Department of Electrical and Computer Engineering

Rooftop PV with Battery Storage For Constant Output Power Production

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature:………. N. Jabalameli…………......

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ABSTRACT

The increasing penetration of rooftop photovoltaic generation systems (PVs) in the residential networks has encouraged many researchers and electric utilities to investigate their limitations, advantages and impacts on distribution systems. One of the main limitations of rooftop PVs is the dependency of their output power to environmental factors such as sun radiation, panel temperature, passing clouds and shading. In addition, the net output power delivered to the grid will also depend on the household loads which may significantly change during hot summer days due to air conditioning usage. These dependencies will result in sudden output power variations of rooftop PVs particularly during cloudy days with passing clouds.

In this thesis, the application and control of a battery storage (BS) system at the point of common coupling (PCC) is introduced and developed to compensate for output power changes of rooftop PVs due to variations in the environmental conditions and household loads. This approach will also have an important role in mitigating the intermittent behaviour and uncertainties associated with PV systems. A relatively simple and practical battery storage energy management strategy (BS-EMS) for operating small scale grid-connected rooftop PVs will be proposed such that the net delivered output power to the grid at PCC ($P_{Grid\text{-}ref}$) is constant under various operating conditions. To do this, the power balance between rooftop PV, battery and grid is considered by dynamic control of the battery converter while a PI controller is also implemented to reduce voltage variations at PCC. In addition, a simple approach based on BS-EMS is also developed to estimate the battery rating.

Detailed simulations are performed for a 24-hour period using developed codes in PSCAD to demonstrate the performance of BS-EMS under various grid, load and

environmental conditions. In particular, impacts of battery size, passing clouds and short PV outages, as well as duration and magnitude of $P_{Grid\text{-}ref}$ on system performance are investigated.

ACKNOWLEDGMENTS

I am heartily thankful to my supervisor, Professor Mohammad A.S. Masoum, whose encouragement, supervision and support from the preliminary to the concluding level enabled me to develop an understanding of the subject and completion of my thesis. It is a pleasure to thank the chair of my research committee, Professor Syed Islam for his support and guidance throughout my research. I would also like to express my gratitude to Prof. Masoum's HDR (higher degree by research) group at Curtin University for their contribution, help and support during the completion of the project.

I also offer my regards and blessings to my beloved family who have given me their invaluable moral support, encouragement and prayers during my education. Finally, I would like to express special appreciation to my husband and daughter for their endless dedication, love and patience throughout the completion of my MS thesis.

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ABBREVIATIONS

AC	Alternating current [A]
$BCAP_{estim}$	Estimated battery capacity [%]
BESS	Battery energy storage system [kWh]
BS	Battery storage [kWh]
DC	Direct current [A]
DG	Distributed generation
DOD	Depth of discharge [%]
EJ	Exajoules
ES	Energy storage [kWh]
ESS	Energy storage systems
I_0	Reverse saturation current [A]
Icell	DC output current [A]
I_{ph}	Photocurrent [A]
PL	Power level of load [kW]
MPPT	Maximum power point tracking
PCC	Point of common coupling
P_{max}	Maximum solar output power [kW]
P_{PV}	Constant output PV power [kW]
$P_{ref,grid}$	Output power production [kW]
PV	photovoltaic
PVs	Photovoltaic systems
R_s	Solar cell consists of series [Ω]
R_{sh}	Solar cell consists of shunt [Ω]
SC	Super capacitor
SOC	State of charge [%]
SOC_{max}	Minimum battery state-of-charge [%]
SOC_{min}	Maximum battery state-of-charge [%]

TOU	Time of use
vd_1	Diode voltage [V]
$k\Delta t$	Time interval [hr]
$P_{Bs,k}$	Active power [kW]
$Q_{Bs,k}$	Reactive power [VAR]
uc	Switching function(continuous time)
εc	Charging efficiency [%]
εd	Discharging efficiency [%]

CHAPTER ONE

INTRODUCTION

Currently, most of the world's electrical energy consumption is generated through non-renewable fossil fuel resources such as coal, natural gas and oil. These sources of energy are limited and produce emissions with detrimental environmental greenhouse effects. Therefore, it is essential to look to the future and move toward very high penetration of pollution free and renewable energy sources for generating electricity. Most renewable energy sources are plentiful and naturally unlimited. They do not produce any environmentally harmful carbon emissions and do not contribute to the problem of global warming.

Unfortunately, there are still a few difficulties and challenges associated with the applications of renewable energy such as their stochastic nature, dependency to environmental factors and the economic justification due to their high initial capital investments and long payback periods. It is currently difficult to change from fossil sources to renewable energy sources as renewable sources of energy generation are significantly more expensive. However, the cost of fossil fuel based energy is increasing in many countries as these resources are becoming more depleted and with technology improvements renewable energy production costs are gradually reducing. Therefore, it is very likely that at some point in the future the cost of fossil fuel based power will reach a point where it is more expensive than renewable energy based power. With the increasing world's population and concerns about the important environmental factors, it is clear that the use of renewable and clean energy sources must be a priority for the future.

There are many available renewable energy sources such as biomass, hydropower, wave power, geothermal, ocean thermal, solar thermal, solar photovoltaic (PV), wind power and tidal power. However, current technology shows that only solar PV, wind energy, biomass and solar thermal electricity can provide large quantities of sustainable electricity with a reasonable (greater than 10%) overall efficiency. Among these green resources, only solar PV and wind power have been efficiently utilized on a small scale. The present renewable energy technology can be classified into two categories:

- Large scale renewable technology- There are currently many renewable energy plants such as relatively large wind farms around the world that produce clean electricity. However, these systems require significant capital outlay and infrastructure.
- Small scale distributed renewable technology. There is now significant interest utilization of small scale electricity generators with limited infrastructure requirements such as PV systems (PVs) and small wind power plants. This will allows a much larger number of operators to invest in such plants and contribute to increasing the proportion of electricity generated from renewable energy resources.

In recent years, there has been a growing interest by the residential customers to install single-phase grid-connected rooftop PVs due to new energy and incentive polices in several countries such as Australia [1]. The most important characteristic of the present rooftop PV technologies is that their injected output power to the grid is not controlled and dependents on the amount of sun radiation that changes over the 24 hours [2]. In addition, there are several technical problems associated with these systems such as harmonic distortion, voltage regulation, voltage imbalance and power loss that have been significantly investigated in the literature [3-5]. One of the main power quality concerns with the increasing number of rooftop PV applications in residential loads, which are usually distributed randomly among the customers of the network, is the impacts of their penetration level, random locations and ratings on voltage magnitude and voltage imbalance. Reference [6] have investigated the maximum allowable number of grid connected PVs in European and UK distribution networks based on voltage imbalance standard limitations. References [7, 8] have performed sensitivity analysis of voltage imbalance in distribution networks with rooftop PVs. References [9] investigates the impacts of high PV penetration on LV distribution network.

It is anticipated that the sophisticated structure and communication backbone of emerging smart grid systems will allow easy, safe and reliable integration of these distributed renewable energy resources at very high penetration levels while significantly limiting their detrimental impacts on voltage profile and system losses. However, it could take years before smart grid infrastructure is ready.

1.1. Research Objectives

The main objective of this research is to investigate the application of a battery storage (BS) system at the output terminals of an existing rooftop PV for constant output power production during daylight while regulating the voltage profile at the point of common coupling (PCC). The specific objectives of the study are:

1. Simulation of a typical residential system with an existing rooftop PV connected to the power grid and analyzing the injected output power and PCC voltage over the 24 hour period.
2. Connection of BS system at the terminals of the existing rooftop PV and propping a BS-EMS to achieve constant net output power production ($P_{\mathbf{ref,grid}}$) during daylight while regulating the PCC voltage.
3. Proposing a simple and practical approach to estimate battery rating.
4. Investigating the impacts of battery size, constant output power level ($P_{\mathbf{ref,grid}}$) and duration on the performance of BS-EMS.
5. Investigating BS-EMS performance with passing clouds and PV outages.

1.2. Thesis Contributions

In this research the main contributions are as follow:

- Development of a relatively simple and practical BS-EMS for existing grid-connected rooftop PVs that will deliver constant net output power under different grid, load and environmental conditions.
- Development of a simple approach based on BS-EMS to estimate battery rating.
- Mitigating for the intermittent behaviour and uncertainties associated with rooftop PVs and compensating output variations due to passing clouds and short PV outages.
- Exploring impacts of battery characteristics such its rating, minimum and maximum state of charge (SOC).

1.3. Thesis Outline

This thesis is organized into six chapters. Chapter 2 presents technical aspects of PV and rooftop PVs. It considers the application of PV in residential networks. Chapter 3 presents different types of BS systems. In addition, it emphasizes the importance of BS technologies for PV application. Chapter 4 investigates a house with rooftop PV and BS for constant output power production by implementing a BS-EMS. Chapter 5 consists of all simulation results performed for rooftop PV and BS which produces constant output power to the grid. Simulations are based on PV generation in Perth (Western Australia) in different weather and environmental conditions while considering the household load. Conclusions and recommendations for future research directions are presented in Chapter 6.

CHAPTER TWO

TECHNICAL ASPECTS OF PHOTOVOLTAIC AND ROOFTOP PV SYSTEMS

The demand, consumption and price of electricity are rapidly increasing in many developing countries such as Australia. To meet current and future energy requirements, more electric power plants have to be introduced or the structure of energy production needs to be changed with different approaches such distributed generation (DG) sources at distribution feeders or directly at the consumer (residential) side [10]. Among DG technologies, renewable energy resources have found more applications mainly due to the increasing concern about environmental issues and adopted feed-in tariffs for grid-connected PVs. Within various renewable energy resources, wind power and PVs have found more applications in distribution and residential networks [11].

2.1. Renewable Energy Resources

All renewable energy sources are primarily originated from the sun's radiation. The incoming solar radiation totals to over 5.4 million exajoules (EJ) per year of which only about 30% is reflected back into space. In principle, the remaining 70% (approximately 3.8 million EJ/year) is available for use on Earth which is more than 10 thousand times the rate of fossil fuel and nuclear consumption of [12]. Solar energy is generally classified into two categories:

- Direct Solar Energy- such as solar thermal and solar PV where the solar radiation is directly converted into useful energy using various methods and technologies.

- Indirect Solar Energy- such as hydropower, wind power, wave power and bioenergy where the solar radiation is converted into useful energy through other energy forms.

Considering innovations and high interests in DG and smart grid technology, the future power systems will be populated with both types of the above mentioned green energy resources.

2.2. Solar Energy

Solar energy is generated when energy from the sunlight is converted into electricity. Solar energy can also be used to heat air, water or other fluids as illustrated in Fig. 2.1. There are two main approaches of generating electricity from the sun:

- Thermal Energy Systems- using the infra-red radiation (heat) of sunlight, usually to heat water into steam that runs a turbine to generate electricity.
- Photovoltaic Systems (PVs) - generating electricity directly from sunlight by transforming solar energy into DC electricity.

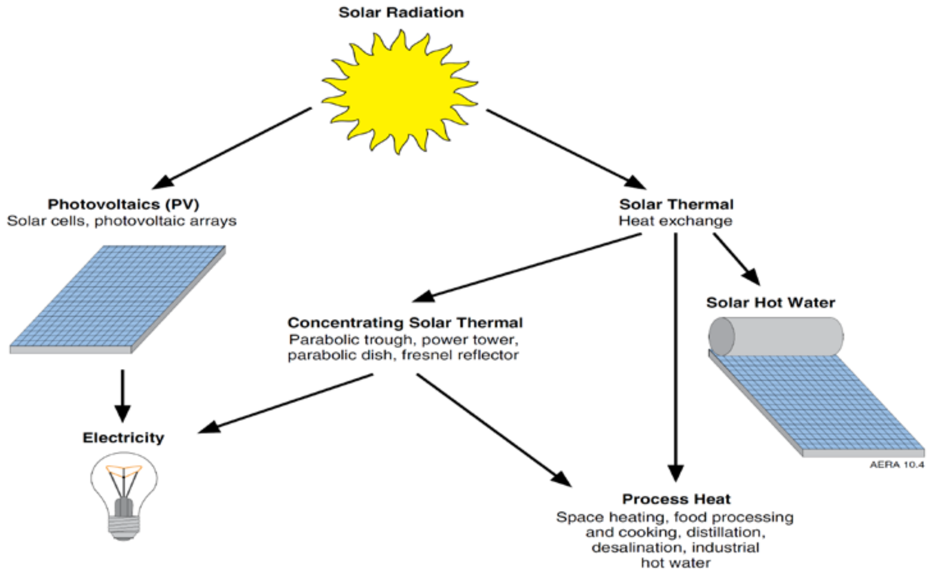


Figure 2.1: Two types of solar energy technology [13]

The term “Photovoltaic” is derived from combining the Greek word for light, photos, with volt, the unit of electromotive force that causes the motion of electrons otherwise known as current. The discovery of the PV effect is generally credited to the French physicist Edmond Becquerel who published the effect in 1839. The first report of the PV effect in a solid state substance appeared in 1877 by two Cambridge scientists. In 1883, an electrician constructed a low efficiency (less than 1%) selenium solar cell which was similar to the silicon solar cells of today. However, it wasn't until the 1950's that the a breakthrough occurred in the development of modern, high efficiency solar cells by bell labs while researching the effects of light on semiconductors. In 1953 the Chapin-Fuller Pearson team produced 'doped' silicon slices that were much more efficient than earlier devices in producing electricity from light [14]. They successfully increased the conversion efficiency of their silicon solar cells to 6%. The first application of solar cells was in 1958 to power a small radio transmitter in the US space satellite Vanguard I. Following this successful demonstration, the utilization of PVs as power sources for spacecraft became almost universal which resulted in rapid progress in increasing their efficiency and reducing their cost over the past few decades. Their terrestrial applications of PVs are now widespread, particularly in providing power for telecommunications, lighting and other electrical appliances in remote locations where a more conventional electricity supply would be too costly.

With the current researches that have been done in DG and the growing desires for smart grid technology and renewable energy resources, it is expected that the future power systems will be populated with many rooftop PVs and solar power plants. Presently, a growing number of domestic, commercial and industrial buildings in

Australia have rooftop PV arrays providing a substantial proportion of their energy needs. The efficiency of the best single-junction silicon solar cells has now reached over 24% in laboratory test conditions. The best silicon PV modules that are now commercially available have an efficiency of over 17% which is expected to rise to over 20% in the next decade. This thesis will mostly consider the PV energy in form of rooftop PVs distributed in the residential networks.

2.3. Photovoltaic Cells

A solar cell is an electronic device that generates electricity directly from sunlight. The output PV electricity is proportional to both the intensity and the direction of the light and will be at maximum when rays of sunlight are perpendicular to the PV modules. PV uses the energy of the light itself to create electric current. Moreover, the electrons are freed by the combination of the semiconductor materials in the cells and electric current is generated by sunlight. PV produces electricity from a free, clean and infinite resource and produces no pollution or noise.

2.3.1. Construction of PV Cells

PV cells are small, square shaped semiconductors manufactured in thin film layers from silicon and other conductive materials. PV cells are manufactured in different types depending on the efficiency, price and quality. The efficiency is measured as the fraction of sunlight energy falling on the cell that is converted into electricity. There are different types of PV cells including [15]:

- Single Crystalline Silicon (Monocrystalline) - is the first material used for making PV cells and is still popular. The conversion efficiency is 14-18%.

- Polycrystalline and Semi Crystalline Silicon- are cheaper to produce; however, it has a lower efficiency compared to Single crystalline Silicon.
- Thin Film Cell- is a good absorber of light and is very thin at only 1 micron which reduces the material cost compared to the high cost associated with crystalline Silicon.
- Amorphous Silicon- is the most popular cell in the thin film cell technology. It uses only 1% of the material compared to crystalline silicon, therefore it is much cheaper. However, it has about 50% less efficiency.
- Spheral cell- with a silicon thickness of 2um, it has a higher conversion efficiency of 16 to 20%.
- Concentrator Cell- has a higher efficiency and is suitable for small areas. However, it requires expensive focusing optics to operate.
- Multifunction Cell- generates electricity from red and infrared light. Other colors such as blue and ultraviolet wavelengths are not converted. It has an efficiency of around 34%; however, the cost is also high.

2.3.2. PV Arrays

A single solar cell cannot produce enough energy for most practical applications. Therefore, PV cells are usually joined together to make PV modules while for higher power applications, multiple PV modules are combined and interconnected to form a PV array (Fig. 2.2). The electricity produced by PV cells in an array are interconnected and combined to produce direct current (DC) power at selected voltage and current ratings. For most applications, the DC power is converted into AC power using an inverter. The power is then directly useable by individual homes and businesses or can be connected into the bulk electricity grid.

