ENERGY MANAGEMENT OF MICROGRID WITH STORAGE SYSTEM CONNECTED TO UTILITY GRID

A PROJECT REPORT

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by

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THESIS CERTIFICATE

This is to certify that the thesis titled **ENERGY MANAGEMENT OF MICROGRID WITH STORAGE SYSTEM CONNECTED TO UTILITY GRID**, submitted by **Vamshi Ballikonda**, to the Indian Institute of Technology Madras, Chennai for the award of the degree of **Dual Degree**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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Vamshi Ballikonda

ABSTRACT

KEYWORDS: Microgrid, MPPT, grid integration, energy management.

With a significant amount energy lost during the transmission and distribution, the depletion of the non-renewable resources and the increasing the earth's surface temperature due to greenhouse gases, the need to have decentralised energy sources using renewable energies can be helpful to solve the problems. The usage of these renewable energies to the maximum efficiency and the interconnection between these distributed energy sources with the main utility grid is a challenging issue.

Owing to the fluctuations of the energy produced by the renewable sources, to have an efficient system, The Microgrid system should facilitate the maximum power extraction. The variations in the energy produced and the variations in the load, the DC link voltage does vary, which has to be tackled using an energy storage device, so as to maintain the DC link voltage.

The DC bus is connected to the utility grid, the power sharing and transfer should be in such a way to maximize the efficiency. An efficient algorithm is to be used to attain maximum efficiency through interactive inverter. The state of charge is an important aspect for understanding the efficiency of the battery system, so the SOC is to be used in the algorithm so as to effectively the energy. Efficiency should be increased by also considering an algorithm with SOC of the battery into the consideration, so as to effectively contact with the grid and have the interaction with the utility grid.

The project explains the modeling of the components of the PV array, and uses Maximum Power Point Tracking to utilize the maximum power from the PV array and the is connected to an energy storage so as to maintain the DC link voltage using a control strategy. Algorithm for energy management is proposed to connect the Microgrid to the utility grid. The simulations are carried out, and the results are analyzed. The simulation is carried out in Matlab/Simulink environment.

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ABBREVIATIONS

DER	Distributed Energy Resource
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
PV	Photo Voltaic
PI	Proportional Integral
PWM	Pulse Width Modulation

NOTATIONS

I_{sc}	Short circuit current of the PV cell (A)
V_{oc}	Open circuit voltage of the PV cell (V)
I_{pv}	Current from the PV cell (A)
I_{ph}	Photon Current of the PV cell (A)
I_d	Diode Current of the PV cell (A)
α	Short circuit current temperature coefficient (%/^{o}C)
T	Absolute temperature (K)
β	Solar irradiance value (W/m^2)
I_s	Saturation current of the diode (A)
q	Charge of electron (1.6×10^{-19} C)
V	Voltage across the diode (V)
n	Ideality factor of the diode
k	Boltzmann constant(1.381×10^{-23} J/K)
I_o	Reverse saturation current of the diode
T_{ref}	Reference Temperature (298 K)
v_g	Band gap voltage of the semiconductor (V)
β_{ref}	Irradiance reference value (1000 W/m^2)
I_{ref}	Current reference value (A)
T_{on}	ON Time for Boost Converter (s)
V_o	Output Voltage of Boost Converter (V)
D	Duty cycle for Boost Converter
V_{bus}	Voltage of DC bus (V)
$V_{battery}$	Voltage of the Battery (V)
f	Frequency (1/s)
D_1	Duty cycle of Buck converter
L	Inductor value (H)
C	Capacitor value (F)
ΔI	Current Ripple (A)
ΔV	Voltage Ripple (V)
SOC	State of Charge of the battery

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

With the ever increasing of population of India, there is a need for the improvement in not only the amount of power produced but also to improve the access to electricity in remote places. With the limitation on the emissions forced due to the treaties signed, there is a need for an alternate eco-friendly solution not only to reduce our emissions internationally but also cope with the extra ordinary demand of power faced by the developing country.

With an urgent need for a clean and efficient solution, few renewable sources are promising. One of such renewable energy source is the solar energy. With the effective usage of solar energy, India can not only be in a better position in power distribution but also can help in maintaining the stability of the grid as a whole [1],[2].

1.1 Traditional Power Transmission

The traditional power generation comprises mainly of thermal energy of coal, oil, natural gas, etc. In the traditional power generation, the power generating centers are usually located far away from the load, power generation and transmission is inefficient and there is an urgent need for the shift from the traditional system to a decentralised system for effective usage of the power produced and also to reduce the transmission losses. In India about 20% of the losses occur in the transmission. In 2013, 21% of the total output which amounts to 222,412,000,000 KWh has been because of the losses in the transmission and the distribution side.

From the Figure 1.1 we can observe the criticality of the situation, every year a significant percentage of the power produced is being lost due to transmission and distribution. With the decentralised system, where the load centers are near power sources, this transmission loss will decrease and the energy can be utilized in an efficient manner.

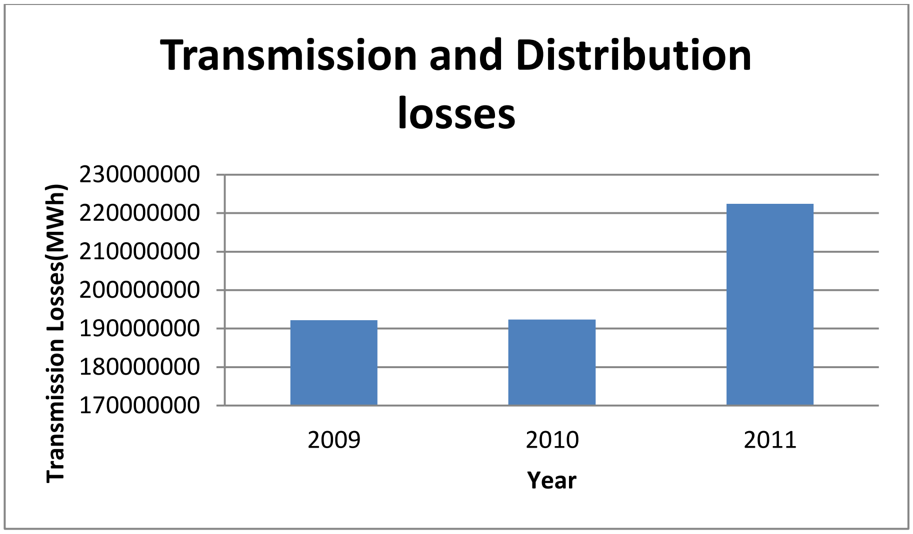


Figure 1.1 Transmission and distribution losses of India in the recent years [3]

Since the conventional system uses the thermal energy as the main source of energy, the emission due to the energy production is also a major concern. With the increase in the surface temperature which is caused due to the increase of the greenhouse gases, has been a wakeup call for many countries, by which a shift from the conventional to newer methods of power production.

Also the depleting fossil fuels are also a concern to be noted, the non-renewable resources are depleting at a very high rate unable to cope up with the increase in the demands of the power consumption. With the following problems mentioned, there exists an efficient alternative, which is the usage Microgrid with solar power acting as an energy source. The solar energy is still an untapped easy and renewable energy with literally no problems to the environment, makes it a green and eco-friendly energy source which is sustainable. With the increasing priority to sustainability, the solar energy is recently gaining its reputation.

With the consideration of extremely energy deficient country like India, if the solar energy is effectively used, can change the country's status from power deficient to power surplus. With every one household in four lacking electricity in India, the usage of solar powered Microgrid can be useful in not only the inclusion but also can improve the stability of the whole grid. With many Microgrids, the mutual sharing of energy can be encouraged without the stress applied on the utility grid.

In India still solar energy is an untouched power source yet, the solar powered Microgrids have the potential to be used in small units, like villages which can help in supplying the important requirements.

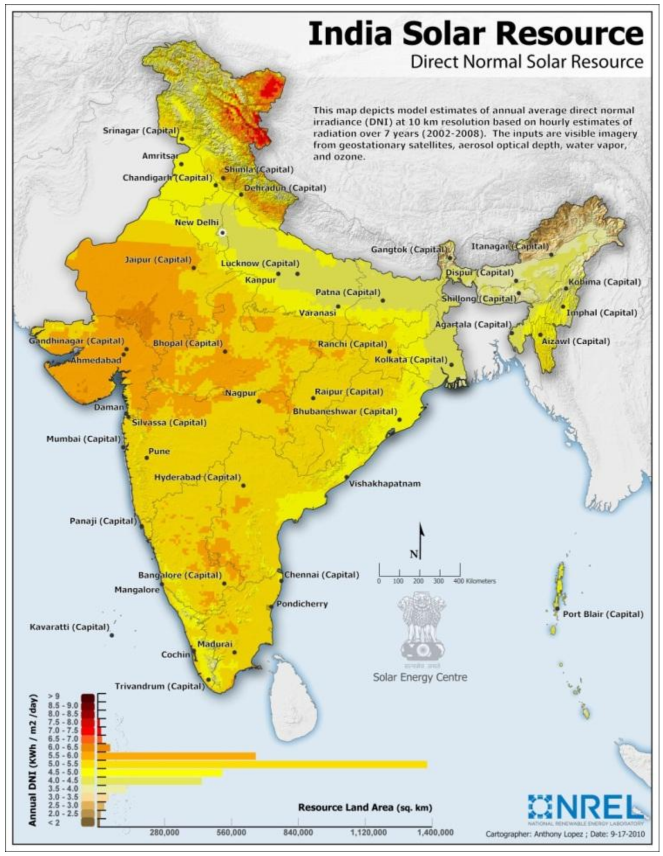


Figure 1.2 Annual Direct Normal Irradiance of India [4]

The Figure 1.2 emphasizes the aspect of availability of unused solar energy in India; with most of India receiving more than 5kWh/m^2/day the usage of this energy in the recent past is minimal. If the following energy mentioned above is used, then there can be sustainable improvement in not only the energy produced but also the inclusion of electricity.

1.2. Evolution of Microgrids

With the need for the decentralised power generation and consumption, the Microgrids have grown importance recently. With the distributed energy resources (DER) have been a priority in the recent years. Owing to awareness of the greenhouse gases and the transmission losses, the Microgrids came into emergence for solving of these problems [5].

The Microgrid has two modes of operation[6] are listed below

- Grid connected mode
- Islanded mode

In the grid connected mode, the Microgrid is connected to the grid and the required power for the local loads are either given from the energy storage device or from the renewable energy source and if additional power is required, it can be accessed from the grid. The reliability of grid connected Microgrid is very high. In the islanded mode, the grid is on its own, the Microgrid energy storage provides the required energy by the load which is not being supplied by the renewable source, if the energy storage device charge has reduced below certain critical value, and the required power cannot be supplied to the load and the reliability of the system decreases. The usual case is when the grid is unavailable or during fault.

