-1);
P_bat_previous= P_bat_time(n,(ttt-1));
P_inv_ramp=P_inv(n,ttt)-P_inv(n,ttt-1);

%INITIATE FIRST SECOND OF THE DURATION

else
SOC_bat=60;
P_bat_previous=0;

end
end
P_inv_ramp=0;
end

%assign V1_time(n,ttt) as VPCC
VPCC=V1_time(n,ttt);

%CALCULATE RATE OF CHANGE OF CHARGE RATE BASED ON THE VOLTAGE AT PCC
if(VPCC>1.1) && (VPCC<1.11) %1.095
  if (SOC_bat<SOC_max_bat)
    V_BS=V_charging_C40(round(SOC_bat));
    CHG_R= (2*VPCC-1.1)*(6.25/VPCC);
    P_BS= -(V_BS * CHG_R)/1000; % C/80 charging rate
  else
    P_BS=0;
  end
elseif(VPCC>1.11) && (VPCC<1.12) %1.095
  if(SOC_bat<SOC_max_bat)
    V_BS=V_charging_C20(round(SOC_bat));
    CHG_R= (2*VPCC-1.11)*(12.5/VPCC);
    P_BS= -(V_BS * CHG_R)/1000; %C/40
  else
    P_BS=0;
  end
elseif(VPCC>1.12) && (SOC_bat<SOC_max_bat) %1.095
  V_BS=V_charging_C10(round(SOC_bat));
  CHG_R= (2*VPCC-1.12)*(25/VPCC);
  P_BS= -(V_BS * CHG_R)/1000;
elseif(VPCC<0.94) && (VPCC>0.93) %1.095
  if (SOC_bat>SOC_min_bat)
    V_BS=V_discharging_C40(round(SOC_bat));
    DCHG_R= (2*VPCC-0.94)*(6.25/VPCC);
    P_BS= (V_BS * DCHG_R)/1000;
  else
    P_BS=0;
  end
elseif(\text{VPCC}<0.93)\&\&\ (\text{VPCC}>0.92) \ %1.095

\begin{verbatim}
if \ (\text{SOC\_bat}>\text{SOC\_min\_bat}) \n\text{V\_BS}=\text{V\_discharging\_C20(\text{round}(\text{SOC\_bat}))}; \n\text{DCHG\_R}=(2*\text{VPCC}-0.93)*(12.5/\text{VPCC}); \nP\_BS=(\text{V\_BS} \times \text{DCHG\_R})/1000; \nelse \n\text{P\_BS}=0; \nend
\end{verbatim}

elseif(\text{VPCC}<0.92) \&\&\ (\text{SOC\_bat}>\text{SOC\_min\_bat})
\begin{verbatim}
\text{V\_BS}=\text{V\_discharging\_C20(\text{round}(\text{SOC\_bat}))}; \n\text{DCHG\_R}=(2*\text{VPCC}-0.92)*(15.625/\text{VPCC}); \nP\_BS=(\text{V\_BS} \times \text{DCHG\_R})/1000; \%C/16
\end{verbatim}

\text{%SOC MANAGEMENT ALGORITHM}

elseif(\text{VPCC}<1.1)\&\&(\text{VPCC}>1.05)
\begin{verbatim}
if \ (\text{SOC\_bat}<30)\&\&\ (\text{SOC\_bat}>10) \n\text{V\_BS}=\text{V\_charging\_C10(\text{round}(\text{SOC\_bat}))}; \nP\_BS=(\text{V\_BS} \times 25)/1000; \nelse \n\text{P\_BS}=0; \nend
\end{verbatim}

elseif(\text{VPCC}<0.99)\&\&(\text{VPCC}>0.94) \ %1.095

\begin{verbatim}
if \ (\text{SOC\_bat}>90) \n\text{V\_BS}=\text{V\_discharging\_C10(\text{round}(\text{SOC\_bat}))}; \nP\_BS=(\text{V\_BS} \times 25)/1000; \nelse \n\text{P\_BS}=0; \nend
\end{verbatim}

else \n\text{P\_BS}=0; \nend

\text{%CALCULATE THE POTENTIAL RATE OF CHANGE OF INVERTER OUTPUT WITH OBTAINED RESULTS}

\text{ramp}=\text{P\_inv\_ramp}+\text{P\_BS}-\text{P\_bat\_previous};

\text{%CALCULATE THE INTENDED RATE OF CHANGE OF INVERTER OUTPUT OF THE CONTROLLER}
if (ramp > MARR_max)
    P_BS = P_bat_previous + MARR_max - P_inv_ramp;
elseif (ramp < MARR_min)
    P_BS = P_bat_previous + MARR_min - P_inv_ramp;
else
    end
end

P_bat_RR = P_bat_time(n, ttt);

EnergyVC = (P_bat_RR + P_bat_previous + P_BS)/2;
Energy_total_bat_VC = Energy_total_bat_VC + EnergyVC;
SOC_bat = 60 - (Energy_total_bat_VC/216);

end % end of ttt iteration

% STORE RESULTS IN MATRICES

SOC_time_bat(n, ttt) = SOC_bat;
P_bat_time(n, ttt) = P_BS + P_bat_RR;
P_inv_new(n, ttt) = P_BS + P_inv(n, ttt);

end