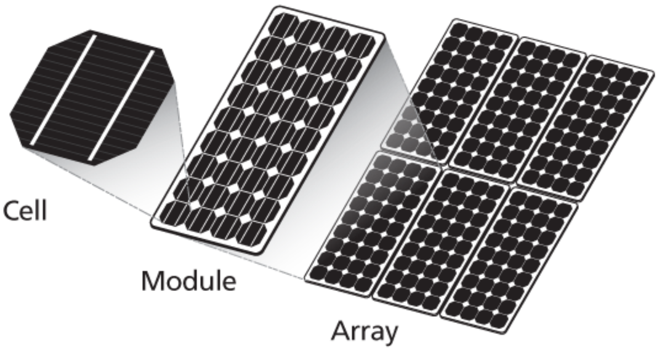


Figure 2.2: Photovoltaic cell [16]

2.3.3. Impact of Sun Angle and Sun Tracking on PV Cells

An important issue in practical utilization of PV generators is the angle of the sun radiation since it has a direct impact on the solar cell electric output power. The DC output current (I_{cell}) of a PV array can be completed as $\mathbf{I_{cell}}=\mathbf{I_o}\cos\alpha$ where I_o is the current with vertical sun impinging and α is the angle from the vertical. This relation holds for sun angles up to 50 degrees while for angles larger than 50 degrees the current significantly decreases. In addition, for angles more than 85 degrees from the perpendicular cell position, there is almost no significant output current.

There are various options to increase the output power of the cell such as the inclusion of a sun tracking system that will actively adjust the position of the cell throughout the day. For example, a PV module installed on a motorized arm can track the sun and thus more energy is collected. Sun trackers can operate on one axis or two axes to follow the suns motion [17]. Tracking may be either simple tilt axis or single/dual axis tracking. Simple tilt will orientate the module to the latitude angle or close to it. Variations to the tilt angle can serve to maximize output at load peaks or to maximise the summer or winter PV outputs. A static orientation angle is the least efficient with the least cost, followed by single, then dual axis tilting.

Another option for increasing the conversion efficiency of the PVs is to include an electrical Maximum Power Point Tracking (MPPT) unit [14]. In this approach, the effective impedance of the load is actively adjusted to get maximum possible output power from the solar cell [17].

2.3.4. Geographic Conditions

The amount of electricity that can potentially be produced by PV solar cells varies around the world as the intensity of solar radiation varies depending of the location, temperature and climate. In particular, the sunny and temperate climates especially along the equator can generate more PV electricity in a given area than other climates where the weather is cloudy and overcast.

The suns radiation is measured in kW per square meter of space (kW/m^2). Just outside the earth's atmosphere, the suns radiation has a power density of about 1.365 kW/m^2 while the standard insolation level is 1 kW/m^2. Fig. 2.3 shows the average daily solar exposure hours in Australia [18]. According to these figure, the average annual daily global solar radiation and sunlight hours in Western Australia are 18 to 21 MJ/m^2. However, highly efficient PV panels, large solar power plants, and high partition of rooftop PVs will be required to effectively capture this gifted, renewable and pollution energy and convert it to usable electrical energy.

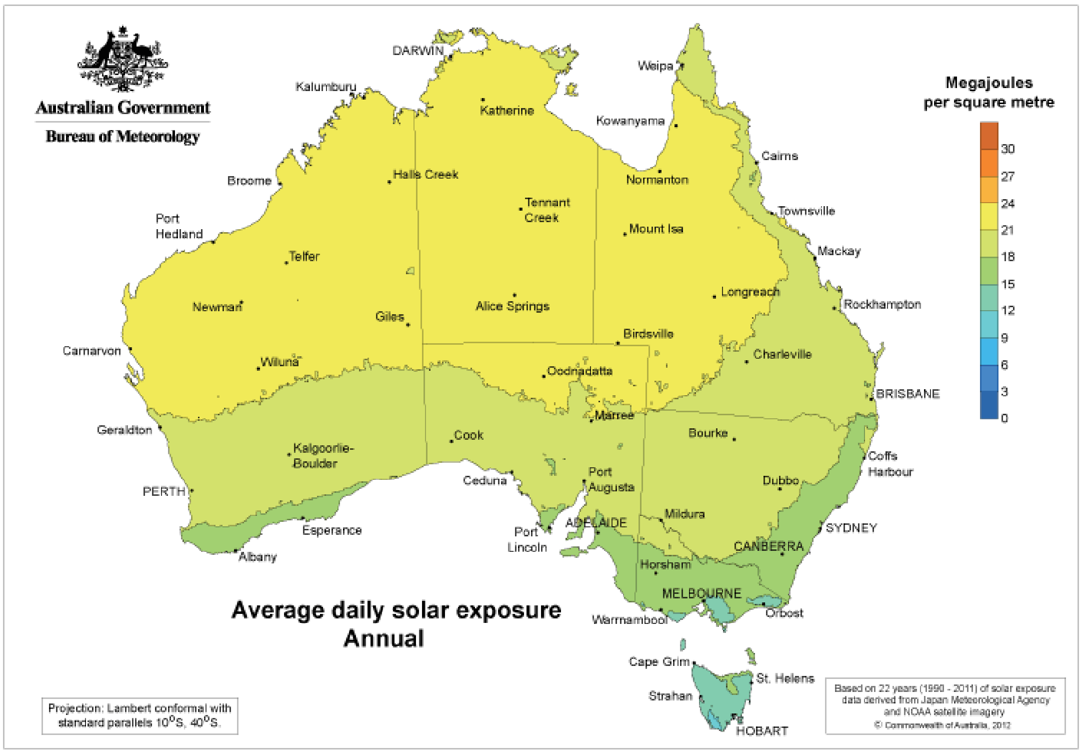


Figure 2.3: Average annual daily solar exposure in Australia [18]

2.3.5. Efficiency and De-Rating of PV Cells

De-rating and efficiency of PV cells and PV panels are affected by many environmental factors including dust, temperature and aging. PV panels should be periodically cleaned for dust as the cells may lose up to 10% of their output from dusty environments. In this direction periodic rain provides a convenient means to clean the modules from dust. Furthermore, temperature is the largest de-rating factor and has an important effect on the power output of the cell. The most significant is the temperature dependence of the PV cell voltage which decreases with increasing temperature. The voltage decrease of a silicon cell is typically 2.3mV per degree C. Therefore, the temperature variation of the current or the fill factor are less pronounced and are usually neglected in the PVs design. In space applications, aging of PV cells is the one of the most important factors to consider in estimating power ratings over the spaceship life time due to the harsh environmental conditions.

Efficiency of solar cells under high insolation conditions (e.g., over 1 kW/m^2) may be smaller than anticipated. Datasheets will typically not quote above this standard limit. Sites in Western Australia are among the highest performing in the world and during the summer may reach insolation levels as much as1.2 kW/m^2.

2.4. Solar Cell Model

Solar cells are fabricated from thin layer of semiconductor materials containing P-N junction as shown in Fig. 2.4. When the sunlight (photons) hits the solar cell the electrons (located in the valence band) acquire energy and move from the valence band to the conduction band [19]. This allows the electrons to flow freely through the material and produce electricity. Complementary positive charges (holes) are created at the same time and flow in the direction opposite of the electrons. Electric circuit is then formed by attaching electrical loads to the positive and negative sides and the photon excited electrons form the photocurrent (I_{ph}).

The amount of solar energy (photons) absorbed by the solar cell determines its efficiency. If a photon has energy lower than the band gap energy of the semiconductor it is unable to create an electron-hole pair and if photon energy is more than the band gap energy, the excess is dissipated as heat. Some semiconductors are manufactured with several layers, each layer having a different band gap to maximise absorption of photon.

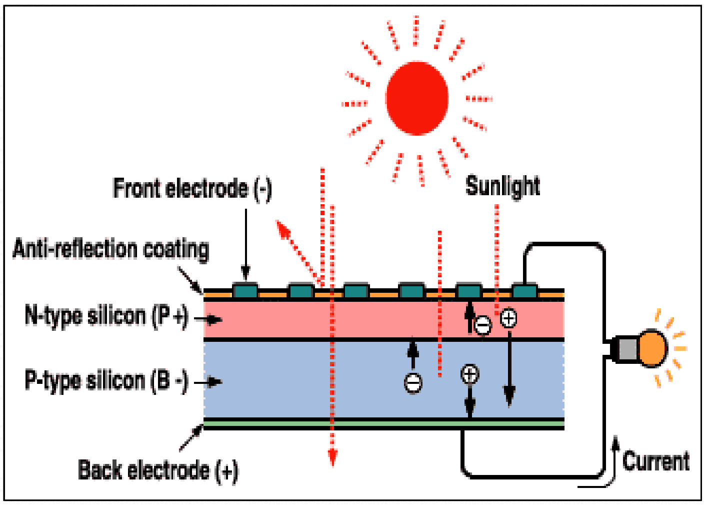


Figure 2.4: A PV cell showing the lifecycle of the PV effect [20]

2.4.1. Generalized Model of Solar Cell

Figure 2.5 shows the generalized model of a solar cell consists of series (R_s) and shunt (R_{sh}) resistances and takes into consideration the effects of recombination diodes [17]. R_s have a large impact on cell short-circuit current I_{sc}. R_{sh} alters the cells open-circuit voltage V_{oc}. However, for most applications, this model is complicated to implement as it is difficult to obtain its circuit parameters for analysis and simulation. Thus, a simplified equivalent of solar cell model is required.

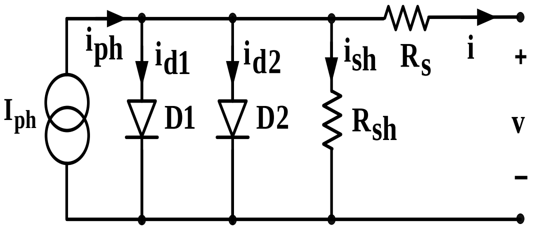


Figure 2.5: Generalize model of a solar cell [17]

2.4.2. Simplified Solar Cell Model

For most applications, the simplified equivalent one diode circuit of a solar cell as shown in Fig. 2.6 can be used. The ideal solar cell is modelled as a current source in parallel with a diode. The current source models the level of solar irradiance and the diode represents the p-n junction of a solar cell. Clearly this model is dependent on the photon current (I_{ph}) and the diode (D1) characteristics. I_{ph} (known as the short-circuit current) varies in direct proportion to the solar irradiance. The operation of diode D1 is heavily dependent on the reverse saturation current (I_0) and both I_{ph} and I_0 depend on the structure of the device. However, it is the value of I_0 which can vary by many orders of magnitude, depending on the device geometry and processing. The maximum solar output power (P_{max}) is reached at a point (on the i-v characteristic) where the product IV is maximum.

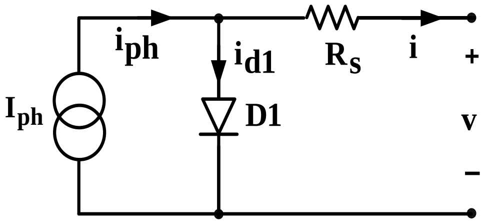


Figure 2.6: Simplified model of a solar cell [17]

The behaviour of an ideal diode can be described by the Shockley diode equation:

$$i_{d1} = I_0(e^{(v_{d1}/nV_T)} - 1) \qquad (2\text{-}1)$$

where i_{d1} and v_{d1} are the diode current and voltage, respectively, I_0 is the reverse bias saturation current, V_d is the voltage across the diode, V_T is the thermal voltage (given by V_T=kT/q), n is the emission coefficient (that can vary from about 1 to 2 depending on the fabrication process and semiconductor material and in many cases is assumed to be 1), q ($=1.602\times10^{-19}$ C) is electron charge, k ($=1.38065\times10^{-23}$ JK^{-1}) is Boltzmann's constant, and T is the absolute temperature of the p-n junction in kelvins ($^oK = {}^oC + 273$).

Given $i_{d1}= I_{ph} - i$ (where i is the solar cell current as shown in Fig. 2.6), the diode voltage (v_{d1}) can be found by re-arranging the Shockley diode equation:

$$v_{d1} = nV_T \ln(\frac{I_{ph} - i + I_0}{I_0}) \tag{2-2}$$

Considering effect of cell series resistance ($v= v_{d1} - i R_S$), the cell output voltage is:

$$v = nV_T \ln(\frac{I_{ph} - i + I_0}{I_0}) - iR_S \tag{2-3}$$

Figure 2.7 shows the power-voltage (P-V) and current-voltage (I-V) characteristics of an ideal solar cell [14].

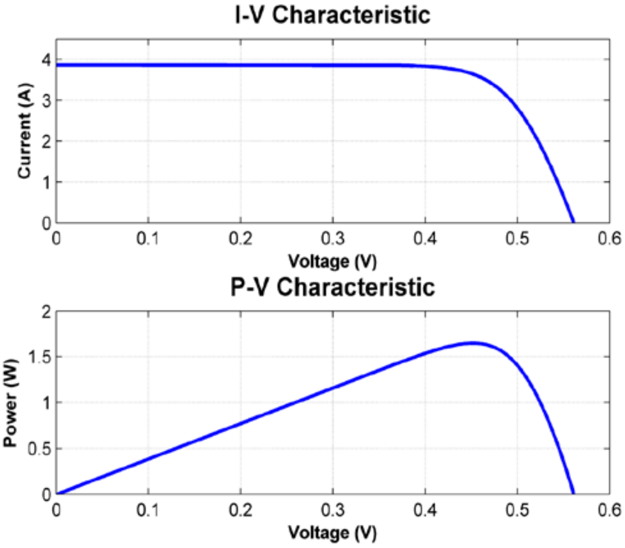


Figure 2.7: Simulated power-voltage (P-V) and current-voltage (I-V) characteristics of 12 series solar cells [14]

2.5. Solar Module Model

In commercial and residential applications, solar cells are rarely used individually. Instead, cells with similar characteristics are connected and encapsulated to form modules. Furthermore, as the maximum voltage from a single cell is limited (e.g., about 600mV for a silicon cell), cells are usually connected in series to obtain the desired voltage. This is usually about 36 series cells used for a normal 12V charging system. Under peak sunlight (1000 mW/cm2), the maximum current delivered by a cell is approximately 30mA/cm2. Cells can also be paralleled to obtain the desired current.

2.5.1. Mismatched Cells

In practice, the cells in a module will not exhibit identical characteristics and the module i-v curve would not have the same shape as that of the individual cells. Mismatched cells within a module can result in some cells generating and some dissipating power. In the worst case, the output powers of the normally operating cells can be dissipated in the low output cell. Dissipation of power in poor cells can lead to breakdown in localized regions of the cell p-n junction, may cause enormous power dissipation in a small area leading to local overheating, or “hotspots”, which in turn leads to destructive effects, such as cell or glass cracking or melting of solder.

2.5.2. Bypass Diodes

Bypass diodes are added to overcome problems associated with mismatched cells. Under normal conditions, with no shading, each diode is reverse-biased and all cells generate power. When a cell is shaded, it ceases to generate, acts as a high resistance and tends to be reverse-biased by the other cells, causing the diode across the cell to conduct, bypassing the shaded cell.

The internal resistance of the diode is greater than that of a PV cell when exposed to sunlight. The current follows the path of least resistance and flows through each consecutive cell in the string. When a cell in the series string is shaded, cell resistance increases significantly, making the bypass diode the path of least resistance. The current naturally follows the path of least resistance, shunting the power through the bypass diode. For modules in parallel, an additional problem, thermal runaway, can occur when bypass diodes are exercised. When one string of bypass diodes becomes hotter than the rest, they take up a larger share of the current, hence becoming even hotter. Diodes should be rated to handle the parallel module current.