The Figure 1.3 shows the basic architecture of the Microgrid connected to a utility grid. From the Figure, we can observe that the renewable energy source and energy storage device are connected to the DC bus by which, they are connected to the DC to AC converter

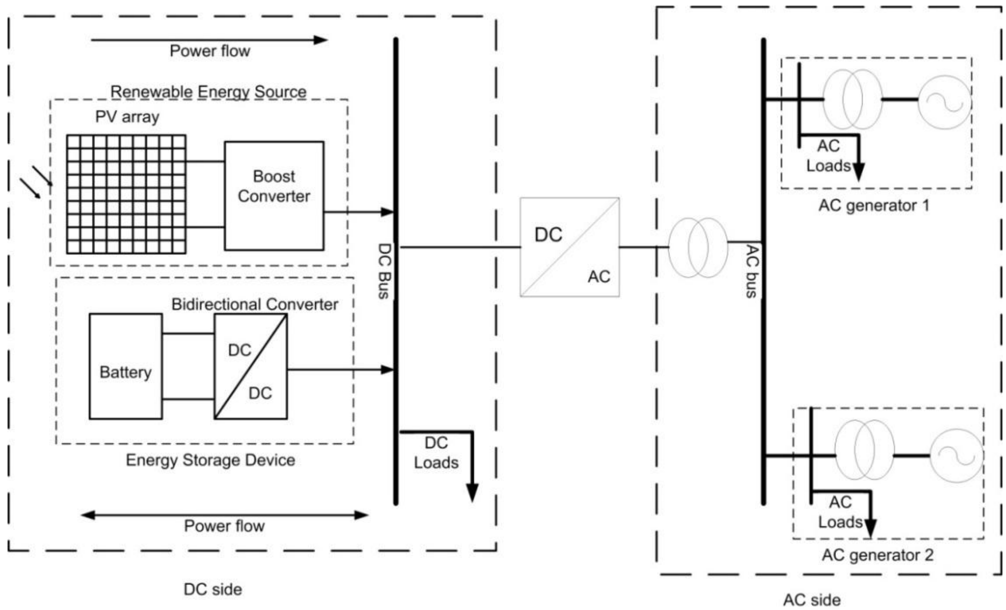


Figure 1.3 Basic Architecture of Microgrid connected to grid

1.3 Advantages of Microgrid

The Microgrid has many advantages to that of the conventional power generation and distribution. Few of them are listed below

- Usage of Renewable Energy
- Eco Friendly by reducing greenhouse gases
- Improves the power quality of the utility grid
- Helps in providing electricity at remote locations
- Helps in meeting the increasing demand
- Reduces transmission and distribution losses
- Operation in both islanded and grid connected mode
- Uninterruptable power supply to critical loads

With the advantages mentioned above, there are few challenges in operating the Microgrid, few of the important challenges are mentioned below

- Control of DC voltage
- Transition from grid connected islanded mode
- Power quality maintenance in acceptable limits

1.4 Problem Definition

The main problem statement is the efficient energy balance of Microgrid and its integration with the utility grid. With the Microgrid connection to a utility grid, the energy management between the source, storage and the load is an issue so as to maintain the voltages constant of the DC bus constant.

With the energy generation by the renewable sources like wind, solar being highly fluctuating, the maintenance of the DC bus voltage at a constant value is difficult. With the variation of the loads, the maintenance of the voltage is more difficult. The effective utilization of the renewable energy by the local loads and its integration to the utility grid is the main concern.

1.5 Objectives and Scope

The project deals with the design of few important components of the Microgrids, modeling different controllers and the control strategy to share power between the components. Thus, maintaining the energy balance. The main objectives of the project can be subdivided into four important aspects

- To study the behavior of the PV array connected to a DC bus and its variation with varying loads and emphasizing the usage of energy source
- To understand and implement a control algorithm for the effective maintenance of DC voltage by the PV array connected to an energy storage device even during varying loads
- To effectively integrate the Microgrid to a utility grid and be able to transfer the active and reactive power from the DC bus
- To analyze and suggest an algorithm for effective energy management of the Microgrid connected to a utility grid

1.6. Organization of Thesis

The project involves different stages in which includes the modeling of the essential component required for the Microgrid and also the implementation of the algorithms for the effective power sharing between components in the Microgrid, the project can be organized into the chapters mentioned below,

Chapter 2 deals with the modeling of components required for the Microgrid, the PV cell and PV array are modeled and the analysis is carried on to understand the dependence of these components on the input parameters. A brief analysis about the energy storage device is mentioned.

In **Chapter 3** the power voltage curve of the PV curve is explained and an algorithm is proposed for the maximum power to be transmitted from the PV array. The Maximum power is transmitted from the PV array for a given irradiance value.

Chapter 4 discusses about the PV array operation with and without connecting it to the storage unit. The importance of the storage unit in Microgrid emphasized where the power is either injected or absorbed by the storage unit in order to maintain the voltage at a constant value.

Chapter 5 deals with the connection of the Microgrid to the utility grid. The chapter concentrates on improving the power quality of the utility grid by providing the active and reactive power command received from the Energy Management system from a central power station. An algorithm is also proposed for power sharing between the Microgrid and the utility grid and effective utilization of the energy. The working of the algorithm is discussed and also the merits of the algorithm are emphasized.

Chapter 6 has the concluding notes about the project and the future scope.

1.7 Literature Review

The distributed energy resources are gaining the importance [7] in the recent past. Many renewable energy sources are used in order utilize the renewable energy for decreasing the greenhouse gases and also the inclusion of the remote areas into the electricity access map.

With the future energy production slowly getting decentralised, the distributed energy sources are gaining the importance, the main renewable energy sources that are used are the solar and wind power.

1.7.1 PV cell

The PV cell works on the principle of photo voltaic effect. When the photons hit the PV cell, due to the energy of the photon hitting the atom, the valence electrons get excited and jump towards a conduction band and become free. These electrons move towards the junction and get accelerated to another material by a built in potential. This generates some electromotive force and the light energy is converted to electrical energy.

The PV cells re usually connected in series for having an additive voltage. Connecting the cells in parallel can create better current but there are significant disadvantages because of the parallel connection. The effect is seen when a shadow falls on a part of the system which can create power loss even sometimes damages the weaker cells by excessive reverse bias currents.

The array is maintained a voltage at which the maximum power is possible so as to extract the maximum power using some MPPT algorithm.

The simple explanation for the production of current can be mentioned below,

- Photons in the sunlight hit the solar panel which is made up of semiconductor devices like silicon
- Electrons are knocked from their valence orbits and flow through the material to produce current. The current is unidirectional from the property of the solar cell
- The array converts solar energy into usable DC electricity

The photons with energy higher than that of the band gap of the silicon, the photon produces an electron hole pair. The free electrons are in the conduction band move in order to produce the PV cell current.

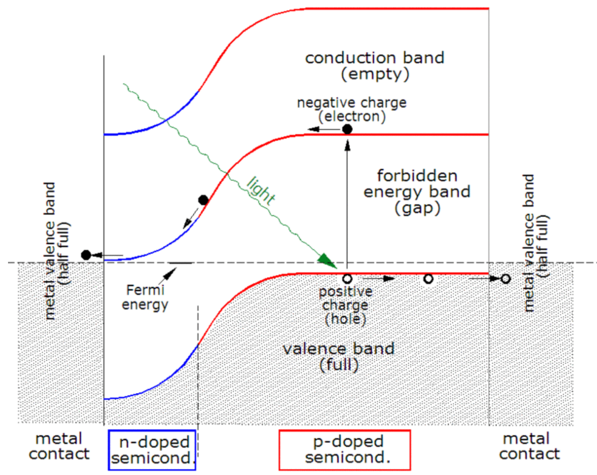


Figure 1.4 Band diagram of silicon cell under short circuit conditions

The following Figure from Wikipedia shows the image of band diagram of silicon cell under short circuit conditions. From the shown Figure 1.4, it can be observed that when the photon hits the silicon, an electron is excites and moves towards the conduction band, which also produces a hole. The electron movement and the hole movement is also shown in the Figure 1.4.

1.7.2 Wind Turbine

The main analysis of the project is by considering the PV model; hence the PV model is given priority in the following project. The wind turbine converts the kinetic energy into electrical energy. The winds produces due to the variable heating of the earth surface is utilized in producing the electrical energy. Usually two types of the wind turbines are seen usually, one being the constant speed wind turbine model and the other being the variable speed wind turbine generator. Usually field wound synchronous generator, doubly fed induction generator and PMSM generators for producing the electricity.

1.7.3 Battery – Charge Efficiency

The energy storage device usually used in is he battery, the main aspects of battery is to be considered as the battery life and efficiency. The lead acid battery consists of two alternating plates of electrodes immersed in electrolyte. The electrodes are lead (Pb) and lead oxide (PbO_2) and the electrolyte is Sulphuric acid (H_2SO_4). The electricity is produced due to a chemical reaction between the electrode plates in electrolyte.

Knowledge of the charge efficiency of lead acid batteries at the top of charge is important for the design of the PV cell. The charging usually done by SOC of the battery but the charging efficiency is an important aspect so as to effectively utilize the energy produced by the PV cell efficiently.

It can be noted that the lead acid batteries are not 100% efficient; usually we can observe an efficiency of about 85% in the battery. The efficiency might depend on many factors, rate of charging or discharging. If high discharge rate, the efficiency will be lower.

The SOC is important in understanding the charging efficiency of the system, it is to be noted higher the SOC, lower the charging efficiency, the lower the SOC, higher the charging efficiency. It would be better if the battery is worked at a lower SOC than the traditional high value of SOC.

The charging efficiency of half charged or less may over 90% and around 60% when the battery is charged more than 80% [8],[9].

The charging efficiency is an important aspect for effectively using the energy produced by the PV cell. The charging efficiency depicts the number of Ampere hours can be extracted from the battery for a given Ampere hours fed into the battery.

In general understanding the efficiency is higher at lower charges and lower at higher charges, it is not a linear function. If the SOC increases the charge efficiency of the battery rapidly drops [9]. The details of the charge efficiency are useful in choosing the PV cell, if it the charge efficiency is overestimated, then the PV cell cannot charge the required battery and it always remains undercharged, which is in efficient for the battery, or the if it underestimated, the PV cell can overcharge and a problem can be faced. So, an apt understanding on the PV array required to charge the battery. If the load is around 30Ah and a battery of 100Ah is used, the battery is expected to operate at 70-100% of SOC, but the charging efficiency in that range is inefficient.

CHAPTER 2

MODELING OF MICROGRID COMPONENTS

Microgrid components can be classified into two main categories

- Distributed Energy Resources (DER)
- Storage components

The Distributed energy resources in a Microgrid are usually solar, wind, micro turbine, fuel cells, biomass, etc. The storage component helps the Microgrid to conserve energy by taking the additional power produced by the energy source and provides energy when the energy source is unable to cope with the load requirements. Thus, using an energy storage component not only increases the efficiency but also helps in stability of the DC voltage bus [10]. In this project the energy source taken into consideration is PV cell and the storage component is a battery. These two components are chosen by taking the availability aspect into consideration.

2.1 Modeling and Analysis of PV cell

PV cell is a solid state device which converts solar energy into electrical energy using photovoltaic effect. Model of Photo Voltaic cell is developed by analyzing the properties using matlab simulink.

2.1.1 Analysis of PV cell

The PV array consists of individual solar cells. These solar cells are typically large area silicon PN junction diodes. The working principle of PV cell is same as a PN junction diode [11].