2.5.3. Shading and Its Effects on PV Operation

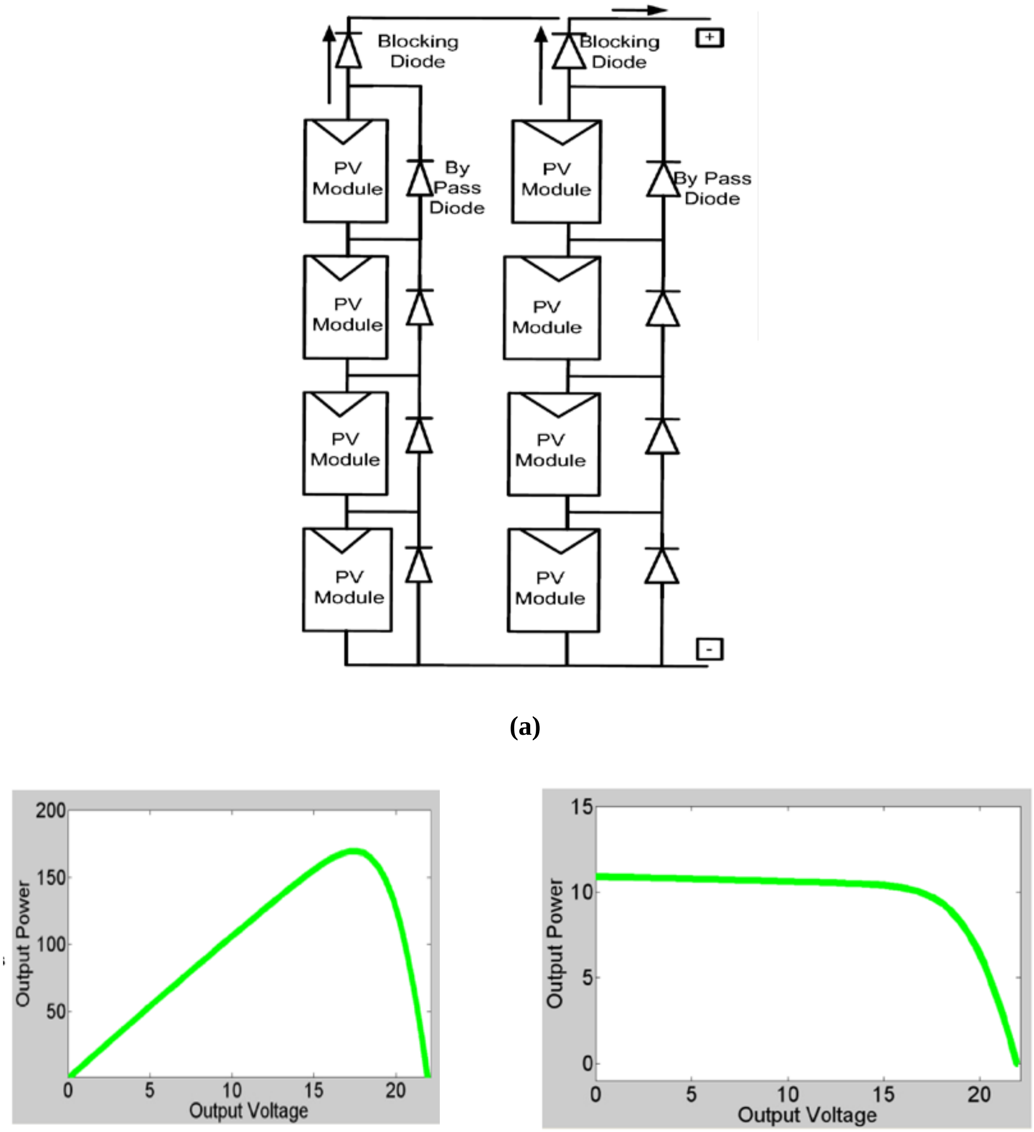
Shading of solar cells not only reduces the cell power but also changes the open circuit voltage, the short circuit current and the efficiency. Partial shading condition is a common situation due to the shadow of buildings, trees, clouds, and dirties, etc. Under partial shading condition, only one of the series strings of PV modules is less irradiated and which then has to disperse some of the power generated by the rest of the modules. In the other word, the current available in a series connection of PV modules is measured by the current of the PV module which is less illuminated. This can be eliminated by placing bypass diodes across the PV module [21].

The current available in a series string is limited by the current of the solar cell with the lowest level of illumination. This can be avoided by including bypass diodes across every solar cell or across part of the series string.

Since short circuit current density of a solar cell is proportional to the value of the irradiance, shading can easily be linked to the short circuit current of the cell (Isc=Iph) as:

$$I_{ph} = I_{SC}(1000W/m^2)(1 - \frac{\%Shading}{100}) \qquad (2\text{-}4)$$

To illustrate the effect of shading, Fig. 2.8 shows the characteristics of a PV array that consists of 2 strings connected in parallel. Each string includes four series module under identical conditions. On the other hand, Fig. 2.9 shows the characteristics of the same PV array while two modules of one string are partially shaded. In this case, the output PV curve contains multiple peaks. This will affect the performance of the PV converter and may reduce the amount of output power particularly if the controller is incorporating a MPPT scheme.

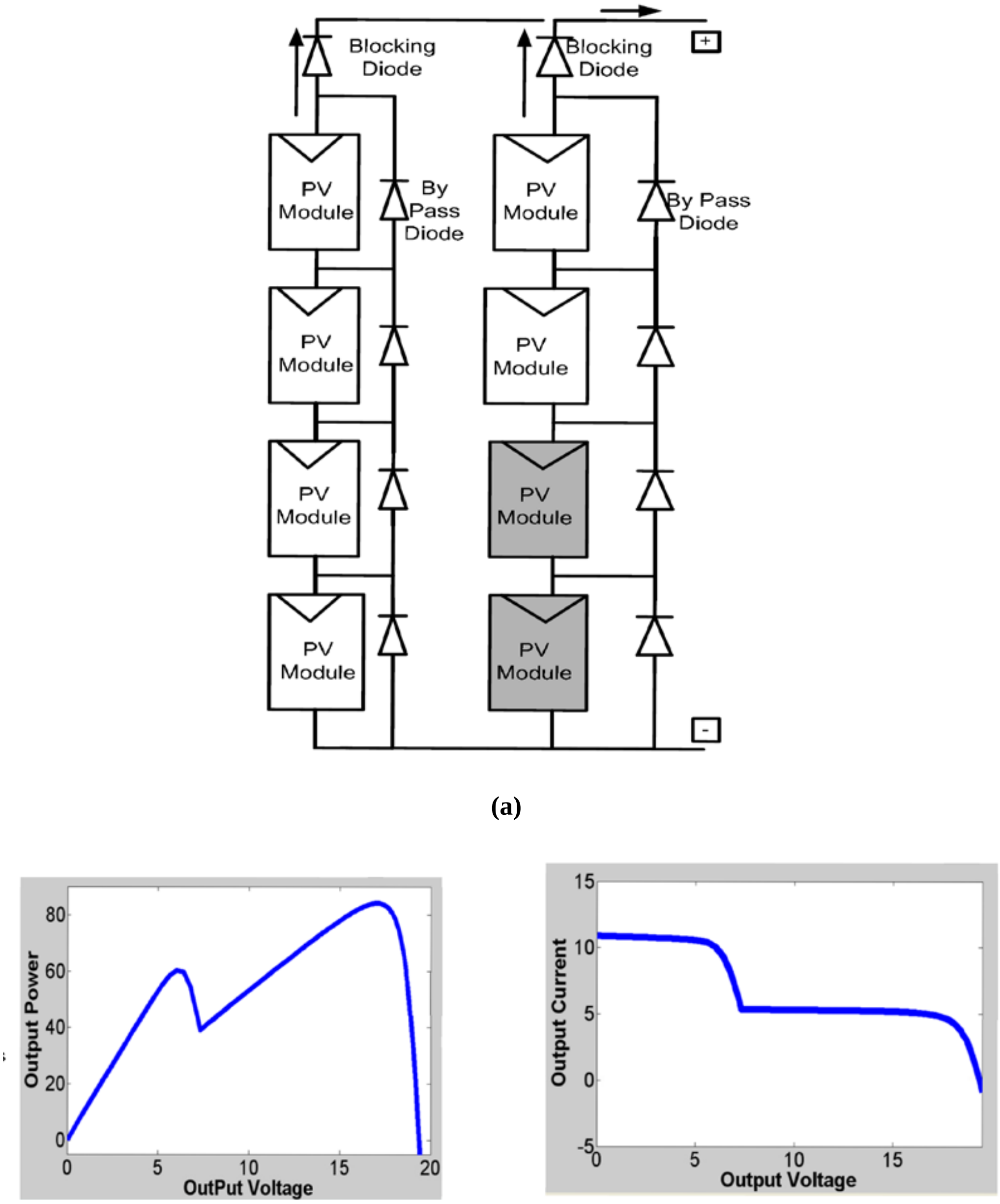


(a)

(b)

(c)

Figure 2.8: Characteristics of PV array under identical condition; (a) PV array configuration, (b) P-V characteristics, (c) I-V characteristics [21]



(a)

(b)

(c)

Figure 2.9: Characteristics of PV array under partially shaded condition; (a) PV array configuration, (b) P-V characteristics, (c) I-V characteristics [21]

To overcome the effects of partial shading in a series string, a bypass diode can be connected across the cell which is experiencing shading. Fig. 2.10 shows the schematic of n solar cells connected in series, with cell 1 having its bypass diode activated. Note that the bypass current dependents on both the current from the unshaded cell and the level of shading:

$$\begin{aligned} i_{bp} &= i_{c2} - i_{c1} = (I_{ph2} - I_{ph1}) - (i_{d2} - i_{d1}) \\ &= (I_{ph}^{unshaded} - I_{ph}^{shaded}) - (i_{d}^{unshaded} - i_{d}^{shaded}) \end{aligned} \tag{2-5}$$

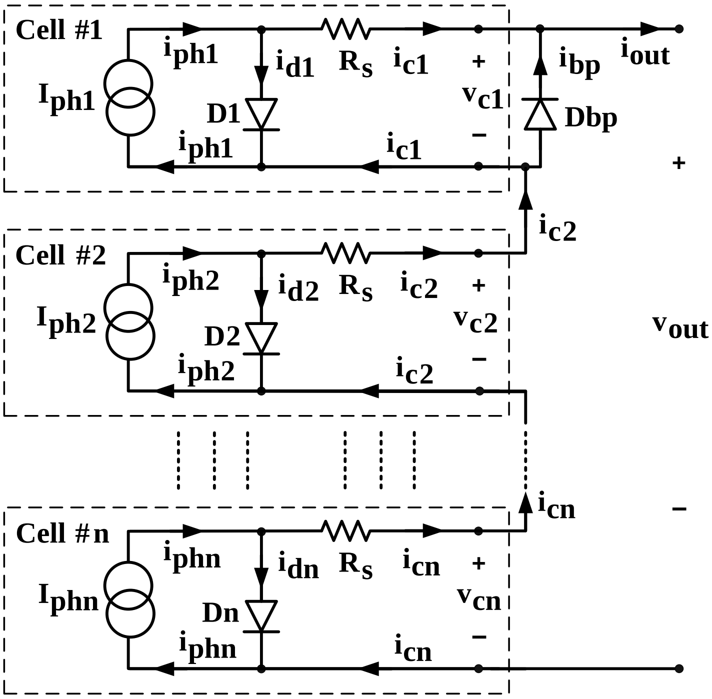


Figure 2.10: Two cell schematic incorporating bypass diodes [17]

2.6. Rooftop PV Systems (PVs)

Figure 2.11 shows the main components of a typical grid connected PVs consisting of PV module, inverter and smart meter. There are other auxiliary components such as fuse box (to control the input and output), wiring circuits (between equipment and fuse box) and isolating switches (to isolate components to perform maintenance or to upgrade the system). Currently, most PV generators are designed with MPPT abilities to justify their relatively high investment cost. That is the main task of the PV converter is to extract the maximum possible energy from the sun and deliver it to the power grid to increase the profit. However, due to the stochastic nature of the solar cell power output, large developments of grid-connected PVs involve large fluctuations of the frequency, power, and voltage in the grid. Utilities are beginning to detect these problems in both the distribution (due to moderate and large PV power plants) and residential networks (caused by large penetrations of rooftop PVs).

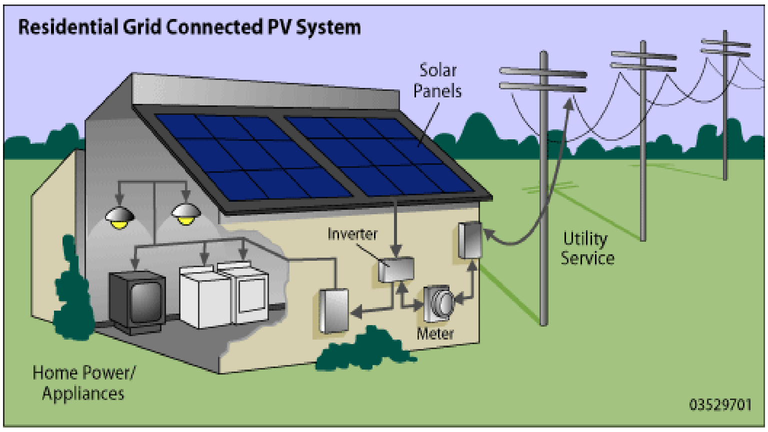


Figure 2.11: Residential grid connected PVs [47]

Rooftop PVs are growing in popularity as low emission modes of distributed energy generations in many developing countries including Australia. Utilities are concerned about the potential effects of these distributed energy resources on the residential and commercial networks. Integration of rooftop PVs in residential networks at moderate penetration levels is becoming a reality in many countries including Australia. However, the present state of rooftop PV technology causes detrimental effects on the grid at high PV penetrations that have not fully explored to most power utilities. The main limitations of rooftop PVs are:

- The dependency of output power on the environmental factors such as sun radiation, panel temperature, passing clouds and shading. This dependency may result in sudden output power variations of rooftop PVs during cloudy periods.

- The dependency of output power on loading that will change the operating point on their nonlinear v-i characteristics and reduce the overall efficiency.
- Difficulties in optimal design, modelling, control of rooftop PVs due to the intermittent behavior and uncertainties associated with their output power.
- Rooftop PVs are generally expensive compared with the conventional energy resources and have a relatively long payback time. However, as the electricity price rises steadily; their cost efficiency becomes more attractive particularly for residential applications.
- Rooftop PVs can force unbalance operating conditions as the majority of their applications are randomly distributed single-phase residential systems.
- Rooftop PVs will cause reversed power flow conditions particularly under during high sun radiation and low residential periods. This may cause disturbances to the power grid.

CHAPTER THREE

ENERGY STORAGE TECHNOLOGIES FOR PV APPLICATIONS

The unpredictable and stochastic nature of renewable energy sources such as wind and PV is becoming a serious issue in controlling the grid balance under different operating conditions [22-24]. In this term, energy storage (ES) units such as researchable batteries [24, 26], ultra-capacitor and fuel cells [22, 23] can be used to balance the lack of power during peak load hours while storing the extra power during the off-peak hours. Reference [23] presents an economic EMS based on time of use (TOU) rating for grid-connected PV with BS system that will increase cost efficiency. Similarly, reference [27] investigates the design of an optimal charge\discharge algorithm for distributed BS systems connected to PVs that also consider cost analysis. Reference [25, 26] presents grid-connected distributed energy systems in combination with lithium-ion (Li-ion) battery as the storage element. References [28] show advantages of Li-ion battery technology compared to lead-acid batteries and nickel-metal hydride batteries, such as high power and energy density, high working cell voltage, low self-discharge rate and high charge-discharge efficiency.

Reference [29] explains how batteries interconnected to distributed systems can be utilized to expand the energy production of conventional grid-connected PV power plants, mostly under mismatching operating conditions. Apart from these works, Hector ei al. proposed an EMS for large-scale power plants operating with different ES ratings [22]. On the other hand, some researches have considered application of ES in isolated PVs. In this regard, [30] investigates the performance and energy supplies of different types of battery technology suitable for usage in isolated power systems. While, there are a few literatures in terms of PV sources combined with ES [22], more research is required to evaluate the application and capacity of BS in grid-connected PVs particularly with consideration of real-time weather and load conditions**.**

3.1. Energy Storage Systems (ESS)

Electrical energy in an alternating current (AC) system cannot be stored electrically, and must typically be generated at the time of demand. However, energy can be stored by converting the electrical energy and storing it electromagnetically, electrochemically, kinetically or as potential energy. Each ES technology usually requires an energy conversion unit to convert the energy from one form into another and back again.

There are many applications of ES in utility systems including transmission enhancement, power oscillation damping, dynamic voltage stability, tie-line control, short-term spinning reserve, load levelling, sub-synchronous resonance damping and power quality improvement. The four leading ES technologies are briefly introduced in the following sections.

3.1.1. Superconducting Magnetic Energy Storage (SMES)

The main element of an SMES unit is a superconducting coil of high inductance (L_{Coil} in Henrys) at the cryogenic temperature which is controlled by a power electronic conversion system. SMES stores the energy in the magnetic field generated by DC current I_{Coil}. The stored energy (E in Joules) and the rated power (P in Watts) are the common parameters and specifications of the SMES device. Power conversion may be achieved through two main power electronic converter topologies. One approach is to employ a current source converter (CSC) to interface to the AC system and charge/discharge the coil. The other another approach is instead of CSC select a voltage source converter (VSC) along with a DC-DC chopper. In the later approach, the VSC and DC-DC chopper share a common DC bus. The charge, discharge, and standby modes are obtained by controlling the voltage across the SMES coil (V_{coil}). Several factors need to be considered in designing the SMES coil to achieve the best and most economic performance such as coil configuration, energy capacity, structure, and operating temperature.