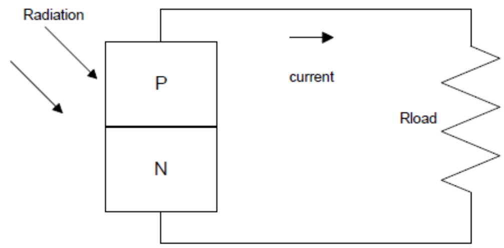


Figure 2.1 PV cell

Due to the solar irradiance there is an excess production of free electrons and holes in the p and n type semiconductors respectively, which forces the current to flow through the semiconductor

2.1.2 Equivalent circuit of PV cell

For electrical evaluation of any component an equivalent circuit is essential. By observing the properties mentioned above, we can deduce the equivalent circuit of the PV cell as shown in Figure 2.2

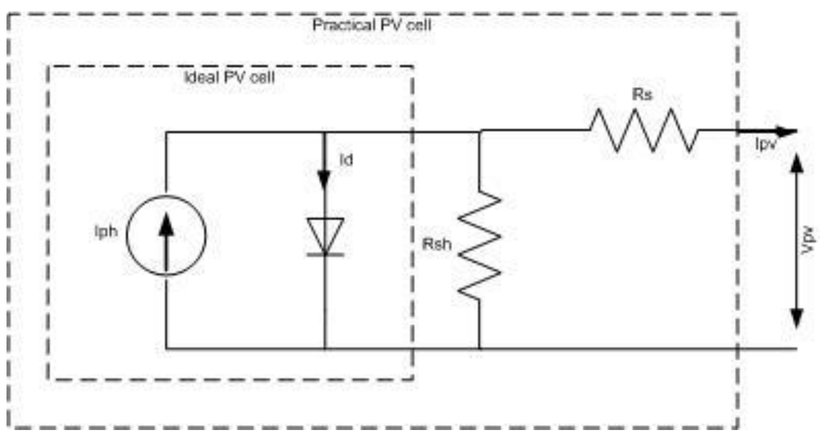


Figure 2.2 Equivalent Circuit of PV cell

I_{sc} is the short circuit current, which is the photon current during short circuit condition and V_{oc} is the open circuit voltage, which is the voltage produced by the p-n junction diode, which shunts the photon current [12] . For the analysis of PV cell in the project we consider ideal PV cell as shown in the Figure 2.2

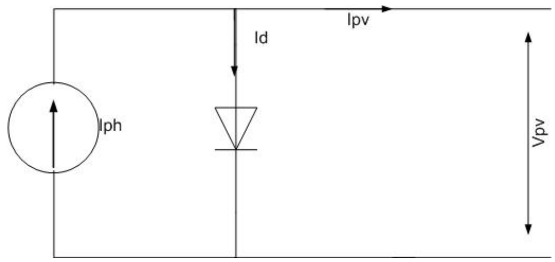


Figure 2.3 Equivalent circuit of Ideal PV cell

From the Figure 2.3 we can observe using Kirchhoff's law

$$I_{pv} = I_{ph} - I_d \tag{2.1}$$

The photon current is a dependent on the current and irradiance given by the following equation 2.2

$$I_{ph} = (I_{sc} + \alpha(T - T_{ref}))\frac{\beta}{\beta_{ref}} \tag{2.2}$$

Where,

I_{ph} is the photon current(A)

I_{sc} is the photon current at standard conditions (T_{ref}=298K, β_{ref}=1000W/m^2)

α is the short circuit current temperature coefficient(%/^{o}C)

T is the absolute temperature(K)

β is the solar irradiance (W/m^2)

The diode current (I_d) is given by

$$I_d = I_s(e^{\frac{qV}{nkT}} - 1) \tag{2.3}$$

Where,

I_d is the diode current(A)

I_s is the saturation current of the diode(A) q is the charge of electron (1.6×10^{-19} C)

V is the voltage across the diode (V)

n is the ideality factor

k is the Boltzmann constant(1.381×10^{-23} J/K)

T is the absolute temperature (K)

The saturation current of the diode varies with temperature as

$$I_s = I_o \left(\frac{T}{T_{ref}}\right)^3 e^{\frac{qv_g}{nk}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \tag{2.4}$$

Where,

I_o is the reverse saturation current

T_{ref} is the reference Temperature (298 K)

v_g is the band gap voltage of the semiconductor(V)

Under the initial conditions, the reverse saturation current can be calculated. Ipv =0 in open circuit condition and constant temperature. Equation 2.1 can be transformed as

$$0 = I_{sc} - I_d$$

$$I_{sc} = I_s(e^{\frac{qV}{nkT}} - 1)$$

$I_s = I_o$ at $T = T_{ref}$

$$I_{sc} = I_o(e^{\frac{qV}{nkT}} - 1)$$

$$I_o = \frac{I_{sc}}{\left(e^{\frac{qV}{nkT}} - 1\right)} \tag{2.5}$$

From equation (2.1) the PV current can be expressed as

$$I_{pv} = I_{ph} - I_s(e^{\frac{qV}{nkT}} - 1)$$

Since voltage across the diode itself is the voltage across the PV cell V_d=$V_{pv.}$

$$I_{pv} = I_{ph} - I_s(e^{\frac{qV_{pv}}{nkT}} - 1) \quad (2.6)$$

So, the output PV current can be expressed as equation 2.7

$$I_{pv} = (I_{sc} + \alpha(T - T_{ref}))\frac{\beta}{\beta_{ref}} - I_s(e^{\frac{qV_{pv}}{nkT}} - 1) \quad (2.7)$$

2.1.3 Simulink model of PV cell

With the above equations a model which fits the configuration is simulated using Matlab Simulink. The following parameters are used for the simulation

Table 2.1 Parameters for PV cell simulation

Parameters	Value
Short Circuit Current(I_{sc})	1.8A
Open Circuit Voltage(V_{oc})	0.6V
Band Gap Voltage(v_g)	1.12V
Diode Ideality Factor	1.24
Short circuit current temperature coefficient(I_{sc})	2.47×10^{-3}

For the PV cell simulation, temperature and the irradiance are the inputs to the cell, I_{pv} flows through the PV cell. The Voltage is varied to find the Voltage Current relationship and Power Voltage behavior. The behavior observed is verified with the ideal PV cell from the literature.

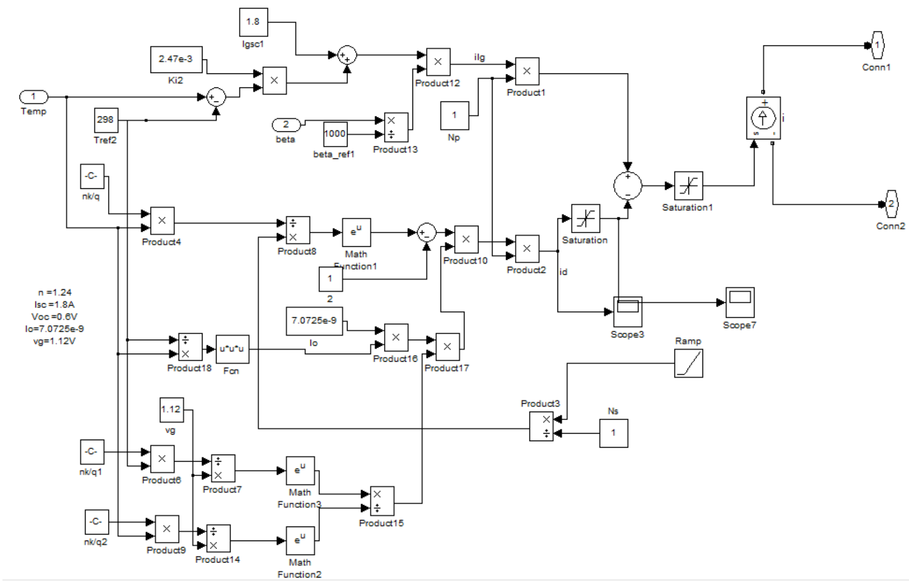


Figure 2.4 PV cell simulink model

The simulation is carried out and the results are shown in the Figures 3.5 and 3.6

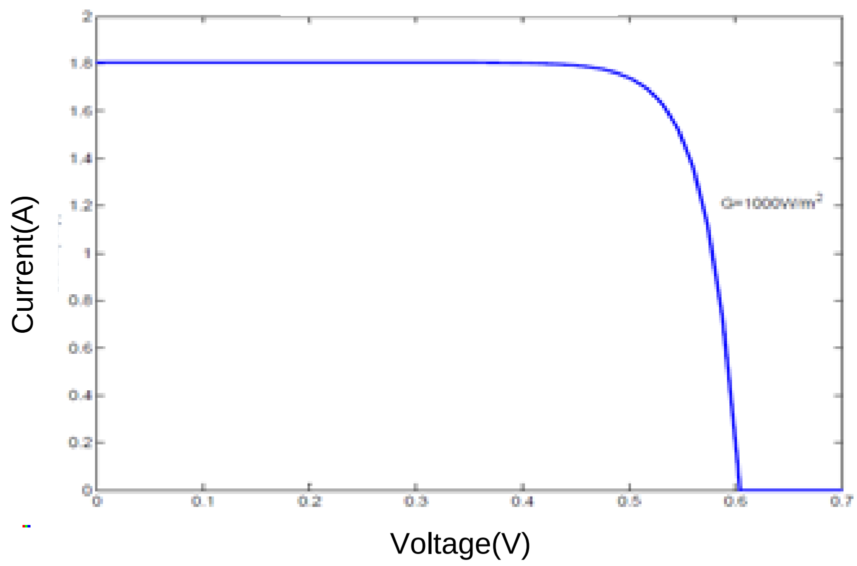


Figure 2.5 Current vs Voltage for single cell

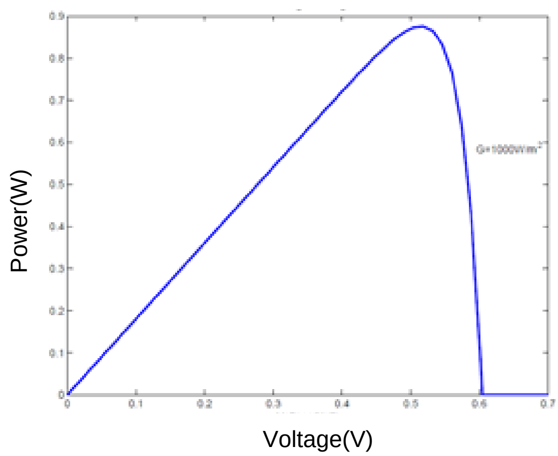


Figure 2.6 Power vs Voltage for single PV cell

2.1.4 Validation of the model

By the first observation from the Figures we can verify that the present model is apt. Since the equivalent circuit of PV cell is mostly a constant source of current with a diode, we can observe inverted diode characteristics for the current with minimum current being zero. From the Figure 3.5, we can observe inverted diode current characteristics with a maximum current at 1.8A (I_{sc}). The power voltage curve follows from the current voltage curve. Hence the model is apt for the consideration of a PV cell model.