3.1.2. Super Capacitor (SC)

An electric double-layer capacitor (EDLC) is known as super-capacitor (SC) or ultra-capacitor. The rating of a super-capacitor can be much greater than an electrolytic capacitor. SC ratings can reach up to 5000 farads. The highest energy density in production is 30 Wh/kg, which is slightly below the density of rapid-charging Lithium-titanate batteries. However, due to the high permeability and close proximity of the electrodes, SCs have a low-voltage-withstand capability (typically 2–3V) [31]. SC store energy by physically separating positive and negative charges which has profound implications on cycle life, efficiency, energy, and power density. Envisaging the fact that ideally there are no chemical changes on the electrodes under normal operating conditions, SCs have a long cycle life and high efficiency. They also provide exceptional power density, since the charges are physically stored on the electrodes. On the other hand, energy density is low since the electrons are not bounded by chemical reactions. This also implies that the SCs can be completely discharged and create larger voltage swings as a function of the SOC. Therefore, SC cannot totally replace the battery. However, hybrid SC-battery system improves storage performance and battery life time. This hybrid SC energy storage option can be useful for electric vehicle and wind energy applications.

3.1.3. Flywheel Energy Storage (FES)

Flywheel energy storage (FES) operates by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system in form of rotational energy [32]. When energy is removed from the system, the flywheel's rotational speed is reduced as a result of the principle of conservation of energy. The speed of the flywheel is increased by adding energy to the system. Furthermore, a bidirectional AC to AC converter can be used for wind turbine applications to accelerate and decelerate the motor/generator connected to the flywheel. The speed of flywheels can be varied from 20,000 to over 50,000 rpm [33]. FES has many attractive characteristics including high energy efficiency (as high as 90%), long lifetime, high energy densities (100-130 Wh/kg) and large maximum power outputs with typical capacities range from 3 kWh to 133 kWh. Rapid charging of a system occurs in less than 15 minutes [37]. The energy flows in a FES system is usually controlled by a three-phase AC motor/generator unit attached to the flywheel. It can also be used for frequency regulation and power quality improvement in power grids with large scale wind penetration.

3.1.4. Battery Energy Storage System (BESS)

A battery consists of one or more electrochemical cells that convert stored chemical energy into electrical energy. Batteries are the most popular and widely used ES technology because of their portability and ruggedness. There are many types of battery technologies including lead acid, Li-ion, Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Sodium-Sulfur (NaS), Zinc Bromide, Vanadiom Redox (VRB), Polysulphide Bromide, Zinc-Air, Li polymer, Zebra, and Flow batteries (FBs) (Table 3.1).

Lead acid batteries have been used since mid-1800s and still prevalent in cost-sensitive applications such as automotive starting, lighting, ignition, and uninterruptible power supply (UPS). However, most batteries have comparatively low energy density and limited life cycle. Recent research intends to replace lead with lighter materials such as carbon to increase battery power and energy density. Li-ion batteries are more expensive than the conventional lead-acid technology; however, they have more advantages such as higher energy-to-weight ratios, lower self-discharge and no memory effects [35]. Main applications of Li-ion batteries are laptops, cameras, mobiles phones, and other portable electronic devices. They may become the most promising battery technology in future due to their high energy density for applications like plug in hybrid/electric vehicle and wind energy power generations. NiCd batteries have a higher energy density and longer cycle life than lead acid batteries but are inferior to chemistries such as Li-ion and NiMH batteries. Other disadvantages of NiCd batteries compared to NiMH are shorter life cycle, memory effect, lower energy density, flat discharge curve, and toxicity of Cd that requires a complex recycling procedure, as well as negative temperature coefficient that may cause thermal runaway in voltage-controlled charging.

Relatively high power density, proven safety, good abuse tolerance, and very long life at a partial SOC have recently made NiMH batteries more applicable over NiCd batteries. The disadvantages of NiMH battery are the relatively high self-discharge rate, although the introduction of novel separators has alleviated this problem. When overcharged, NiMH batteries use excess energy to split and recombine water. Therefore, the batteries are maintenance free. However, hydrogen build up can rupture the cell when batteries are charged at an excessively high charge rate. If the battery is over discharged, the cell can be reverse-polarized, leading to capacity reduction.

NaS batteries exhibit several advantages including high power and high energy density, high efficiency, good temperature stability, long cycle life, low cost, and good safety. NaS batteries are made of low-cost materials, making them suitable for high-volume mass production. NaS batteries can be used for load leveling, emergency power supply, or UPS applications. They are also suitable for utility applications and wind energy systems [36-37].

FB is an encouraging technology that decouples the total stored energy from the rated power. The rated power depends on the reactor size while the stored capacity is determined by the auxiliary tank volume. These characteristics make the FB suitable for providing large amounts of power and energy required by most electrical utilities. The main advantages of the FBs are long life due to easy electrolyte replacement, fast recharge by replacing exhaust electrolyte, high power and energy capacity, full discharge capability, use of non-corrosive materials, and low-temperature operation. In contrast, the disadvantage of FBs is the need for moving mechanical parts such as pumping systems that make system miniaturization difficult. The main technologies used currently are summarized in Table 3.1 [38].

References [39] indicate that it is necessary to have a good understanding of battery characteristics and SOC for efficient storage management of the batteries.. The SOC of a battery is defined as its available capacity expressed as a percentage of its maximum available capacity:

$$SOC = \frac{Available\ capacity\,(Ah)}{Maximum\ available\ capacity\,(Ah)} \tag{3-1}$$

Battery SOC can also be defined from the perspective of energy as shown in Eq. 4-7. Life cycle of a battery decreases with increased depth of discharge (DOD) and cell chemistries of battery in many cases does not tolerate deep discharge which may lead to permanent damage. Consequently, to improve the life cycle of a battery and to protect it from permanent damage, it is necessary to set a minimum level of discharge it terms of SOC, which is usually expressed as $SOC_{\mathbf{min}}$.

Most batteries provide quick response for charging and discharging. However, the discharge rate depends on the battery type and the associated chemical reaction. Table 3.2 provides a comparison of different types of batteries. According to this table, Li-ion battery technology shows many advantages compared to lead-acid and nickel-metal hydride batteries such as high power, energy density, high working cell voltage, low self-discharge rate and high charge-discharge efficiency, which makes it suitable for DG connected and grid connected applications.

Table 3.1: Flow battery characteristic

Technology	**Potential**	**Efficiency**
Zinc Bromide	1.8	70%
Vanadiom Redox (VRB)	1.2-1.6	80%
Polysulphide Bromide	1.5	-
Zinc-Air	1.6	50%

Table 3.2: Comparison of different types of batteries

	Lead Acid	Li-ion	Li polymer	Ni-MH	Ni-Cd	NaS	Zebra
Voltage (V)	2.1	3.6	3.7	1.2	1.2	-	2.58
Energy Density (Wh/Kg)	30-40	150-250	130-200	30-80	40-60	150	120
Power (W/Kg)	180	1800	3000	250-1000	150	-	400
Charge/Discharge Efficiency (%)	70-90	80-90	-	66	70-90	90	100
Self-discharge (%/month)	3-4	5-10	-	30	20	-	-
Durability Cycle	500-800	1200	500-1000	500-1000	1500	-	1000
Durability (Yr)	5-10	2-3	2-3	-	-	-	-

3.1.5. Hybrid Energy Storage System

There are a few factors to be considered in selecting an appropriate ES device for a given application including energy rating, response time, weight, volume, and operating temperature. Most practical applications require a combination of these factors in terms of power rating, energy density, cost and life cycle that is not attainable from a single ES technology; therefore, a hybrid ES system may be considered to fulfil the requirement. In a hybrid system, two or more different types of the above-mentioned ES devices (SMES, SC, FES, and BESS) with complementary characteristics are electronically combined together to achieve superior performance. Some hybrid storage systems include battery and SC [40], battery and flywheels, battery and SMES, fuel cell and battery and compressed air energy storage and battery or super-capacitor [41]. The selection of an appropriate ES technology will significantly depend on the application; however, the following main criteria should be carefully considered:

- Reliability- The ability of the system to meet the load at all times.
- Efficiency- The ability to use the components in a way as to minimize losses.

- Cost- The lifecycle cost of the system including the initial investment plus running costs over the lifespan of the system.
- Technical maturity- Commercial availability and proven reliability of the technologies used.
- Life span- The length of time that the system will be able to operate.

3.2. ES Technologies for PV Applications

Integration of an storage device in PVs provide a combination of financial, operational and environmental benefits to the utilities and consumers through peak shaving, load shifting, grid support, reliability improvement and demand response, as well as compensating for the unpredictable power production of renewable DG systems such as PV and wind [42](Table 3.3).

3.2.1. Peak Shaving

The purpose of peak shaving is minimising demand charges for a commercial customer or reducing peak loads experienced by the utility. Peak shaving for PV applications requires the storage device to provide the essential power above a specified threshold in lack of PV availability. Failure of peak shaving can have economic consequences in cases where customers’ rates are based on monthly peak demand.

3.2.2. Load Shifting

Technically, load shifting is similar to peak shaving, but its application is useful to customers purchasing utility power on a time-of-use basis. Many peak loads occur late in the day, after the peak for PV generation has passed. Storage can be combined with PV to reduce the demand for utility power during late-day, higher-rate times by charging a storage system early in the day to support a load later in the day. In [43] a study of peak shaving and load shifting on a PVs at Public Service Company of New Mexico is presented. The project combines both residential and commercial loads on a dedicated feeder, with high PV penetration ratio, equipped with a 0.5MW substation-sited PVs and large-scale utility storage. The unique aspect of the BS system being used is that both slow (load-shifting) and fast (intermittency-mitigation) power discharge modes are possible. Smart meters and customer demand response management, along with some customer-owned storage are all being implemented. This program targets a minimum of 15% peak-load reduction at a specific feeder through a combination of these devices and measures.

3.2.3. Demand Response

Demand response allows the utility to control selected high-load devices such as heating, ventilation, air conditioning and water heating, in a progressing type of operation during high-demand periods. For both residential and small commercial customers, using an appropriately sized PV-storage system should allow the implementation of demand response strategies with little or no effect on local operations. At least one-way communications between the PV-storage site and the utility will be required by control systems for demand response systems. In [44] an optimization approach to determine operational planning of power output for large PV/battery system is proposed. This approach includes the determination method of charge/discharge amount for battery of electric vehicle as a demand response. The method targets to obtain more benefit deal with electrical power selling. The optimization method applies genetic algorithm (GA) to smooth the fluctuating power output due to PVs, and also to determine the initial SOC of battery. The validity of proposed method is confirmed by simulation results.

3.2.4. Outage Protection

A possible application of PV-storage system is to provide power to a residential or small commercial customer when utility power is unavailable (i.e., during outages). To offer this type of protection it is necessary to intentionally island the residence or commercial customer with utility. There is a number of safety regulations designed to prevent the back-feeding of power onto transmission and distribution lines during islanding or blackout. Islanding is beneficial to both the utility and the customer, because it allows the utility to shed loads during high demand periods while protecting the customer’s loads if the utility fails.

3.2.5. Grid Power Quality Control

In addition to outage protection, storage systems can be utilized to improve grid power quality by regulating bus voltages, adjusting phase angles and eliminating harmonic distortions from the electric grid. This function is currently supplied by UPS devices, on the customer side. Deviations in the AC power being supplied and then corrected by UPS within milliseconds. Integration of small ES can be effectively reduced by the overvoltage caused by reverse power flow. Furthermore, by introducing reactive power compensation and harmonic cancellation, grid power quality can be improved by battery-integrated PVs.

Table 3.3: Different applications of ESS in PVs

Applications of ESS for PV	**Definition**
Peak Shaving	The goal is to counteract the power intermittency from PV by controlling the charge/discharge rate of the energy from the fast ultra-battery.
Load Shifting	Many peak loads occur late in the day, after the peak for PV generation has passed. Storage can be combined with PV to reduce the demand for utility power during late-day by charging a storage system with PV-generated energy during the day to support the load during the peak load hours.
Demand Response	This allows the utility to control selected high-load devices during high-demand periods.
Outage Protection	An important benefit of a PV-storage system is the ability to provide power to the residential or small commercial customer when utility power is unavailable.
Grid Power Quality Control	Battery-integrated PV systems can improve grid power quality by introducing reactive power compensation and/or harmonic cancellation.

3.2.6. Solar Output Power Smoothing

A recent application of BS is for output power smoothing of rooftop PVs as investigated in Chapters 4 and 5 of this thesis. The idea aim is to investigate the application and control of BS technology on an existing rooftop PVs to overcome the sudden output power change of rooftop PVs due to variations in the environmental conditions. This approach can also have an important role in mitigating the intermittent behaviour and uncertainties associated with PV systems. A practical EMS approach for operating small scale grid-connected rooftop PVs with BS connected at PCC will be presented such that the delivered output power to the grid is constant under various operating conditions. The power balance between rooftop PV, battery and grid is considered by dynamic control of the battery converter such that the output power to the grid is constant during the day. Simulation results for a 24-hour period will be presented and analysed for a system comprising of a single phase rooftop PV with BS connected to an infinite bus using PSCAD software.

CHAPTER FOUR

ROOFTOP PV WITH BATTERY STORAGE SYSTEM FOR CONSTANT OUTPUT POWER PRODUCTION

This chapter aims to attain constant-production periods in grid-connected rooftop PVs under different operative and environmental operating conditions by including a BS unit. An EMS is proposed to consider the power balance between rooftop PV, BS, household load and grid to dynamically control BS converter such that the output power to the grid is constant during daylight. Simulation results generated in PSCAD will be presented and analyzed to investigate the performance of BS-EMS for a system consisting of single-phase rooftop PV with BS and linear load connected to power grid.

4.1. Rooftop PV and Battery Storage System

Distributed PVs are being accepted as possible alternatives to the conventional contaminating energy resources. These environmentally friendly renewable energy systems are currently representing only a low percentage of the global electricity production. However, their applications in residential and industrial networks are rapidly growing since the peaks of most industrial and some residential loads usually coincide with the maximum output of the PV modules. Fig. 4.1 shows typical configuration of a house with linear loads and rooftop PV connected to the power grid at PCC.

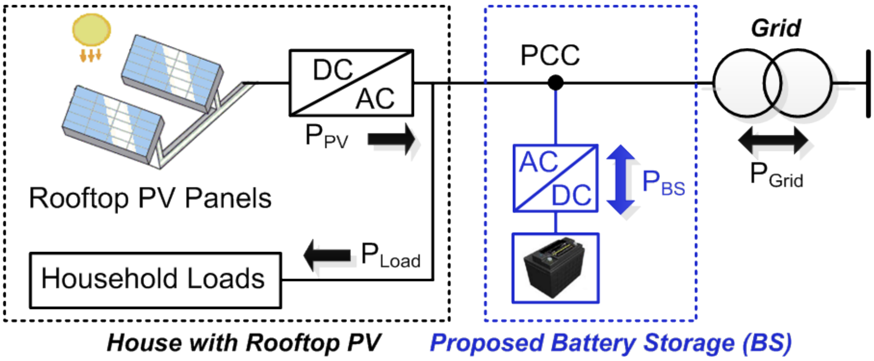
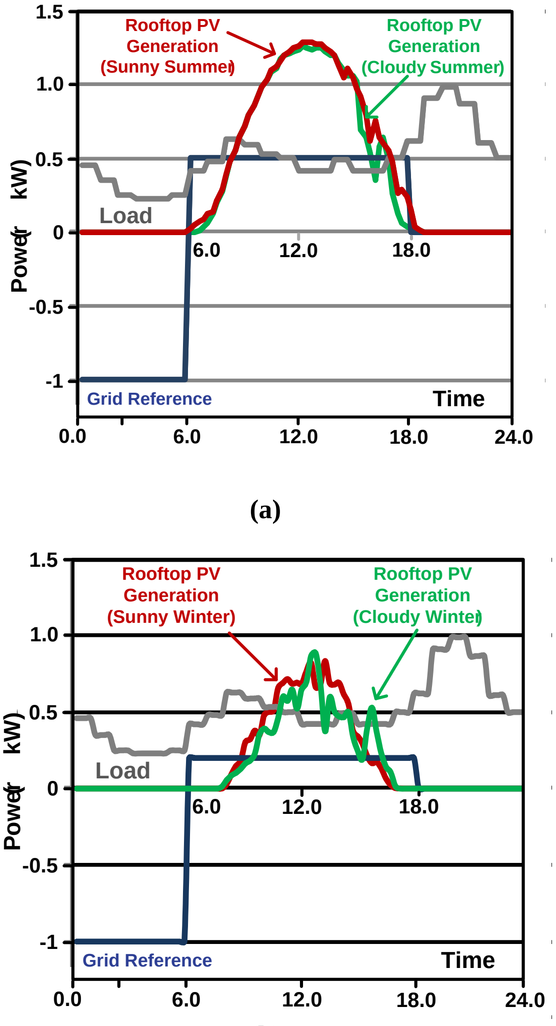


Figure 4.1: Typical house with grid-connected rooftop PV and BS system

One of the main limitations of rooftop PVs is the dependency of their output power to environmental factors such as sun radiation, panel temperature, passing clouds and shading, as well as loading level (operating point on their nonlinear v-i characteristics). This dependency may result in sudden output power variations of rooftop PVs during cloudy periods. Fig. 4.1 also shows a practical solution to overcome this limitation by including a shunt-connected BS system at PCC to ensure constant output power production to the grid during daylight. This configuration allows the consumer to store the excess generated energy in PV storage elements during off-peak hours and return it back to the grid at appropriate times. It can also offer a few advantages:

- Mitigating the stochastic nature of PV production.
- Offer profit by selling/purchasing electricity to/from grid.
- Overcome sudden output power changes of rooftop PVs.