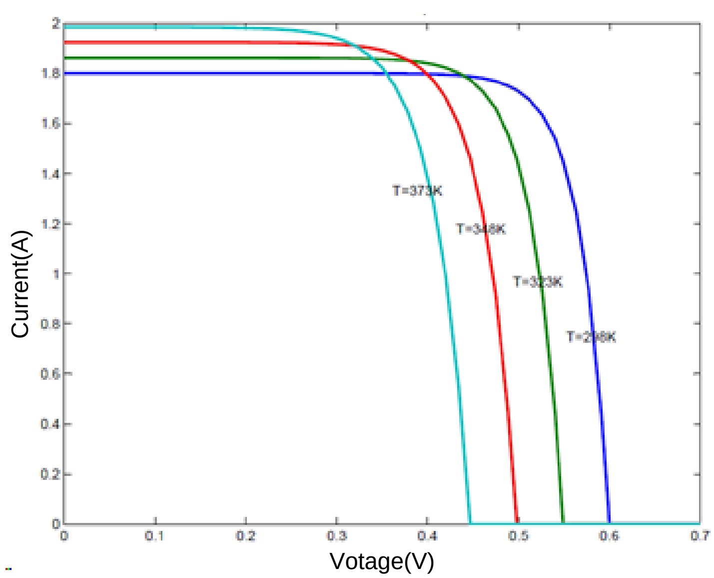


Figure 2.7 IV curve with Temperature variation

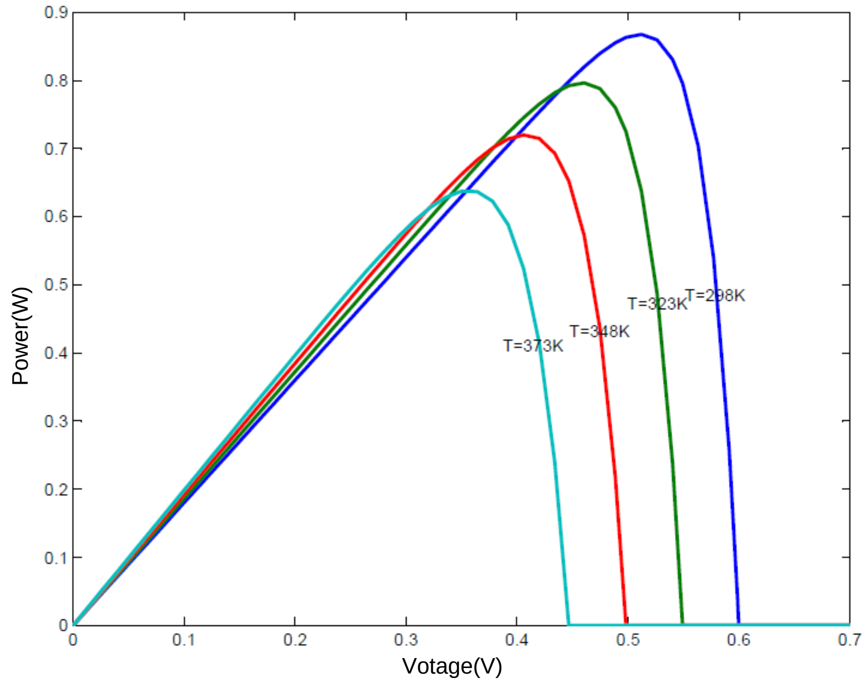


Figure 2.8 PV curve with Temperature Variation

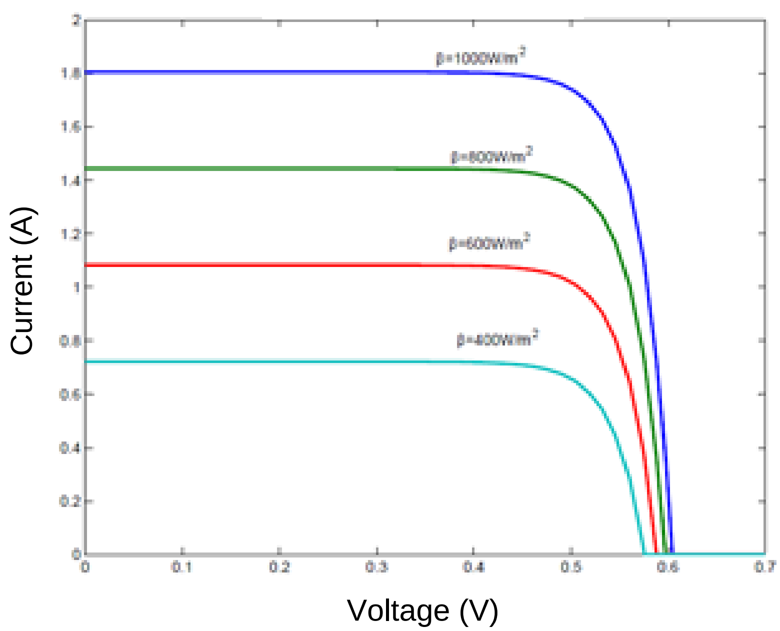


Figure 2.9 IV curve with irradiance variation

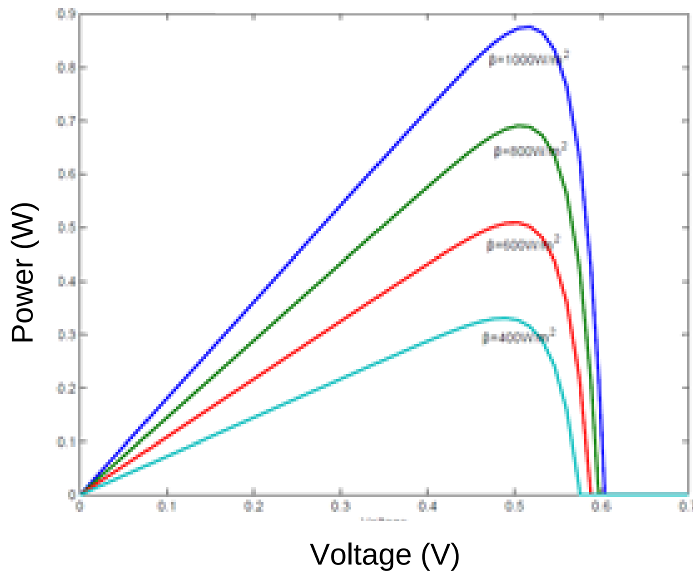


Figure 2.10 PV curve with irradiance variation

The variation of irradiance and also the temperature is simulated to understand about the behavior of the solar cell. Few conclusions are drawn, for the future modeling of PV array which consists of many cells in series and parallel.

With the decrease of irradiance, there is a less photon flux reaching the panel, which results in less photon current. We can observe from Figure 2.9 that for the same voltage, the current through the PV cell varies a lot with the irradiance. The effect is responsible for the decrease of power as observed in Figure 2.10. There variation of V_{oc} is very less, which can be observed from the Figure 2.9

With the increase in temperature, the band gap energy is increased, which means more energy is needed for the electron to cross the forbidden gap. Very few electrons acquire the energy to cross the band gap energy, which is responsible for reduction in the number of mobile holes and electrons, which in turn are responsible for lower current.

Note that the variation of temperature is small when we observe in the practical case (15^{o}C to 40^{o}C). The observation can be made from the Figure 2.11, where there is a small variation with temperature and since we try to operate in at maximum power, the variation is minimum.

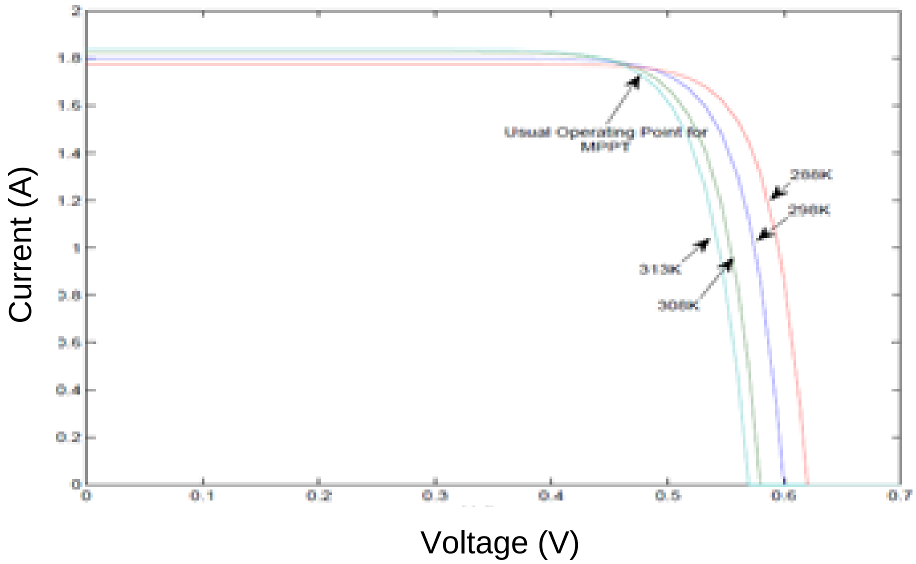


Figure 2.11 IV curve for practical temperature variation

2.1.5 Simulink model of PV array

In the practical case, the temperature effect is very small compared to that of irradiance, so for simplicity from here on the temperature effect is neglected. This is a safe assumption after the observation made from Figure 3.11.

The simulation of the PV array is similar to that of that of PV cell, but instead of current being calculated, the voltage is calculated for simplicity in future simulations.

From the equation 3.7 and operating at reference temperature

$$I_{pv} - I_{sc}\frac{\beta}{\beta_{ref}} - I_s\left(e^{\frac{qV_{pv}}{nkT}} - 1\right) = 0 \qquad (2.8)$$

Solving the following equation, V_{pv} can be calculated, which should be the voltage across the PV cell. For the consideration of an array, the equation 3.8 can be transformed into equation 3.9

$$\frac{I_{pv}}{N_p} - I_{sc}\frac{\beta}{\beta_{ref}} - I_s\left(e^{\frac{qV_{pv}}{nkTN_s}} - 1\right) = 0 \qquad (2.9)$$

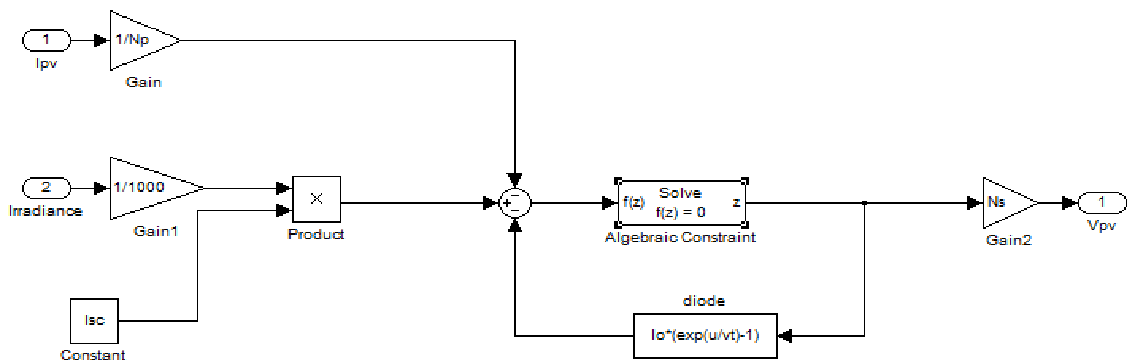


Figure 2.12 Simulation of PV array

The equation in 3.9 is solved using Matlab Simulink using dogleg-trust region algorithm, which makes the inputs into the system to converge to zero by varying the output of the system. In this case the input to the system is the equation 3.9 where the output is the V_{pv}, the algorithm produces an output V_{pv} which converges the input to zero, which is the solution to our equation.