Figure 4.2 represents typical (measured) household daily load curve and daily average summer and winter rooftop PV generation in Perth, WA. According to this figure, there is about 50% reduction in PV output power during winter that can dramatically change the amount of power delivered to the grid. In addition, household loads must also be considered in the storage controller as their type, duration and levels will change depending on the season, temperature, cloud coverage, social activities and standard working hours, etc. Inclusion of the load is very important as its variations will have impacts on the performance of BS-EMS. Several factors influence the load in the electrical network including the weather situation (e.g., temperature, cloud coverage, etc.), social activities (such as holidays), standard working hours, etc.



(a)

(b)

Figure 4.2: Household load curve, constant daily output power to grid (PGrid-ref), typical rooftop PV generation for typical summer (a) and typical winter (b) days in Perth, WA [45]

The BS can store unused energy locally and utilize it in the evening peak load period to reduce the voltage rise problem during peak PV generation by injecting less power to the grid. It can also support the voltage during evening peak hours by serving local household loads and hence reducing stress on the grid.

4.2. Battery Storage Energy Management Strategy (BS-EMS) For Constant Output Power Production

Installed rooftop PVs in residential networks can cause power fluctuations due to the presence of passing cloud and PV outages. To overcome this problem, an EMS in conjunction with a BS system will be implemented to support the rooftop PV (Fig. 1) in providing constant power production during different periods throughout the day. The entire PVs will work according to the BS-EMS. Constant output PV power (P_{PV}) will be produced as a result of dynamically controlling the BS converter under various operating conditions. In this sense, the control scheme of the total system (rooftop PV, BS, household load and grid) is based on the following power balance equation:

$$\sum_t P_{Grid-ref}(t) = \sum_t [P_{PV}(t) + P_{BS}(t) - P_L(t)] \tag{4-1}$$

where $t = \Delta t, 2\Delta t, ...24\,hours$ and Δt is the time interval. $P_{Grid\text{-}ref}$, P_{PV}, P_{BS} and P_L are the instantaneous desired (requested) constant power to be injected into the grid, the instantaneous power provided by rooftop PV panels (which mainly depends on the site location and weather conditions), the current power exchanged by the BS and the instantaneous household load, respectively (Fig. 4.2). The operation of BS system will be dynamically controlled based on the following charge and discharge characteristics:

Charge: If $$P_{BS} < 0 \Rightarrow \frac{d\,E_{BS}(t)}{dt} = -P_{BS}\,(\varepsilon c) \qquad (4\text{-}2)$$

Discharge: If $$P_{BS} > 0 \Rightarrow \frac{d\,E_{BS}(t)}{dt} = \frac{-\,P_{BS}}{\varepsilon d} \qquad (4\text{-}3)$$

where BES, εc and εd are the current stored (available) energy of BS system, charging efficiency and discharging efficiency, respectively.

According to Eq. 4-1, the desired constant output power level to the grid ($P_{Grid\text{-}ref}$) can be changed for each time interval (Δt). In this paper Δt is assumed to be 15 min. Therefore, the power production patters can have up to 24x4=96 different durations Pattern= {p1 , p2, ..., p96}. However, in this paper a single constant output power level is considered during daylight (e.g., 0600h-18:00h) as by the $P_{Grid\text{-}ref}$, waveform in Fig. 4.2.

The PV, load and BS energy profiles during the 24 hour period can be calculated as follows:

$$\tilde{E}_{PV}(t) = \sum_{k=0}^{95} [\tilde{E}_{PV,k\Delta t} = \int_{t=k\Delta t}^{(k+1)\Delta t} P_{PV}(t)dt = \Delta t(P_{PV,k\Delta t,\max})]. \qquad (4\text{-}4)$$

$$\tilde{E}_{L}(t) = \sum_{k=0}^{95} [\tilde{E}_{L,k\Delta t} = \int_{t=k\Delta t}^{(k+1)\Delta t} P_{L}(t)dt = \Delta t(P_{L,k\Delta t,\max})]. \qquad (4\text{-}5)$$

$$\tilde{E}_{BS}(t) = \sum_{k=0}^{95} [\tilde{E}_{BS,k\Delta t} = \int_{t=k\Delta t}^{(k+1)\Delta t} P_{BS}(t)dt = \Delta t(P_{BS,k\Delta t,\max})]. \qquad (4\text{-}6)$$

where P_{PV}, $k\Delta t,max$, P_L, $k\Delta t,max$, P_{BS}, and $k\Delta t,max$ are the maximum values of PV, load and BS power during time interval $k\Delta t$, respectively.

The objective of using the BS-EMS is to utilize the energy stored in the battery and control its charge an discharge rates such that the net output power injected to the grid (after feeding the household loads) is constant during daylight. BS-EMS measures changes in the PV output power and adjust the battery power injection or absorption level to mitigate output power fluctuations and maintain it at a pre-defined level ($P_{Grid\text{-}ref}$). In Fig. 4.3, PV output power, sum of the PV and BS output and BS power are shown in red, blue and green colours, respectively.

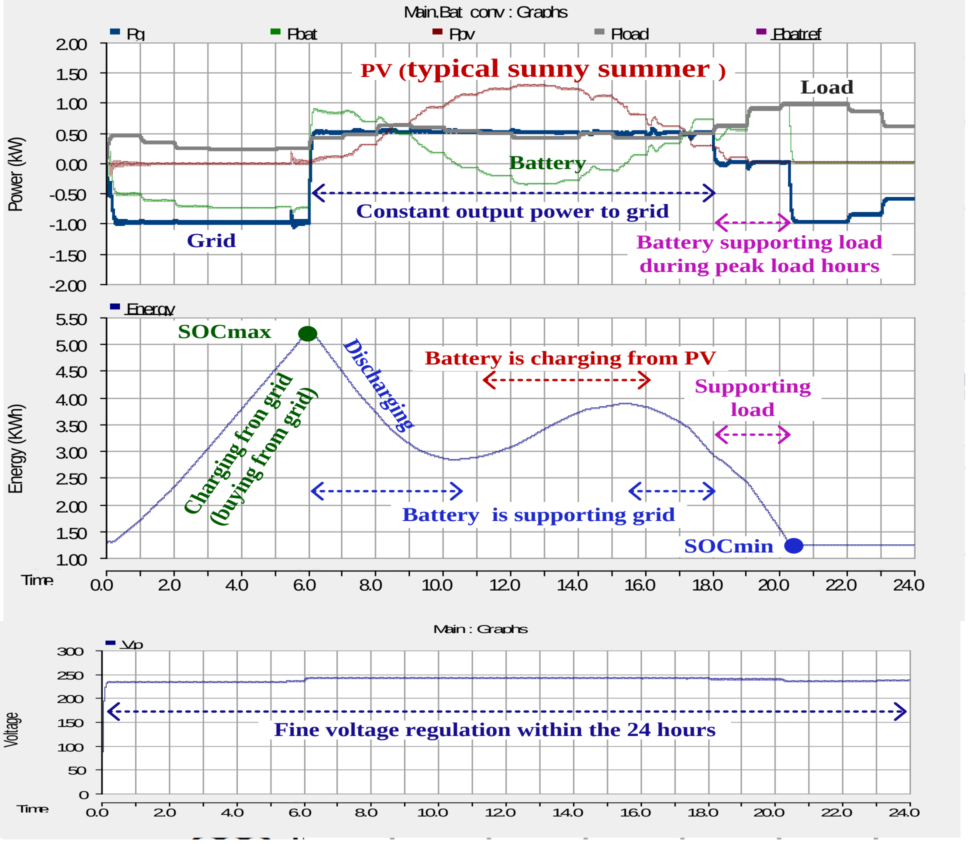


Figure 4.3: Operation of BS-EMS

4.2.1. Flow Chart of the Proposed BS-EMS

A charge/discharge controller limits the amount at which current is added to or drawn from the battery. By applying a close-loop control to monitor the power exchange, the charge controller prevents overcharging and protects the battery against overvoltage, which can reduce battery performance or lifespan. In order to protect the battery and increase its lifetime, BS-EMS is designed to limit the minimum and maximum levels of the battery state-of-charge (SOC) to SOCmin and SOCmax, respectively. The battery SOC can be defined from the perspective of energy as follows [45]:

$$SOC = W_{remain} / W_{initial} \tag{4-7}$$

where Wremain and Winitial are the remaining and initial power of the battery, respectively. In practice, the definition and determination of SOC is more complex. There are few established approaches to estimate SOC based on discharge test, ampere hour measurement, open circuit voltage, constant current voltage, internal resistance, linear model, neural networks, Kalman filter etc. The set points for the charge controller are provided through BS-EMS.

Figure 4.4 shows flowchart of the proposed algorithm for BS-EMS that will dynamically control the battery charge/discharge process according to Eqs. (4-2, 4-3)

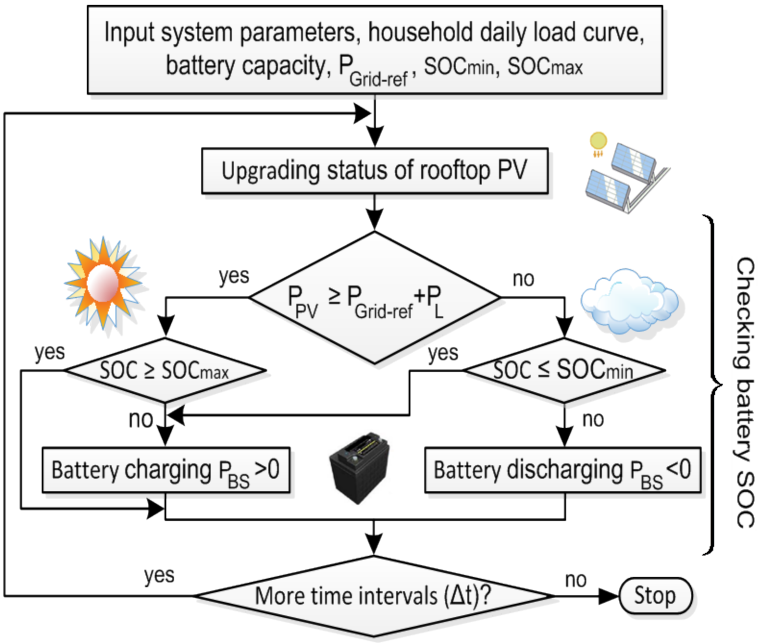


Figure 4.4: Flowchart of the proposed BS-EMS algorithm for battery charge/discharge management to attain constant output power to grid [45]

At each time interval (e.g., Δt =15 min in this paper), BS-EMS will upgrade the status of rooftop PV based on solar radiation, feed the household loads and based on the weather condition (sunny, cloudy) decides to either charge or discharge the battery. This process will continue for 24 hours until reaching the final time interval at t= 96Δt=96(15 min) = 24 hours.

In order to utilize the battery more efficiently, BS-EMS will also try to utilize it to supply the household loads during peak load hours when the price of electricity is high (e.g., 19:00-24:00) and will buy cheap electricity from the grid during off-peak hours (00:00-7:00) to recharge it for the next day. This is done by considering the battery capacity (BCAP) and selecting a relatively small value for $P_{Grid\text{-}ref}$, during peak load hours and a relatively large value during off-peak load hours as shown in Fig. 4.2.

4.2.2. Dynamic Control of the Battery Converter

A typical house with grid-connected rooftop PV and BS system investigated in this paper is shown in Fig. 4.5. A dc–ac converter is used for transferring maximum power from the PV array to the bus. The bidirectional BS converter is a single-phase full-bridge unit used to connect the dc bus to the ac utility grid, which enables bidirectional power flow. The battery with a bidirectional dc/ac converter is used to balance the power differences between PV, household loads and grid.

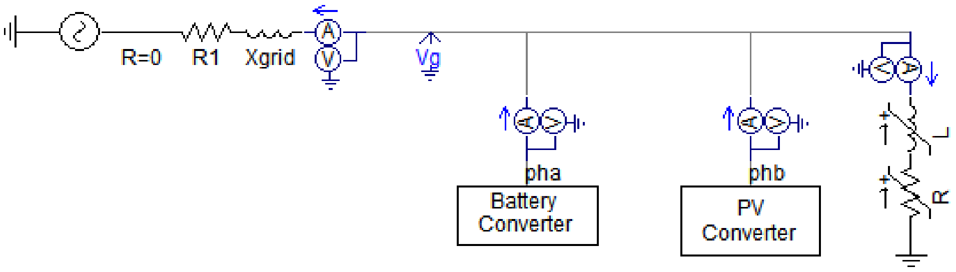


Figure 4.5: PSCAD model the grid-connected rooftop PV and household linear load combined with BS system

A PSCAD computer program (Fig. 4.5) is developed to model the grid-connected rooftop PV and household linear load combined with the shunt connected BS system which is dynamically controlled over a 24 hour period based on the proposed BS-EMS algorithm of Fig. 4.5. PSCAD is selected due to its robustness in transient analysis and relative ease in defining custom nonlinear models. The detailed model for grid connected rooftop PVs and BS which is suitable for load flow calculations is shown in Fig. 4.6.

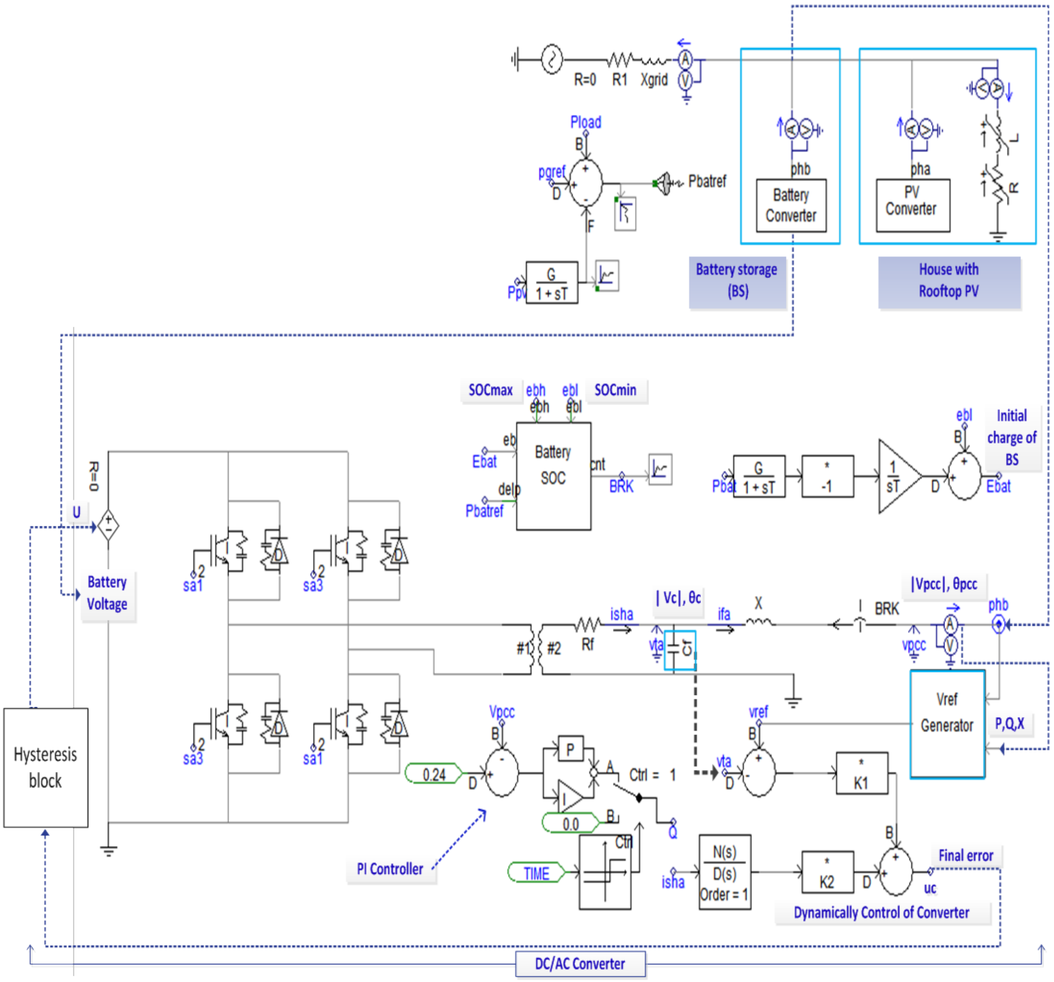


Figure 4.6: Detailed simulated PSCAD model of grid-connected rooftop PV and BS

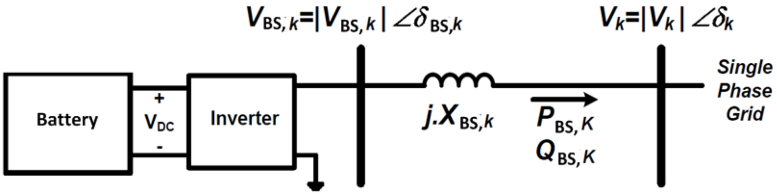


Figure 4.7: Schematic diagram of a BS connection to grid

Figure 4.7 shows the schematic diagram of a BS connection to grid at bus k, along with the definitions of bus voltages and line powers. $\tilde{V}_{BS,K}$ and $jX_{Bs,k}$ are the BS voltage and impedance connected to the kth bus. In this equation, the controlling constant β is equal to 1 when there is a BS connected to the kth bus, otherwise, it is zero [46]. Based on Fig. 4.7, as follow:

$$P_{BS,k} = \frac{\left|\tilde{V}_{BS,K}\right|\left|\tilde{V}_k\right|}{X_{BS,K}}\sin(\delta_{BS,k} - \delta_{BS,k}) \tag{4-8}$$

$$Q_{BS,k=}\frac{\left|\tilde{V}_k\right|}{X_{BS,K}}(\left|\tilde{V}_{BS,k}\right|\cos(\delta_{BS,k} - \delta_{BS,k}) - \left|\tilde{V}_k\right|) \tag{4-9}$$

where $P_{BS,k}$ and $Q_{BS,k}$ are the active and reactive power output of the BS connected to kth bus, respectively. Assuming $P_{BS,k}$ and $Q_{BS,k}$ to be constant and $\left|\tilde{V}_k\right|$ and δ_k are known, then $\left|\tilde{V}_{BS,k}\right|$ and $\delta_{BS,k}$ can be calculated. It must be noted that since the rooftop BS is operating at unity power factor, $Q_{BS,k} = 0$.

To calculate $\tilde{V}_k$ from Eqs. (4-8, 4-9), an iterative method is required. Starting with a set of initial values, the entire network is solved to determine $\tilde{V}_k$.

The aim of converter control is to generate a switching function that can take on +1 or -1 values depending on the status of the (IGBT) switches [46]. A state space approach will be used to implement the converter control. The input state vector is:

$$x^T = [V_{cf} \quad i_f]. \tag{4-10}$$

The state space model and the output state vector are defined as:

$$\dot{x} = Ax + Bu_c \tag{4-11}$$

$$y = V_{cf} = [1 \quad 0]x \tag{4-12}$$

where u_c is the continuous-time version of switching function u.

A hysteresis band approach will be used to turn on/off the (IGBT) switches. The inverter switching logic is

$$\begin{cases} if \quad u_c > h \quad then \quad u = +1 \\ if \quad u_c \leq h \quad then \quad u = -1 \end{cases} \tag{4-13}$$

where h is a small positive constant that defines the hysteresis band.

4.2.3. Voltage and Reactive Power Controls

A PI controller is also implemented to reduce voltage variations at PCC (Fig. 4.8). One of the major grid supporting applications of BS is to provide fast (dynamic) reactive power compensation in response to sudden changes (transients) introduced in the system following faults, non-linear load variations, and/or other type of system switching. The dynamic VAR compensation capability may also be used to perform voltage regulation at PCC. To achieve dynamic VAR compensation and voltage regulation, the BS power conversion system should be able to supply a wide range of reactive power. In this thesis, BS is utilized to provide fast reactive power to compensate for variation sin PV output power due to fluctuations in sun radiations, passing clouds and PV outrages.

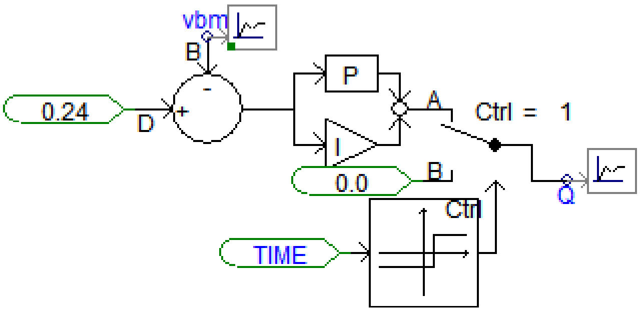


Figure 4.8: PSCAD model of PI controller

4.3. Proposed Practical Approach for Estimating Battery Capacity

As the performance of BS-EMS and the cost of the total system will significantly depend on the rating of the battery; a relatively simple and practical approach is presented to estimate its size. The approach is as follows (Fig. 4.9):

- Step 1- Select a typical (winter) rooftop PV generation profile Fig. 4.2, and a small estimated battery capacity (BCAP**estim**).
- Step 2- Perform BS-EMS of Fig. 4.4: Calculate and plot battery energy profile $E_{BS(t),}$ (Eq. 4-6).
- Step 3- If the peak of $E_{BS(t),}$ is flat during daylight, increase battery capacity (e.g., BCAPestim= 1.05BCAPestim) as it is too small to fully store the excess PV energy after feeding the load and grid.
- Step 4- Repeat steps 2-3 until $E_{BS(t),}$ has a single distinct maximum value during daylight.
- Step 5- Select BCAP =0.95BCAPestim.

BS-EMS estimates the rate of change in real-time and determines contribution from the ES unit to limit the rate of variations for the total power injected to the grid. The difference between P_{PV} and the power actually injected to the grid ($P_{Grid\text{-}ref},$) is supplied (if negative) or absorbed (if positive) by the BS.

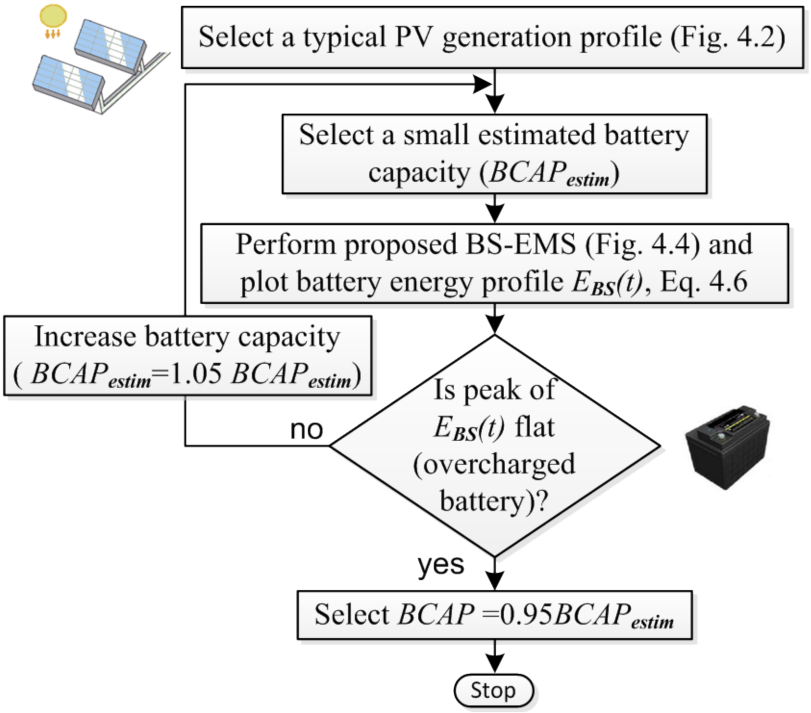


Figure 4.9: The proposed flowchart for estimating BS capacity

CHAPTER FIVE

SIMULATIONS RESULTS AND ANALYSES

In this chapter, performance of the proposed BS-EMS of Fig. 4.4 is investigated for the grid-connected rooftop PV and BS system shown in Fig. 5.1. A PSCAD computer program is developed to model the system and BS-EMS. The selected PV rating is 1.6kW, estimated battery capacity is 6.0kWh and minimum and maximum battery state-of-charges are set to SOC_{min}=0.20 and SOC_{min}=0.80, respectively. The desired consonant output power delivered to the grid during the daylight (0600h-18:00h) for summer and winter periods are assumed to 0.50kW and 0.13kW, respectively. The average computing times for performing each simulation over the 24 hour period is about 24 sec.

Detailed simulations are presented under different grid, battery and rooftop PV operating conditions over the 24 hour period to demonstrate:

- Performance of BS-EMS under normal operating condition for typical summer and winter days in Perth, WA, Australia (Figs. 5.2-5.3).
- Application of the proposed simple and practical approach (Fig. 4.6) to estimate battery rating (Fig. 5.4, Table 5.1).
- Effect of battery rating on performance of BS-EMS (Fig. 5.5, Table 5.2).
- Impact of changing the constant output power ($P_{Grid\text{-}ref}$) on performance of BS-EMS (Fig. 5.6, Table 5.3).
- Ability of BS-EMS to deliver constant output power during periods of passing clouds (Figs. 5.7, Table 5.4).

- Ability of BS-EMS to deliver constant output power for short periods of PV outage (Figs. 5.8, Table 5.5).
- Impact of reducing the duration of constant output power (Figs. 5.9, Table 5.6).

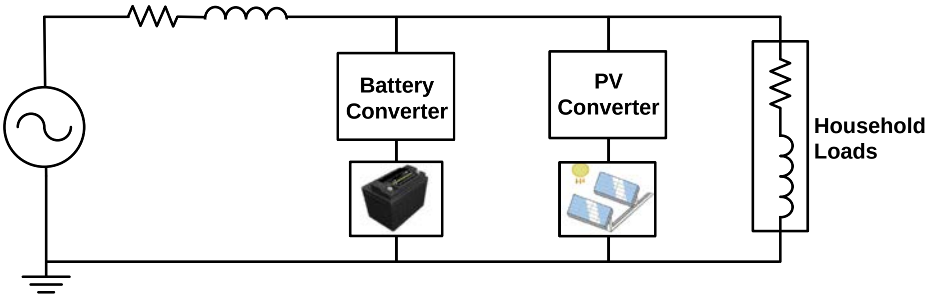


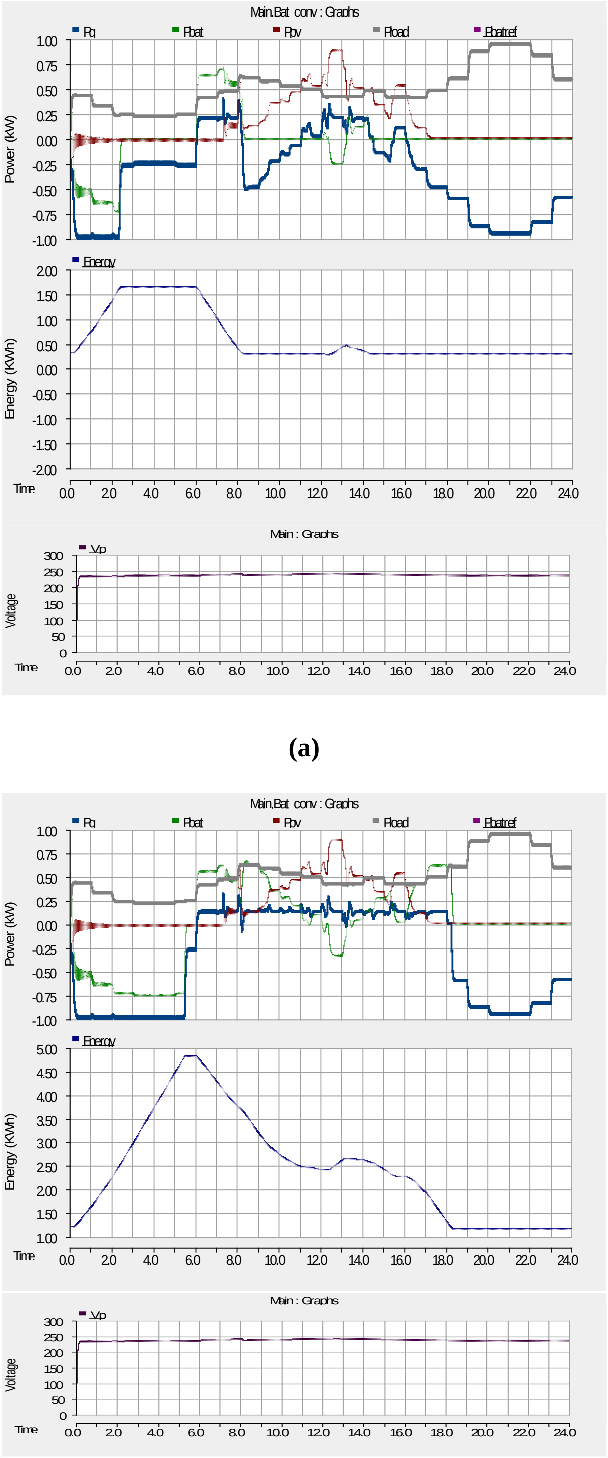
Figure 5.1: Simulated grid-connected residential house with rooftop PV and BS system

5.1. Performance of BS-EMS under Normal Operating Condition

Figures 5.2(a) and 5.3(a) shows detailed simulation results without the BS system for typical winter and sunny days. As expected, the net rooftop PV output power of system delivered to the grid during daylight is not contact and is strongly influenced by the environment conditions (sun radiations). Simulations are repeated with a BS system of 6.0kWh and presented in Fig. 5.2(b) and 5.3(b). Clearly, BS-EMS is keeping the injected output power constant ($P_{Grid\text{-}ref}$) from 06:00h to 16:00h at 0.5kWh and 0.13kWh for summer and winter days, respectively.

According to Fig. 5.2(b), BS-EMS has successfully managed to take advantage of the BS to deliver contest power of 0.13kW to the grid from 0600h to 1800h while also supporting the household loads after daylight until 18:30h. Note that the grid is feeding the load and charging the battery during early morning hours (0000h-0600h). This is justified as the price of electricity will be cheap during off-peak load hours.

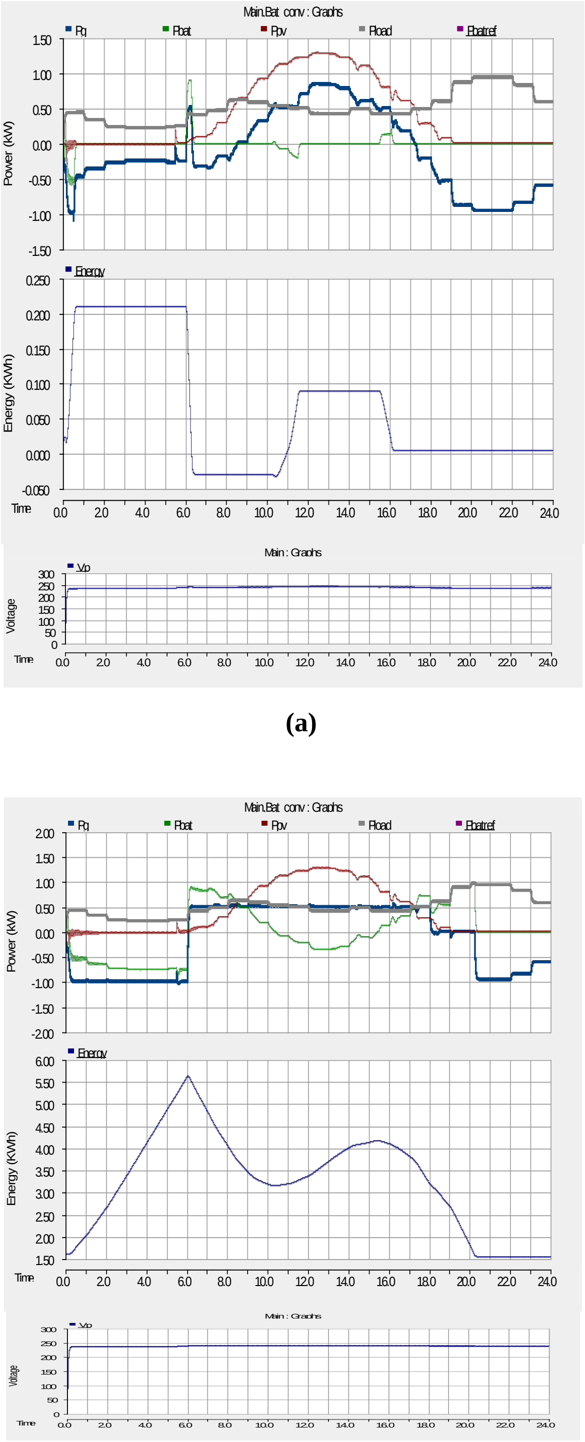
Examination of the battery energy profile indicates that when necessary, the stores energy will be released to the grid through the day (0600h-1030h and 1600h-1800h) to achieve the requested constant output power. However, the excess P_{PV} during high sun radiation hours (1200h-1300h) will be used to recharge the battery. For the situation of Fig. 5.2(b), the battery is nearly discharged during the day at 1800h; therefore it will continue feeding the load until reaching SOC_{min} at 1830h. Note that the BS-EMS has also managed to firmly regulate the PCC voltage regardless of the load and solar variations.



(a)

(b)

Figure 5.2: Simulation results without (a) and with (b) BS system for a typical winter day



(a)

(b)

Figure 5.3: Simulation results without (a) and with (b) BS system for a typical summer day

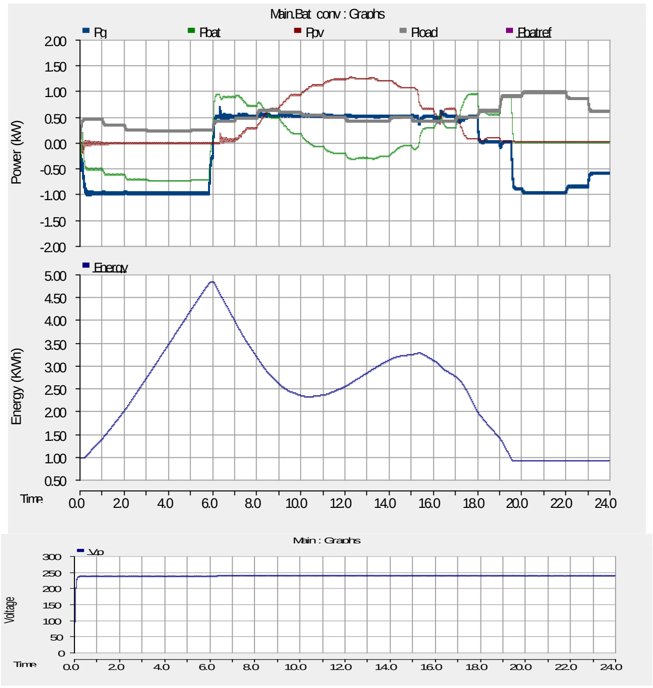
5.2. Estimation of Battery Rating

The battery size is estimated using the proposed simple and practical approach of Fig. 4.7. Battery sizing is performed for typical sunny and cloudy days in summer and winter (Table 5.1). The selected battery eating should be based on the worse operating condition (for example, a typical cloudy winter day). Figs. 5.4(a) and (b) show fine performances of BS-EMS with the selected batter size of 6.0kWh for typical cloudy summer and winter days, respectively.

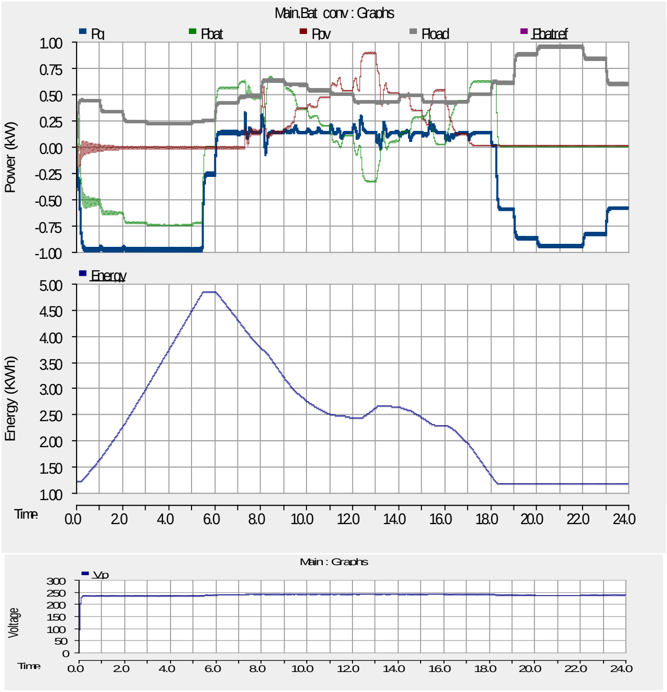
Table 5.1: Estimated battery size based on the proposed simple approach of Fig. 4.9

	Estimated Battery Size [kWh]	
	Sunny Day	**Cloudy Day**
Summer	4.3	5.0; Fig. 5.4(a)
Winter	5.5	6.0*; Fig. 5.4(b)

*) The selected battery size based on the worse operating conditions (typical cloudy winter day.



(a)



(b)

Figure 5.4: Simulation results for typical cloudy summer (a) and winter (b) days used to estimate the battery rating (Table 5.1)

5.3. Impact of Battery Rating on Performance of BS-EMS

To explore the impacts of battery rating on the performance of BS-EMS, detailed simulations are performed for typical sunny and cloudy days in summer and winter with different battery sizes. The summary of results are presented and compared in Table 5.2. The performance of BS-EMS is significantly influenced by the battery rating. According to Table 5.2, the practical and moderate battery rating to fully support the grid within the daylight in both summer and winter seasons while also providing partial support to the household loads after 1800h is 6kWh.

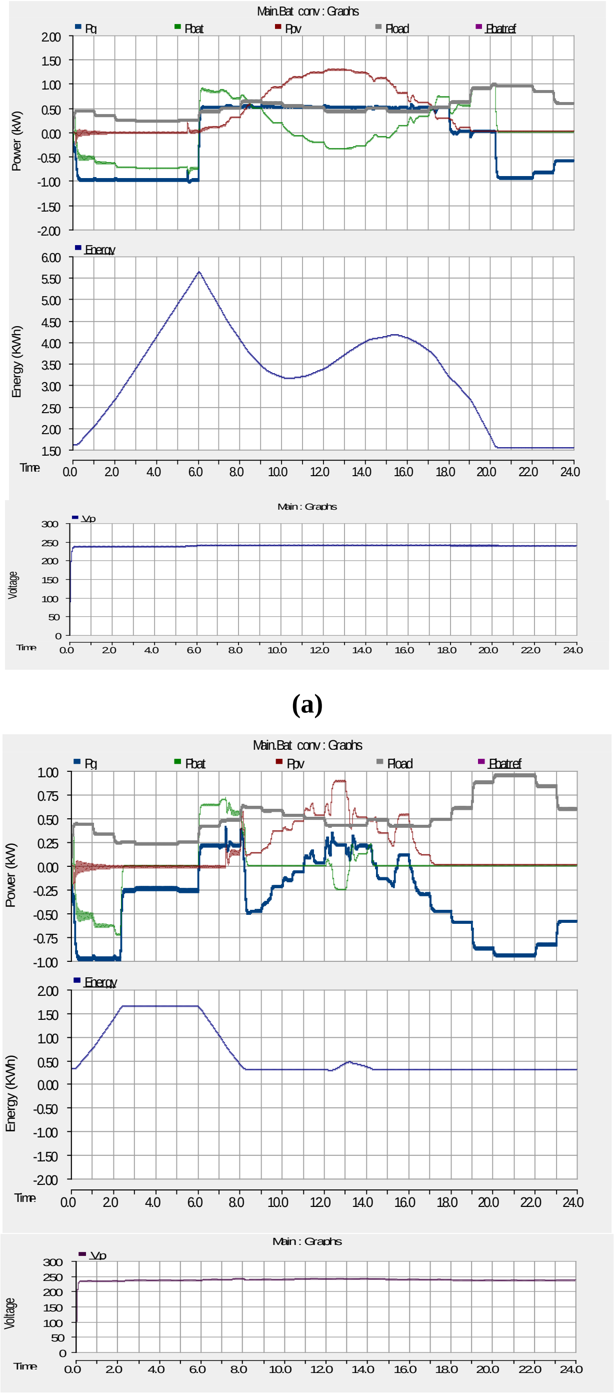
As expected, it will not be possible to support the grid with constant output power if the battery is too small (Table 5.2: rows 4-5, 12-14). On the other hand, it will not be beneficial to select a large battery rating. The only benefit in increasing the battery size beyond the moderate practical rating (6kWh) is to increase the duration of load support in the evenings. However, as demonstrated in Table 5.2 (rows 8-9 and 16-17), the duration of load support is mainly determined by the amount of available solar energy. For example, changing the battery size from 6kWh to 7kWh will only extend the load support period by 15min while a further increase to 8kWh will not have any impact.

Figure 5.5(a) shows system operation in a typical sunny summer day with a large BS of 8kWh (Table 5.2: row 9, columns 1-3) while Fig. 5.5(b) presents operation in cloudy winter with a small BS of 2kWh (Table 5.2: row 12, columns 4-5).

Table 5.2: Impact of battery size on performance of BS-EMS

BS Size [kWh]	**Durations of Constant $P_{Grid-ref}$**	**Duration of Load Support after 6pm**	**Durations of Constant $P_{Grid-ref}$**	**Duration of Load Support after 6pm**
	Summer ($P_{Grid-ref}$ =0.5kW)			
	Sunny		**Cloudy**	
2	6:00-7:45, 10:15-18:00	no support	6:00-7:30, 10:15-17:30	no support
4	6:00-18:00	18:00-18:30	6:00-17:45	no support
5	6:00-18:00	18:00-19:30	6:00-18:00	18:00-18:45
6*	**6:00-18:00**	**18:00-20:00**	**6:00-18:00**	**18:00-19:30**
7	6:00-18:00	18:00-20:30	6:00-18:00	18:00-19:45
8	6:00-18:00 Fig. 5.5(a)	18:00-20:30 Fig. 5.5(a)	6:00-18:00	18:00-19:45
	Winter ($P_{Grid-ref}$ =0.13kW)			
	Sunny		**Cloudy**	
2	6:00-8:30	no support	6:00-8:30 Fig 5.5(b)	no support Fig 5.5(b)
4	6:00-16:45	no support	6:00-16:30	no support
5	6:00-17:45	no support	6:00-17:30	no support
6*	**6:00-18:00**	**18:00-19:00**	**6:00-18:00**	**18:00-18:45**
7	6:00-18:00	18:00-19:15	6:00-18:00	18:00-19:00
8	6:00-18:00	18:00-19:15	6:00-18:00	18:00-19:00

*) Recommended battery rating.



(a)

(b)

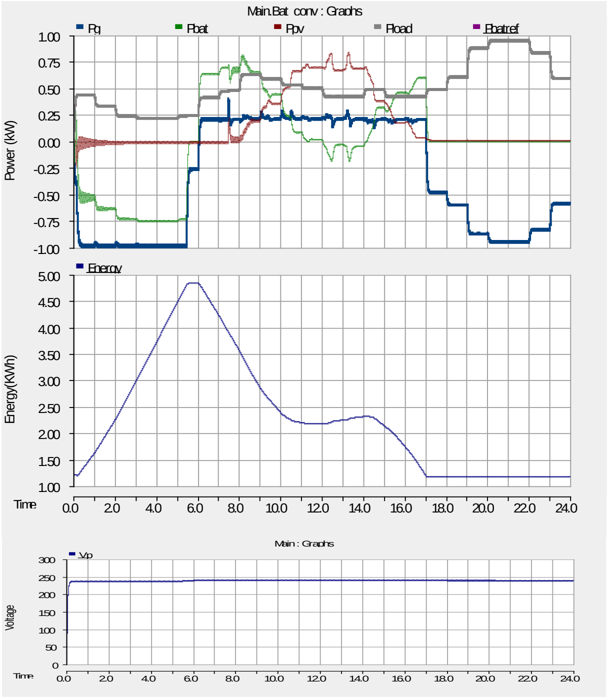
Figure 5.5: Simulation results for typical sunny summer with BS 8kWh (a) and cloudy winter with BS 2kWh (b) days used to estimate the battery rating (Table 5.2)

5.4. Impact of Constant Output Power ($P_{Grid\text{-}ref}$) on Performance of BS-EMS

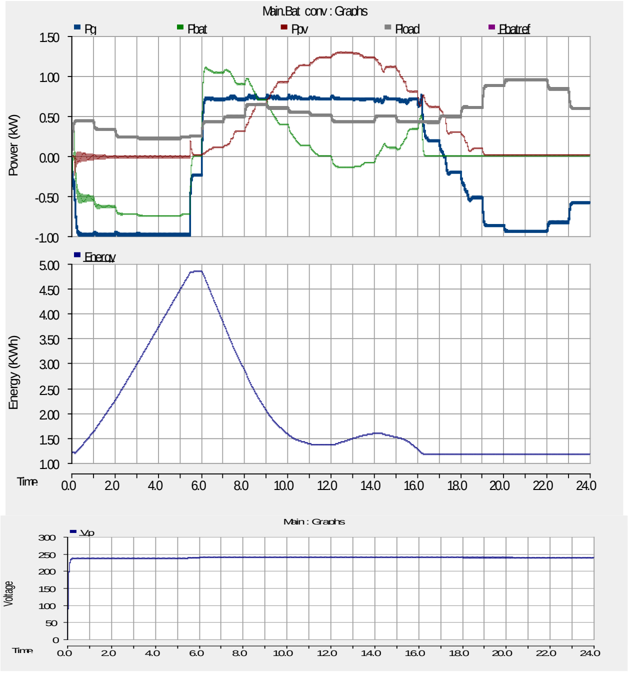
PV owners would like to have high output power levels ($P_{Grid\text{-}ref}$) to increase their profits by selling more electricity to the grid. However, the maximum possible value of $P_{Grid\text{-}ref}$ is primarily determined by the available daily P_{PV} that will considerably decrease during winter and cloudy days. It will also depend on the selected size of the BS. To explore the impacts of $P_{Grid\text{-}ref}$ on the performance of BS-EMS, simulations are performed for typical sunny and cloudy winter days with $P_{Grid\text{-}ref}$ increased from 0.13kW to 0.20kW and summarized in Table 5.3. Clearly, if an unrealistic high $P_{Grid\text{-}ref}$ value is selected, the rooftop PVs will not be able to fully support the grid with content power regardless of the battery rating. Fig 5.6(b) shows that by increasing $P_{Grid\text{-}ref}$ from 0.5kW to 0.7kW (during summer), the PV-battery system will not be able to fully support the grid .