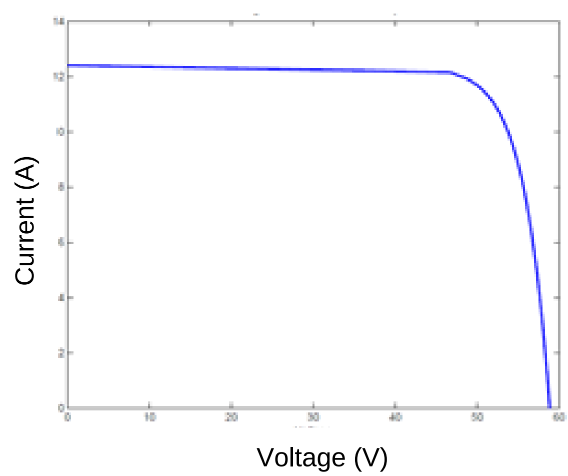


Figure 2.13 IV curve of PV array

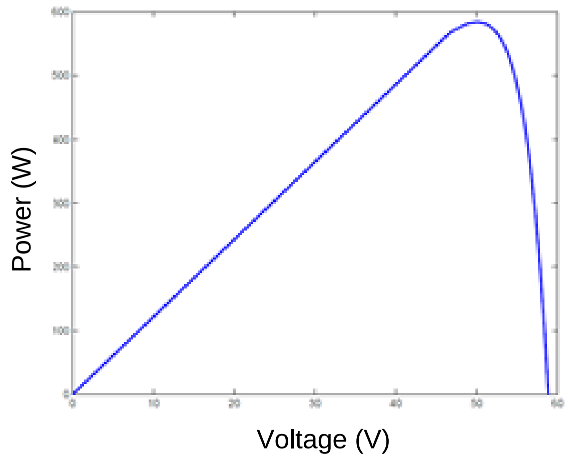


Figure 2.14 PV curve of PV array

The following simulations are carried out for N_s=100 and N_p=10

Note that the following curves behave approximately the same way as an individual PV cell, but with varied magnitude. As already validated, the following PV array model can be used in simulating an ideal PV array.

2.2 Battery Dynamics

The main energy storage unit in the project is the battery. The battery model is used from the Matlab Simulink Library which is an apt model in consideration. The battery is taken into consideration as the energy storage device due to its accessibility and also the cost.

The charging or discharging of the battery is not a linear function. The voltage of the battery varies with the State of Charge of the battery; the variation is also non-linear in nature. After a point of SOC the voltage drops rapidly. From the Figure 3.15, the voltage is in +/-5% of the limit in most of the charging region, i.e., considered to be nominal value. But after a certain SOC (State of Charge) the voltage drops rapidly. It is certain that it would be nominal for usage of the battery in the normal region and it would be difficult to be used in region below 30% SOC. The SOC should be maintained above 30% for effective usage of battery. The following criteria will be considered during designing of algorithm for effective energy management.

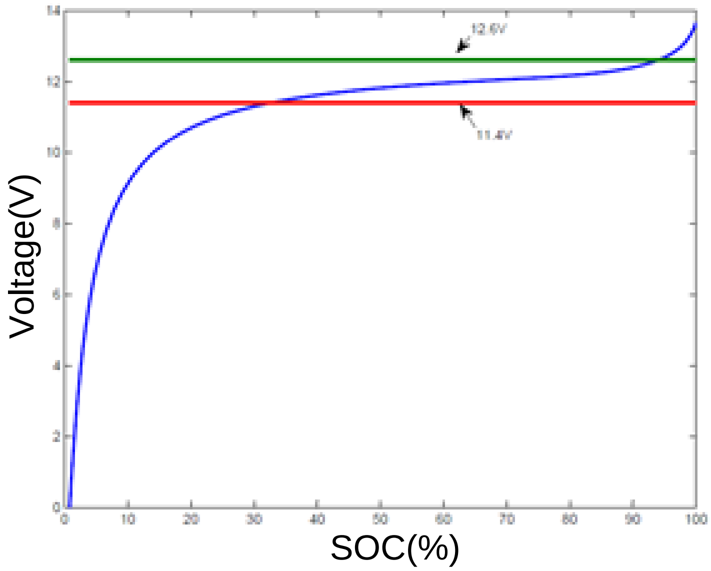


Figure 2.15 Variation of voltage with SOC

This chapter builds the structures to be used in the future chapters, the modeling of PV cell and array is discussed. Since the power voltage and power current profile are nonlinear, so the operation of the PV array/cell should be carried out to have maximum efficiency, which will be discussed in the next chapter.

CHAPTER 3

MAXIMUM POWER POINT TRACKING OF PV ARRAY

The observation from the previous chapters, the maximum power produced by the PV cell or the array is not a linear function with voltage. The PV array should be maintained at a certain voltage or certain current so that the maximum power can be extracted from the PV cell. Since we are utilizing the maximum power produced by the array, the efficiency of the system is improved. Many algorithms are present which track the maximum power point of the PV cell [11], few are discussed in [12],[13].

3.1 MPPT Algorithm and its implementation

As already mentioned in the Chapter 2, the power voltage curve of the PV cell is not a linear function and the power transmitted by the array varies with the voltage and current

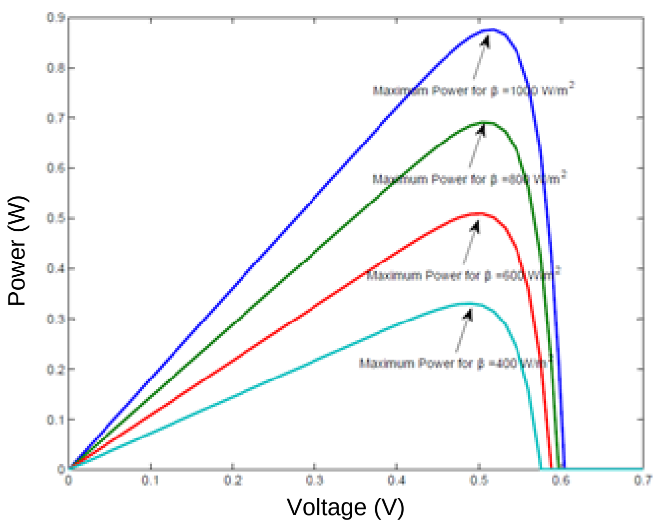


Figure 3.1 PV curve showing maximum power for different irradiance levels

By maintaining the specified voltage and current to attain maximum power, it is possible for to improve the efficiency of the system. An MPPT algorithm is proposed by observing the power and current profile and track a reference current to attain maximum power.

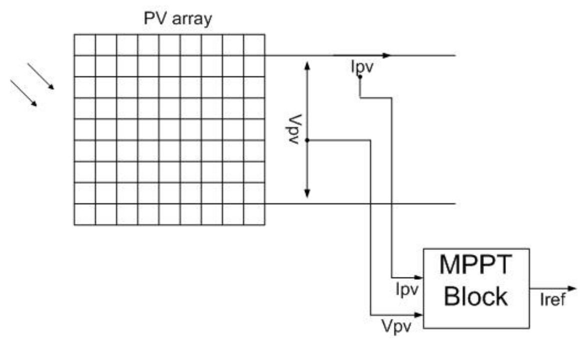


Figure 3.2 MPPT Block Diagram

With the irradiance as input, the current at which maximum is power is tracked. The power current profile is similar to that of power voltage profile of the PV array but with the steep decrease of power after the maximum power is attained, which can be observed in the Figure 3.3.

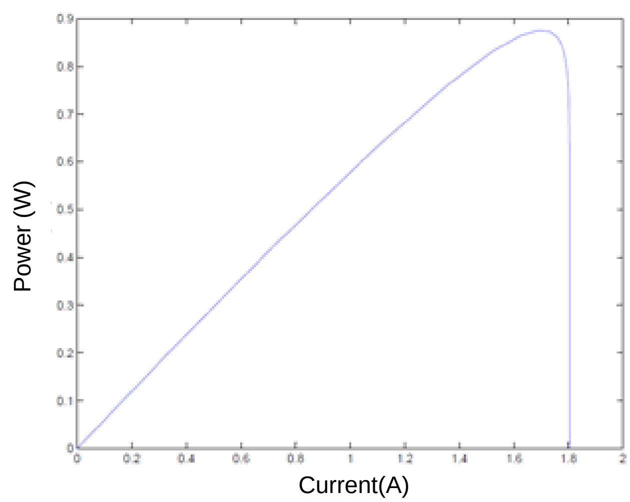


Figure 3.3 Power Current profile

We can observe the power and current curve from the figure 3.3, as already mentioned it differs from the power and voltage curve. The power in the power current curve rapidly falls after attaining maximum power compared to that of the power voltage curve. The main objective in this chapter is to maintain the required current and voltage so as to operate the PV cell/array at the maximum power point. For operating the PV array at the maximum power point the following algorithm is used.

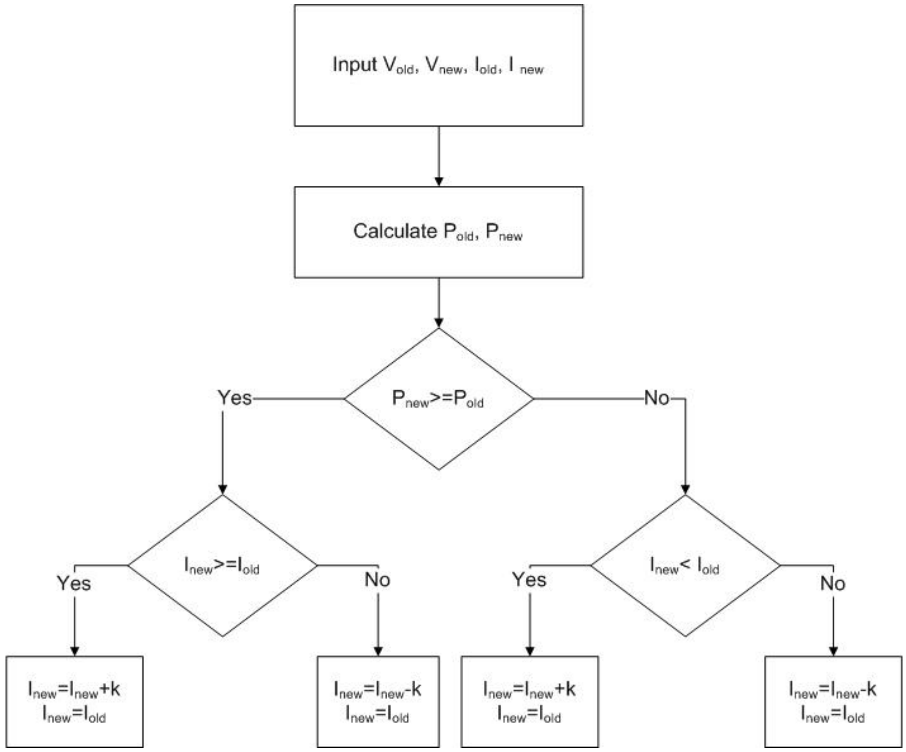


Figure 3.4 Algorithm for the MPPT for PV array

The algorithm for the maximum power works on perturb and observation method. The value of the current is adjusted so as to have maximum power being transmitted by the PV array. From here we can determine the amount of current to be flown at a particular irradiance value. The main objective is to maintain the reference current to be flowing through the PV array. For the following, a boost converter is used which will regulate the amount of current to be flowing through the PV array, which will be discussed in the subsequent sections.

The MPPT algorithm works on the main principle of slope of the PI curve, a positive slope in the PI curve, the reference current should be increased to attain maximum power, if there is a negative slope, the reference current should be decreased to attain maximum power point. The reference current is to be tracked in order to obtain maximum power from the PV array.

The following algorithm is tested for an irradiance values in Hyderabad, data for which is collected from National Renewable Energy laboratory (NREL). These irradiance values are fed as inputs and the outputs are analyzed.

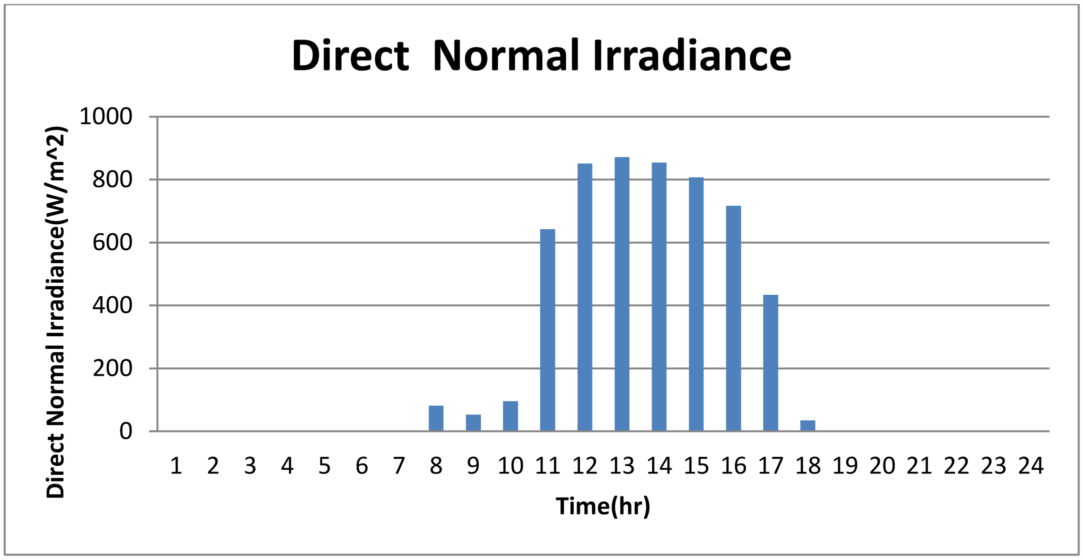


Figure 3.5 Direct Normal Irradiance (DNI) values on 01-01-2008 at Hyderabad

The following simulation is carried out with the values mentioned above, the results are observed in Figure 3.6. The simulation is scaled in such a way that 1s in the simulation is to 1hr in real time. The simulation is carried out in Matlab simulink. The above solar irradiance values are interpolated and is given to the PV array. The interpolation is done to emphasize practicality into the system, since sudden increase or decrease of irradiance is rarely seen.

The main observation from the graphs is that the power generated by the PV array is zero during nights and almost very low during the mornings and evenings. The simulation is done at N_s= 400 and N_p= 10. And the voltage produced is usually inconsistent in nature as shown in the figure. With a significant variation in the voltage levels, we can note that when connected to a DC bus, the voltage will be inconsistent and can affect many appliances. From this we can say only a PV array connected to DC voltage bus will be inconsistent in voltage levels. This point will be further emphasized in the next chapter when only PV array is connected to DC bus without a storage unit.

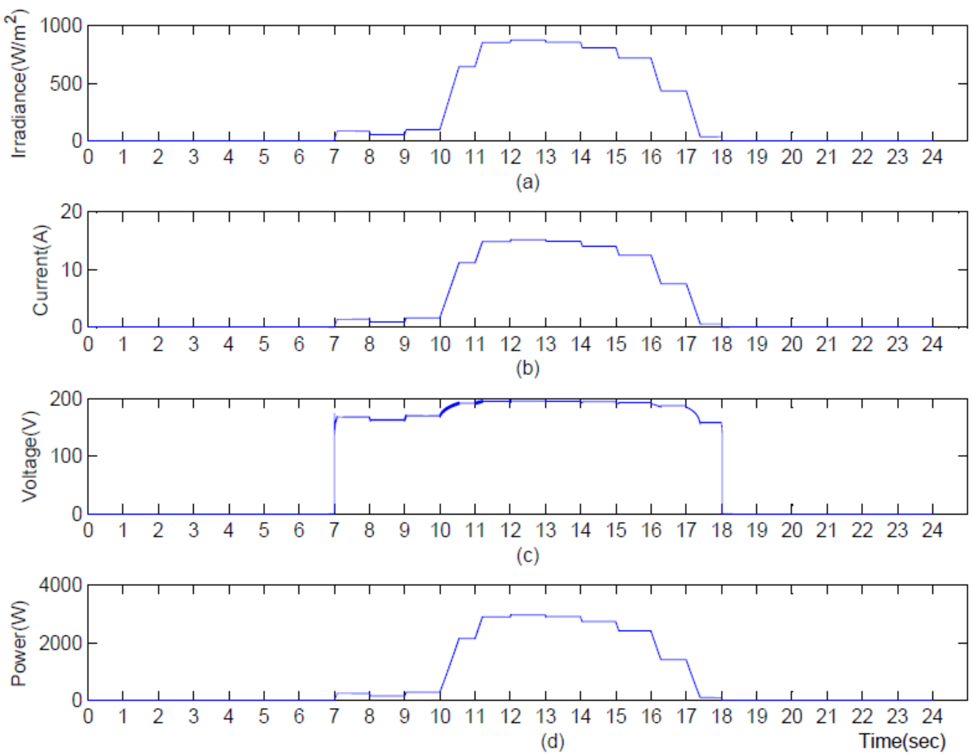


Figure 3.6 (a) Irradiance vs time (b) Current vs time (c) Votage vs time (d) Power vs time

3.2 Boost Converter

The main objective now remains that the I_{ref} produced by the MPPT algorithm is tracked, for the following objective to be achieved, we try to use a Boost Converter and by varying the duty cycle, the I_{ref} is to be tracked and maximum power is transmitted by the PV array [14].

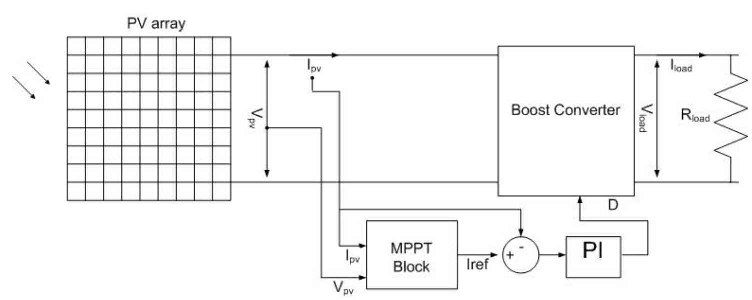


Figure 3.7 Block diagram of Boost converter

The circuit diagram for boost converter is shown in Figure 3.8. Boost converter is also called as step up converter. It is used to convert low DC voltage to high Dc voltage and transmission of DC power from Low voltage side to High voltage side.

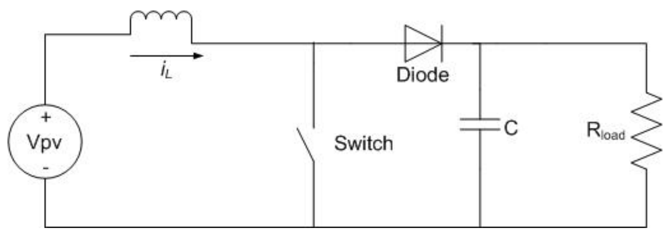


Figure 3.8 Boost Converter

The boost converter is usually used for maintaining the load side voltage constant. But in the following project, it is used for tracking the I_{ref} produced by the MPPT block, so that the maximum power produced by the PV array is utilized.

3.3 Parameters of Boost Converter

The parameters of the boost converter are selected in such a way to have effective voltage output of 600V when the input is around 200V. The main objective still remains to track the reference signal, but for the parameters selection the V_{out} =600V and V_{in}= ~200V.

Based on volt-sec balance across the inverter,

$$V_{pv}T_{on} = V_o(T - T_{on}) \tag{3.1}$$

$$\frac{V_o}{V_{pv}} = \frac{1}{1-D} \tag{3.2}$$

Where, the duty cycle ration (D) is

$$D = \frac{T_{on}}{T} \tag{3.3}$$

Table 3.1 Parameters of Boost Converter

Parameter	Value
Input Voltage	~200V
Output Voltage	600V
D	2/3
Frequency	20kHz
Maximum Power	~3kW

The load voltage should be ~120 ohm for the output voltage to be 600V, but the load resistance varies with time, and not a constant value. The aspects of varying load resistance is dealt in the next chapter in detail, in this chapter the tracking of current is to be given significance. The value of the inductor and capacitor are calculated from the following equations 3.5 and 3.6. The value of ripple is taken as 5% of the nominal values.

$$I_o = \frac{P_{pv}}{V_o} \quad (3.4)$$

$$L = \frac{V_{pv} d}{\Delta I f} \quad (3.5)$$

$$C = \frac{I_o d}{\Delta V f} \quad (3.6)$$

The simulation is carried out with the following values, and the control of the duty cycle input is analyzed in the next section.

3.4 Control of Boost Converter

The control of boost converter is carried out with the objective of tracking the reference current. The reference current from the MPPT is compared with the actual current into the boost converter; the error is given to a PI controller. The output of the PI controller is used to generate PWM signals to the Boost Converter, by which the current is tracked [15].

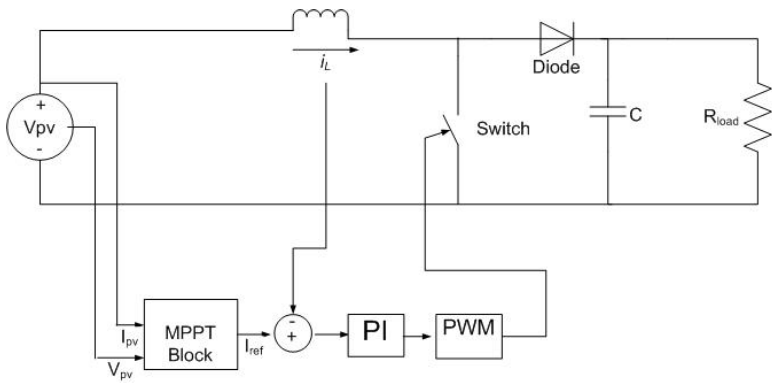


Figure 3.9 Control of Boost Converter

The simulation is carried out for varying irradiance and the results are observed. We can observe that the current through the inductor is being tracked by the reference current. Essentially the operation of the PV array is at maximum power. From the Figure 3.11, the reference current is being tracked by the actual current effectively. Hence the model can be validated; hence we are operating at maximum power for PV array.

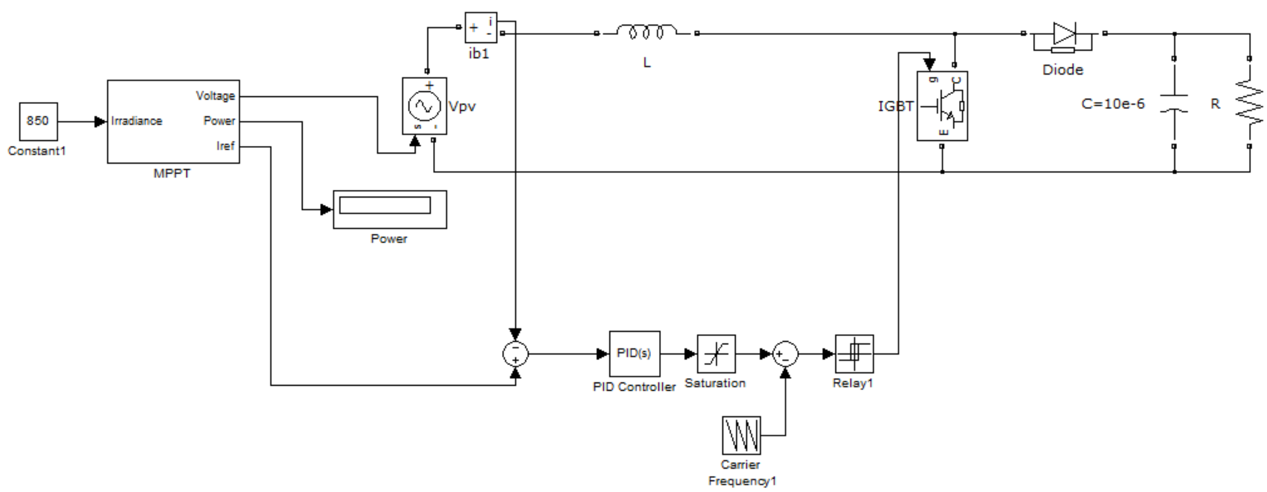


Figure 3.10 Matlab Simulink Model

3.5 I_{ref} tracking using Boost Converter

The above control is carried out to the boost converter and the results are shown in the Figure 3.11. It can be observed that the i_{ref} is being tracked very accurately by the i_L.