Table 5.3: Impact of increasing constant output power during winter from 0.13kW to 0.20kW

dBS Size [kWh]	Durations of Constant $P_{Grid\text{-}ref}$	Duration of Load Support after 6pm	Durations of Constant $P_{Grid\text{-}ref}$	Duration of Load Support after 6pm
	Winter with High Constant Output Power ($P_{Grid\text{-}ref}$=0.20kW)			
	Sunny		Cloudy	
2	6:00-8:00	no support	6:00-8:00	no support
4	6:00-15:00	no support	6:00-10:30	no support
5	6:00-16:30	no support	6:00-15:30	no support
6	6:00-17:10 Fig 5.6(a)	no support	6:00-17:15	no support
7	6:00-17:45	no support	6:00-17:30	no support
8	6:00-17:45	no support	6:00-17:30	no support



(a)



(b)

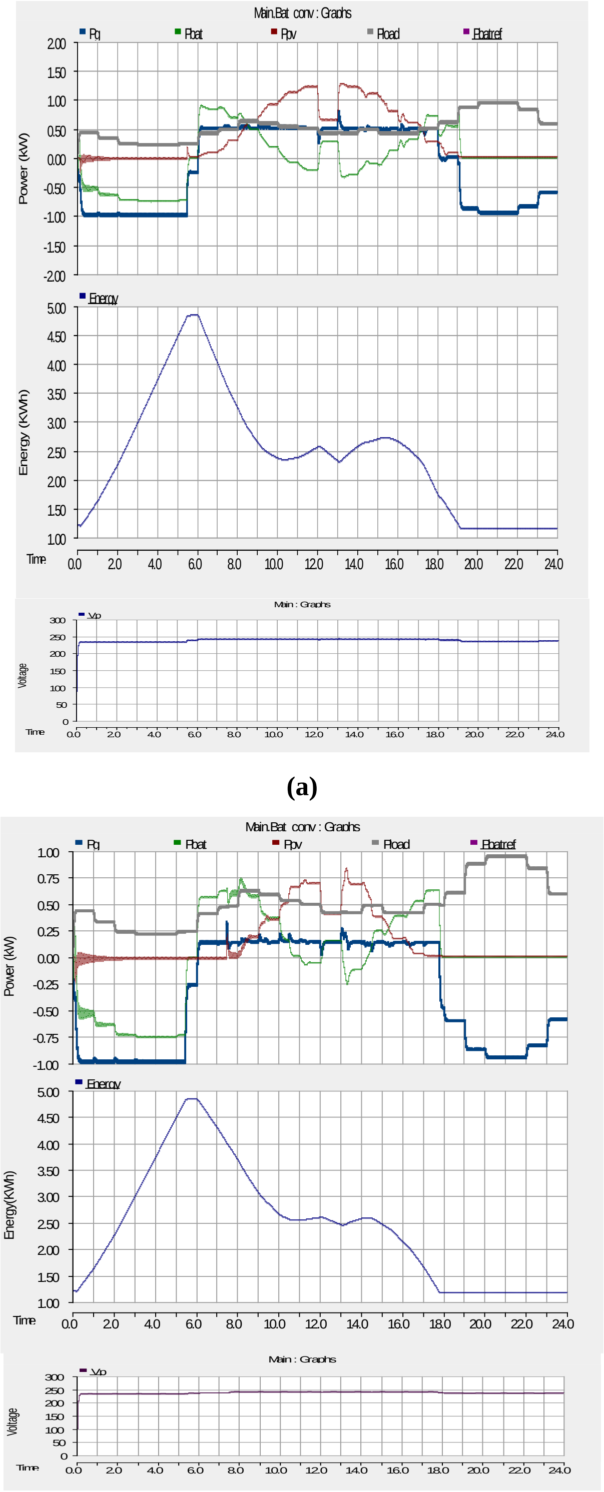
Figure 5.6: Simulation results for typical sunny winter with $P_{Grid\text{-}ref}$ =0.20kW (a) and sunny summer with $P_{Grid\text{-}ref}$ =0.70kW (b) days used to impact of increase output power (Table 5.3)

5.5. Ability of BS-EMS to Deliver Constant Output Power During Periods of Passing Clouds

To examine the ability of BS-EMS in delivering constant output power in the presence of passing clouds, simulations are repeated for typical sunny winter and sunny summer days with passing cloud periods of 30 minutes, one hour and two hours (Table 5.4). Fig. 5.7(a) illustrates the impact of having passing cloud for duration of one hour (12:00h-13:00h) during a typical sunny summer day. Clearly, the proposed BS-EMS has successfully taken advantage of the energy stored in the 6kWh battery to keep the output power constant at $P_{Grid-ref}$=0.13kW for the requested 12 hours (0600h-1800h). Note that BS-EMS has also managed to continue feeding the household load until 19:15h when the battery reaches its minimum SOC.

Table 5.4: Impact of passing clouds on performance of BS-EMS

Durations of Passing cloud	**Durations of Constant PGrid- ref**	**Duration of Load Support after 6pm**	**Durations of Constant PGrid-ref**	**Duration of Load Support after 6pm**
	Sunny Summer ($P_{Grid-ref}$ =0.5kW)		**Sunny Winter ($P_{Grid-ref}$ =0.13kW)**	
No cloud	6:00-18:00	18:00-19:75	6:00-18:00	18:00-18:20
30 minutes	6:00-18:00	18:00-19:56	6:00-18:00	no support
1 hour	6:00-18:00	18:00-19:15 Fig. 5.7(a)	6:00-17:78	no support Fig. 5.7(b)
2 hours	6:00-18:00	no support	6:00-17:35	no support



(a)

(b)

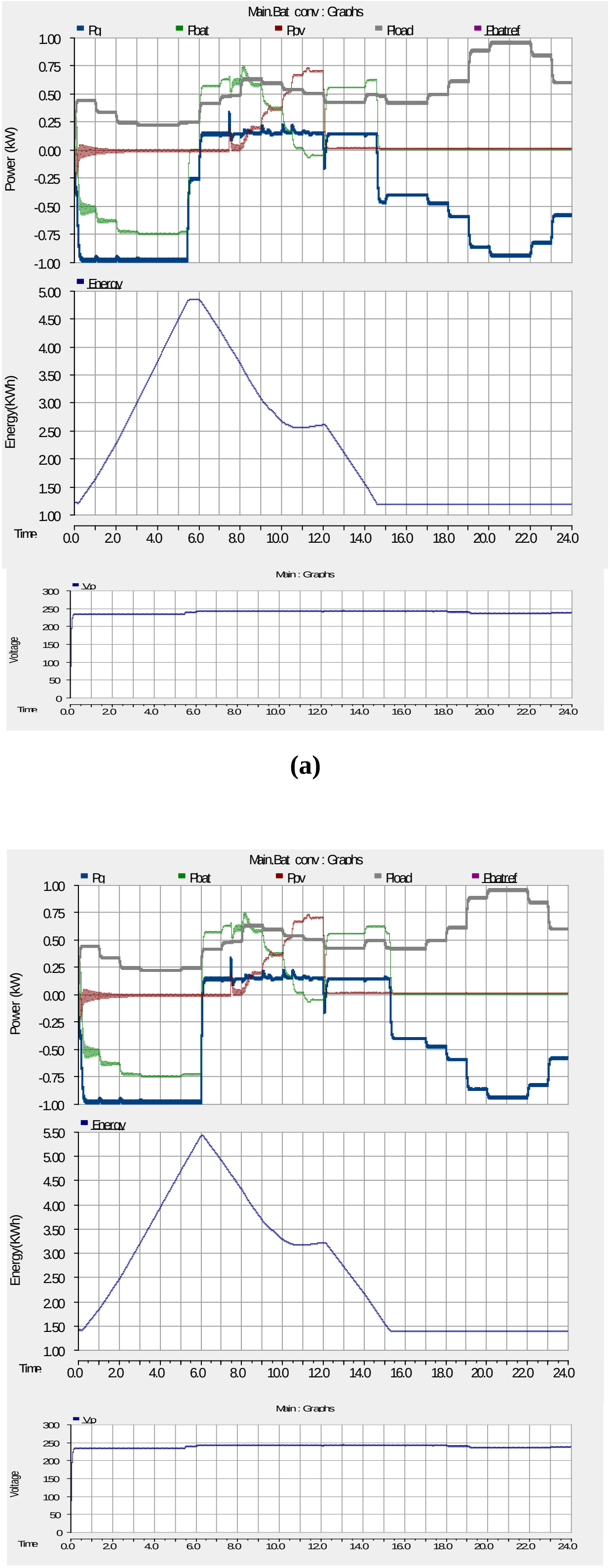
Figure 5.7: Simulation results for typical sunny summer (a) and sunny winter (b) days considering significant passing cloud for a duration of one hour

5.6. Ability of BS-EMS in Deliver Constant Output Power for Short Periods of PV Outage

Table 5.5 summaries the ability of BS-EMS in providing constant output power with no P_{PV} that will depend on the duration of PV outage and the battery rating. As expected, it will be possible to support the grid with constant output power during PV outages for longer periods as the size of battery is increased. On the other hand, it will not be advantageous to select a very large battery rating. The only benefit in increasing the battery size beyond the moderate practical rating (6kWh) is increased the duration of load support in the evenings. However, as demonstrated in Table 5.5 (rows 10 and 12), the duration of grid support is mainly determined by the amount of available BS energy. For example, changing the battery size from 6kWh to 7kWh will only extend the grid support period by 33min from 12:00h-14:37h (with the battery size of 6kWh) to 12:00h-15:20h (with the battery size of 7KWh). Simulation results for a typical sunny winter day considering PV outage after 12:00h are shown in Fig. 5.8 (a) and (b) for battery rating of 6kWh and 0.13kW, respectively.

Table 5.5: Grid support during short periods of PV outage

BS Size [kWh]	**Duration of Grid Support with PV Outage**					
	After 10:00h	**After 12:00h**	**After 14:00h**	**After 10AM**	**After 12PM**	**After 14PM**
	Summer ($P_{Grid\text{-}ref}$ =0.5kW)					
	Sunny			**Cloudy**		
6	1:16	1:37	2:15	1:11	1:33	2:00
6.5	1:26	2:00	2:33	1:27	1:52	2:24
7	1:39	2:00	2:45	1:38	2:00	2:37
	Winter ($P_{Grid\text{-}ref}$ =0.13kW)					
	Sunny			**Cloudy**		
6	2:25	2:37; Fig. 5.8(a)	3:00	2:31	2:13	2:30
6.5	2:48	3:00	3:32	3:00	2:43	3:00
7	3:05	3:10; Fig. 5.8(b)	3:43	3:09	2:51	3:07



(a)

(b)

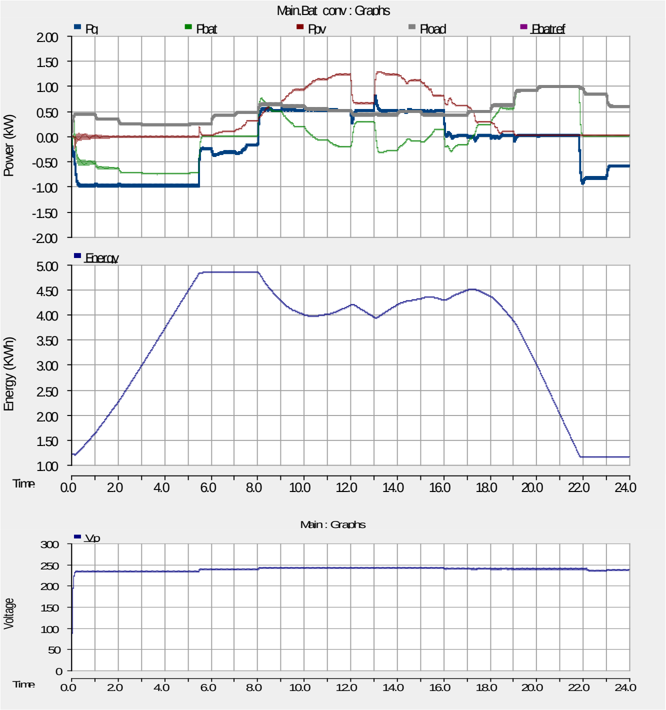
Figure 5.8: Simulation results for a typical sunny winter day considering PV outage after 12:00h with battery rating of; (a) 6kWh, (b) 7kWh

5.7. Impact of Reducing the Duration of Constant Output Power

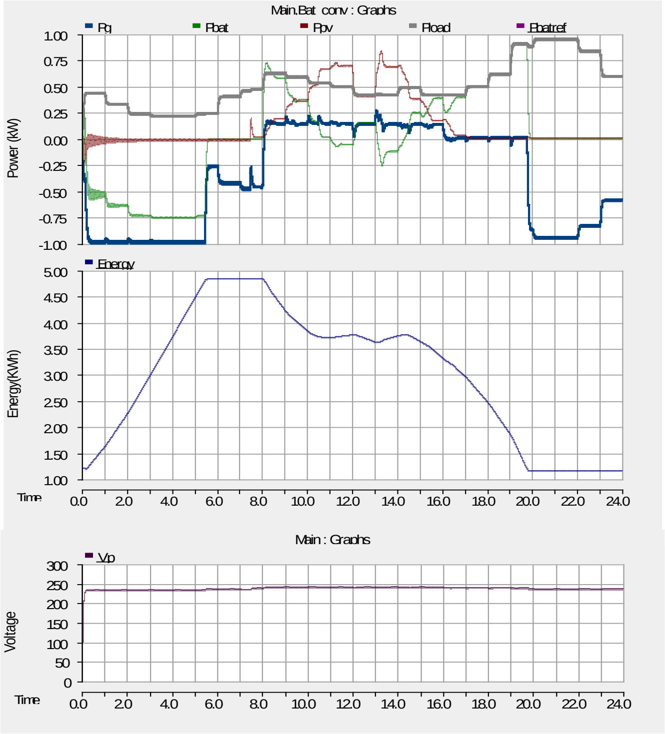
According to Table 5.4, BS-EMS cannot fully support the grid with constant output power for long periods of passing clouds practically during sunny winter days as shown in Table 5.4 (rows 4-6, column 5). To overcome the problem, we can either decrease the level of constant output power ($P_{Grid\text{-}ref}$) or reduce the duration of grid support. Table 5.6 demonstrates the impact of reducing the duration of grid support from 6:00-18:00 to 8:00-16:00. Compression of Tables 5.4 and 5.6 reveals that BS-EMS can not only support the grid with constant power, but also feed the household loads after day light for a much longer period. This is demonstrated in Figs. 5.9 (a) and (b) for sunny winter and cloudy summer days with one hour of passing clouds, respectively.

Table 5.6: Impact of reducing duration of constant output power (8:00-16:00) on performance of BS-EMS considering passing cloud

Durations of Passing cloud	**Durations of Constant PGrid- ref**	**Duration of Load Support after 6pm**	**Durations of Constant PGrid-ref**	**Duration of Load Support after 6pm**
	Sunny Summer (PGrid-ref =0.5kW)		**Sunny Winter (PGrid-ref =0.13kW)**	
No clouds	8:00-16:00	16:00-22:15	800-16:00	16:00-20:10
30 minutes	8:00-16:00	16:00-22:53	8:00-16:00	16:00-19:80
1 hour	8:00-16:00	16:00-22:00 Fig. 5.9(a)	8:00-16:00	16:00-19:73 Fig. 5.9(b)
2 hours	8:00-16:00	16:00-21:30	8:00-16:35	16:19:50



(a)



(b)

Figure 5.9: Simulation results showing improved performance of BS-EMS considering one hour passing clouds with a shorter period of grid support (8:00-16:00) for a; (a) sunny summer day, (b) sunny winter day

qCHAPTER SIX

SUMMARY AND CONCLUSIONS

This thesis introduces application and control of BS systems at terminals of an exciting residential house with rooftop PVs to deliver constant net output power ($P_{Grid\text{-}ref}$) to the grid during daylight. System operation is based on the power balance between rooftop PV, BS and grid by dynamic control of the battery converter while a PI controller is also implemented to reduce voltage variations at PCC. Detailed simulations are performed for a grid-connected rooftop PV and BS over the 24-hour period using developed codes in PSCAD to demonstrate system performance under various grid, load and environmental conditions. Impacts of battery size, passing clouds and short PV outages, as well as duration and magnitude of $P_{Grid\text{-}ref}$ on system performance are investigated.

6.1. Thesis Conclusions

Based on detailed simulations and analyses under different operating scenarios, the main conclusions of this research work are:

- BS-EMS can effectively manage to take advantage of the BS to deliver constant output power $P_{Grid\text{-}ref}$ to the grid during daylight and regulate PCC voltage.
- BS-EMS is designed to increase befit and reduce cost of purchasing electricity by charging the battery during early morning off peak load hours, utilizing the excess PV energy to deliver constant output power during daylight while maintaining high SOC to continue feeding household load after day light without purchasing expensive electricity from the grid during the peak load hours.

- PV owners would like to have high $P_{Grid\text{-}ref}$ to increase their profits by selling more electricity to the grid. However, the maximum possible value of $P_{Grid\text{-}ref}$ significantly depends on the available daily P_{PV} (that will decrease during winter and cloudy days) and to some extent rating of the battery.
- The performance of BS-EMS is significantly influenced by the battery rating. For a moderate increase in the battery size, BS-EMS can also support the household loads during the evening peak load hours to further increase the profit. However, the duration of load support is mainly determined by the amount of available solar energy not the size of the battery.
- With large $P_{Grid\text{-}ref}$ values and/or small battery capacities, BS-EMS will not work properly for the entire day as the battery will quickly reach $SOC_{\mathbf{min}}$.
- With small $P_{Grid\text{-}ref}$ values and/or large battery capacities, BS-EMS will work properly; however, the available battery capacity may not be fully utilized.
- BS-EMS can also maintain constant output power during periods of passing clouds and short term PV outages.

6.2. Thesis Contributions

The main contributions of this research can be summarized as follows:

- Application of battery storage unit to control the output power profile of an existing rooftop PV system.
- Developing a practical BS-EMS to deliver constant output power to the grid during daylight.
- Development of a simple approach to estimate battery rating.

The proposed BS-EMS will also compensate for the intermittent behaviour and uncertainties associated with rooftop PVs particularly during cloudy days and PV short outages.

6.3. Future Work

Future work in this field may be performed considering the following research areas:

1. Practical design, implementation and testing of BS-EMS.
2. Improving the BS converter control and PI voltage regulator with faster and more efficient artificial intelligence (AI) based controllers.
3. Performing cost analysis over system life considering the high price of ES devices. Determining reasonable solar feed-in-tariffs to guarantee consumer profit and make BS-EMS implementation affordable.

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Every reasonable effort has been made to acknowledge the owners of copyright material. I would be pleased to hear from any copyright owner who has been omitted or incorrectly acknowledged.

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APPENDIX A

AUTHOR'S PUBLICATIONS

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