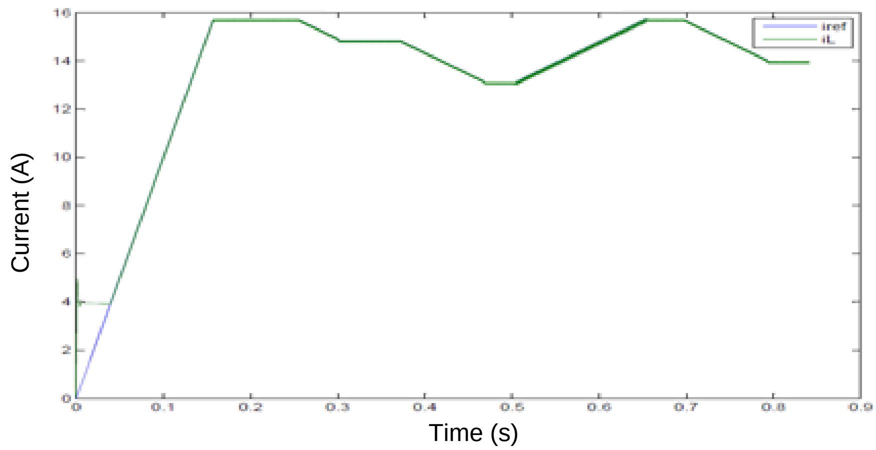


Figure 3.11 I_{ref} tracking

The tracking is very accurate, which can be observed from the Figure 3.11. Hence our objective to track the Iref so that maximum power can be utilized from the PV array is achieved. For a better view of tracking the Figure 3.11 is zoomed at a certain time which can be viewed in Figure 3.12

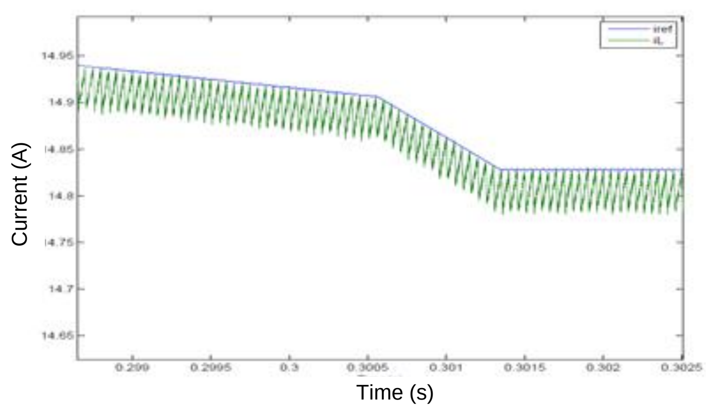


Figure 3.12 Zoomed version of Iref tracking

The I_{ref} is being tracked accurately. Hence, the maximum power is being utilized from the PV array. In the next chapter the load is varied and the behavior of the voltage DC bus is seen.

CHAPTER 4

MICROGRID OPERATION WITH AND WITHOUT STORAGE SYSTEM

In the previous chapter, the operation of PV array at MPPT is analyzed. In the present chapter, PV array is connected to the V_{bus} or the DC grid without energy storage. This chapter will emphasize the importance of the storage unit. As observed in the previous chapter, the value of voltage varies significantly at the output of the PV array. If the PV array is connected to the bus, the same fluctuations are seen as tracking of maximum power point is given importance [16].

4.1 Microgrid operation without storage

The Microgrid consists of mainly the PV array, which is connected to a Boost Converter in turn connected to the Voltage Bus. The DC loads are connected to the voltage bus. The voltage fluctuations in the PV array are seen at the V_{bus}, which emphasizes the importance of the storage unit.

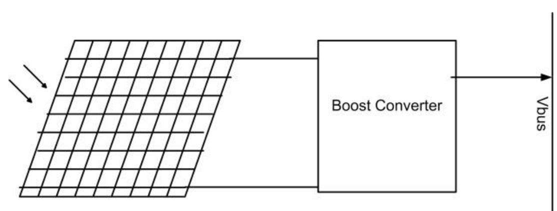


Figure 4.1 Block diagram of Microgrid without storage unit

The Microgrid storage unit without storage unit can be classified into 2 different sections; either the load power at 600V (DC bus rated voltage) is greater than the power produced by the PV array or when the load power at 600V (DC bus rated voltage) is less than that of the PV array. In these two cases the results are different and subsequent analysis is done in this chapter.

4.1.1 Power required by the load at 600V is more than power by PV array

With the maximum rated power at about 3kW, the load resistance at which the nominal value of 600V be reached is approx. R_{load}=120 ohm. Now for loads less than 120 ohm, to maintain a voltage of 600V, additional power is to be injected into the DC grid, but with the lack of any energy source connected to the grid, the bus lacks power and the voltage drops from the nominal value. The following simulation is carried out at R_{load}=60 ohm for which to maintain the 600V nominal value of the V_{bus}, 6kW of power should be transmitted by the PV array, but the maximum power from the PV array is ~3kW, so the V_{bus} voltage drops below the 600V mark. It settles nearly around 400V. For any V_{bus}, this is very unstable situation.

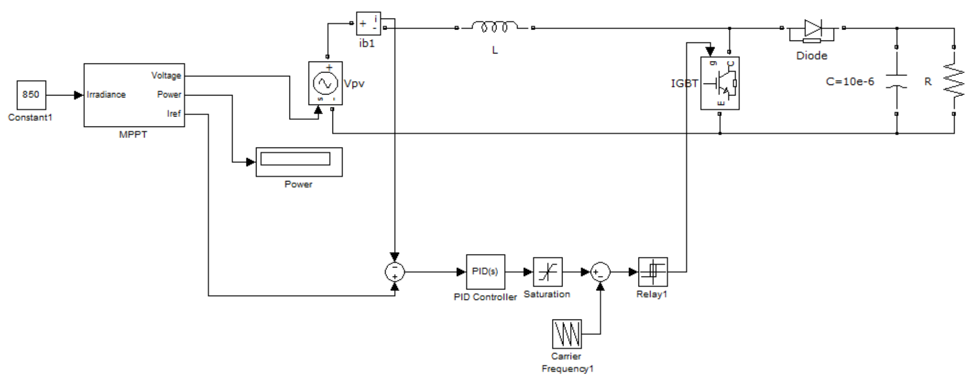


Figure 4.2 Matlab Simulink simulation diagram

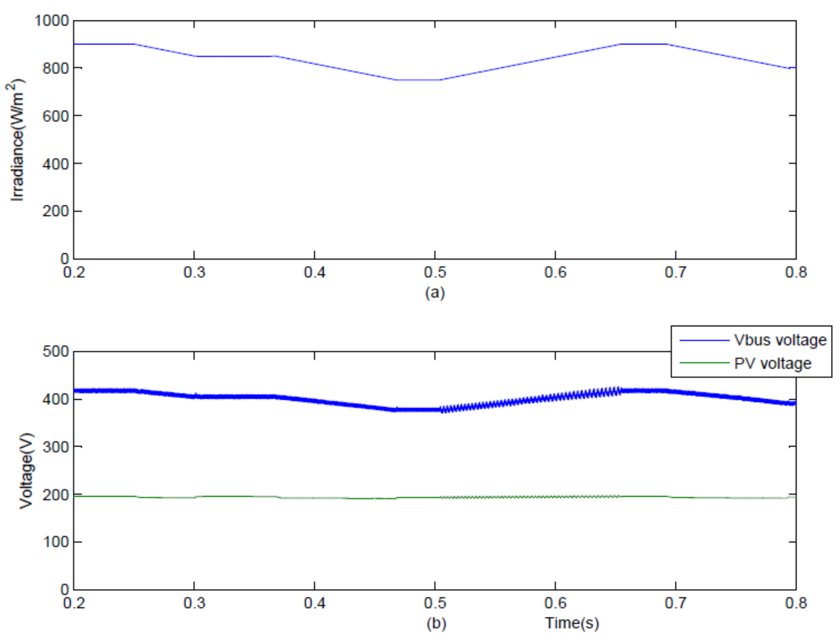


Figure 4.3 (a) Irradiance level (b) PV voltage and DC bus voltage with varying irradiance values

The Figure 4.3 shows the voltage fluctuations, when there is a change in the irradiance values. The variation of this kind in the DC grid is unacceptable. These variations are only during small fluctuations of irradiance, but during nights, when the irradiance is almost zero and PV array is unable to produce any power, then the DC grid voltage drops to zero, which is unacceptable.

The DC grid voltage has to be maintained at about 600V, but from the Figure 4.3, the DC grid voltage is low at 400V due to excess load. Usually the variation in DC Grid bus voltage should be maintained at minimum, but it is not possible to maintain at that voltage due to the excess load. From the following we can conclude that an energy source is essential either for the maintenance of DC grid at a constant voltage. If the following V_{bus} is connected to energy source, which can inject the remaining power to maintain the voltage level at 600V. The importance of the energy source will be reemphasized in the next subsection.

4.1.2 Power required by the load at 600V is less than power by PV array

The same simulation explained above is carried out at R_{load}= 240, and since the load power at 600V is 1.5kW but the power generated by the PV array is ~3kW. Since there is an excess generation of power than the load power, the voltage instead of maintaining at 600V will increase and reach a voltage of around 850V.

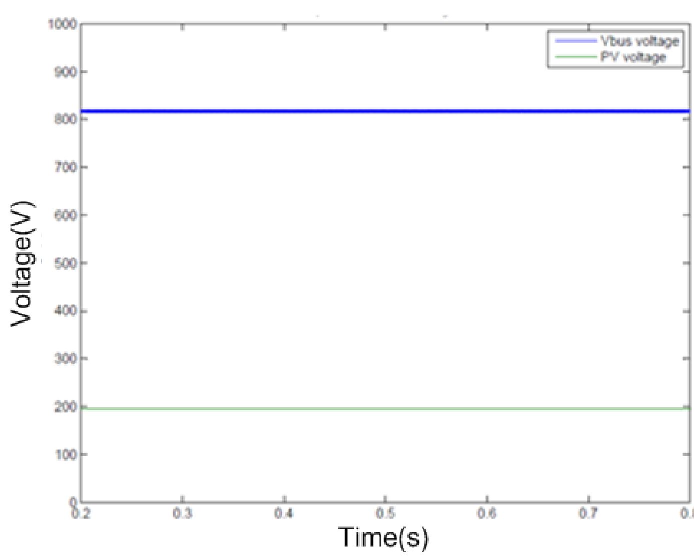


Figure 4.4 PV voltage and DC bus voltage when R_{load} = 240 ohm

As already noted, the V_{bus} is more than the specified 600V. This instability in the V_{bus} voltage is not intended. And the additional power produced by the PV array is not usable, which decreases the efficiency of the whole system. Figure 5.5 shows when both power produced by the PV array is more than the load power in the first region and then switch and the load is increased after 2.6s. The sudden drop of voltage from 800V to 400V is seen.

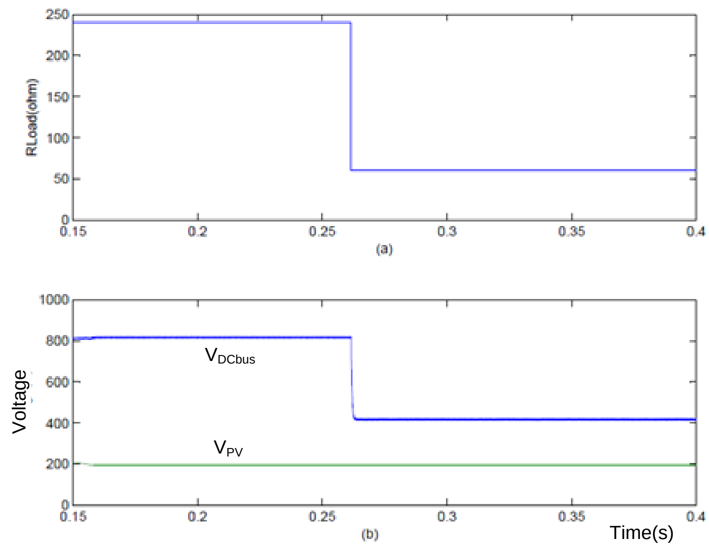


Figure 4.5 (a) R_{load} (b) DC bus voltage

The chapter emphasizes the usage of the energy source, which can either inject the power to maintain the DC bus voltage constant or utilize the excess power produced in order to charge itself and can be utilized when the PV array is unable to produce the required power. With the lack of the energy source the DC bus voltage is not constant and varies as shown in the Figure 4.5 (b) with the change in the load.

4.2 Microgrid with Storage

In the previous section, the importance of the energy source by in a Microgrid is emphasized. It is essential for maintaining the DC grid voltage constant by injecting power if required into the system or conserving the energy by storing the excess amount of energy produced by the PV array [13],[17].

In this section the operation of the Microgrid is carried out with a storage unit and simulations are carried out and analyzed. Since the battery is to be charged or discharged depending on whether the power is to be injected or ejected from the DC grid, an algorithm is proposed for effective maintenance of DC grid voltage.

4.2.1 Storage connected to DC grid

The storage unit cannot be directly connected to the Dc grid directly. The essence of either to inject the power or absorb the power from the DC grid is unknown to the battery. So, the battery is to be connected to a bidirectional converter which can either charge the battery by absorbing the energy from the grid or by discharging the battery and injecting the power into the grid. Bidirectional converter is used for achieving the following, for which the switching has to be in such a way that it either charges or discharges the battery depending on the load condition.

Figure 4.6 shows the block diagram of the Microgrid with storage connected to the DC bus. The PV array is connected to the grid directly using the boost converter and the battery is connected to the grid using the bidirectional converter. The major bidirectional converter used is the Buck Boost converter. There are many bidirectional converters, but buck boost is usually selected with the simplicity of its operation and implementation. The bidirectional converter used in the project is the Buck Boost Converter. Using buck boost converter, the battery is either charged or discharged depending on the switching to the converter.

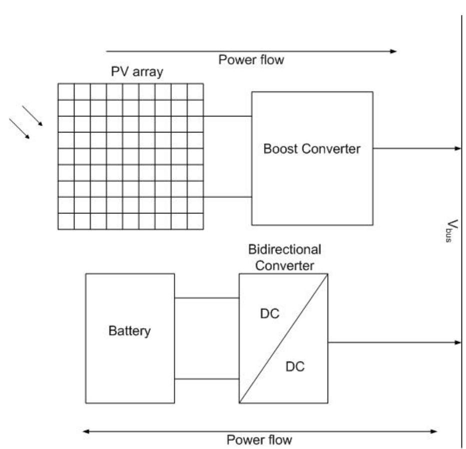


Figure 4.6 Microgrid with storage

4.2.2 Buck Boost Converter

The Buck Boost converter, as the name suggests can act as a buck converter or as a boost converter. The mode of operation depends on the switching to the converter. In the buck operation or the step down operation the power flows from the higher voltage side to the lower voltage side. In the boost operation or the step up operation, the power flows from the lower voltage side to the higher voltage side. By suitably choosing the switching, the power flow can be control to either charge or discharge the battery [5].

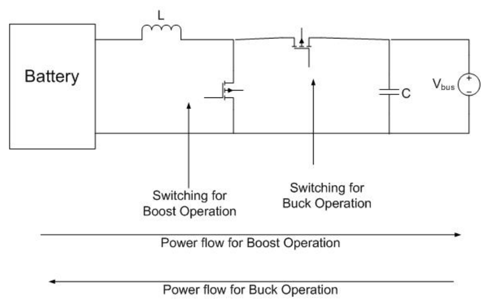


Figure 4.7 Buck Boost Converter circuit diagram with power flow direction

4.2.3 Parameters of Buck Boost Converter

The parameters of the buck boost converter are chosen in such a way that it can act both as buck converter and boost converter in the specified region of operation. The analysis of buck boost converter can be split into buck operation and boost operation and the values of inductor and capacitor are calculated and the value with the lowest ripple is selected. For the buck operation, from the volt-sec balance of the inductor.

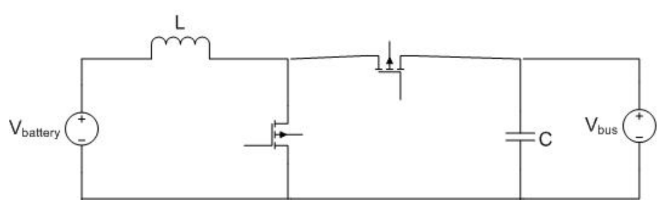


Figure 4.8 Circuit diagram of Bidirectional converter

$$\left(V_{bus} - V_{battery}\right)T_{ON} = V_{battery}(T - T_{ON}) \tag{4.1}$$

$$\frac{V_{battery}}{V_{bus}} = D_1 \tag{4.2}$$

$$D_1 = \frac{T_{ON}}{T} \tag{4.3}$$

The value of L can be calculated as follows

$$L = \frac{(V_{bus} - V_{battery})D_1}{\Delta I\ f} \tag{4.4}$$

The value of C can be calculated as follows

$$C = \frac{\Delta I}{8\Delta V f} \tag{4.5}$$

The parameters of boost converter are calculated from the equation, the value for which the lowest ripple of voltage and current is obtained are selected

Table 4.1 Parameters of Buck Boost Converter

Parameters	Value
V_{bus}	600V
$V_{battery}$	240V
Switching frequency	20 kHz
Inductance(L)	14mH
Capacitance (C)	100μF

4.2.4 Energy management Algorithm for Microgrid connected to Energy storage

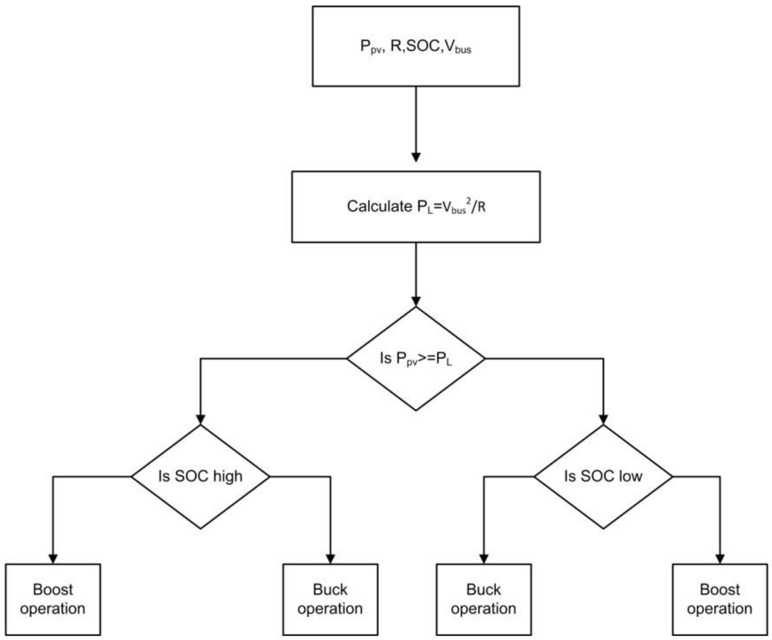


Figure 4.9 Algorithm for Energy management of Microgrid with storage

The selection of Buck/Boost converter is very important in determining either the power should be injected or to be absorbed from the grid. For the following a selection mechanism is required. From the few observations in the previous chapter, it is noted that if the $P_{pv} > P_L$ then the voltage of the DC bus increases above the desired value; hence the power should be absorbed so as to maintain the DC voltage steady at the required voltage. And when $P_{pv} < P_L$ the voltage of the DC bus decreases from the required voltage, hence the power should be injected into the DC grid so as to maintain the DC bus voltage at the required value [18].

4.2.5 Control of Buck Boost Converter switching

The switching for the buck boost converter should be in such a way so that the voltage reference is maintained at the DC side voltage bus. To achieve the following, the Voltage of the DC bus is sensed and the error between the DC grid voltage and the reference voltage is fed to a PI controller from which an Iref is generated.

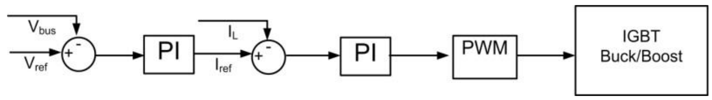


Figure 4.10 Control of Buck Boost Converter switching

The following I_{ref} should be tracked in order to achieve the DC bus at the reference voltage. The error signal between the Iref and the current through the inductor I_L is fed to another PI controller, output of which is given compared with a triangular pulse and pulses generated are given either to have buck operation or boost operation.

4.2.6 Results and analysis

From the previous chapter, it is known that the voltage of the DC bus varies rapidly with the load value. There is a need for maintaining the voltage at the DC bus level constant, for the following a bidirectional converter is used with the battery in order to either inject the power or absorb the power so as to maintain the required voltage at the DC bus level.

The DC load is varied in order to observe the variation in the voltage level, when it is connected to the battery which is connected to bidirectional converter. The value of the Rload is varied as shown in the Figure 4.11.

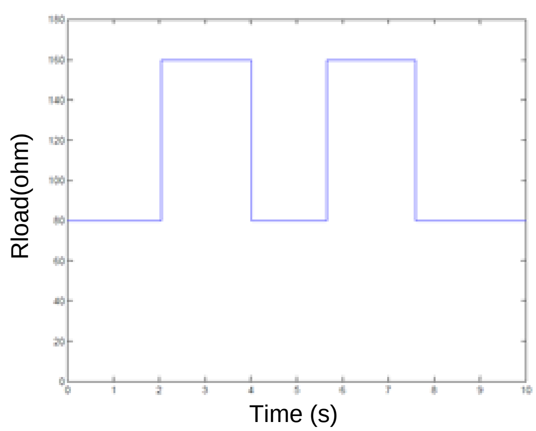


Figure 4.11 Variation of R_{load} with time

With the following variation in R_{load}, the voltage of the DC bus varies when the Microgrid is connected without storage unit, but with a storage unit, the voltage is maintained constant by the energy source. The following Figure 4.12 shows the variation of voltage at the DC bus when the load is varied as shown in the Figure 4.11.

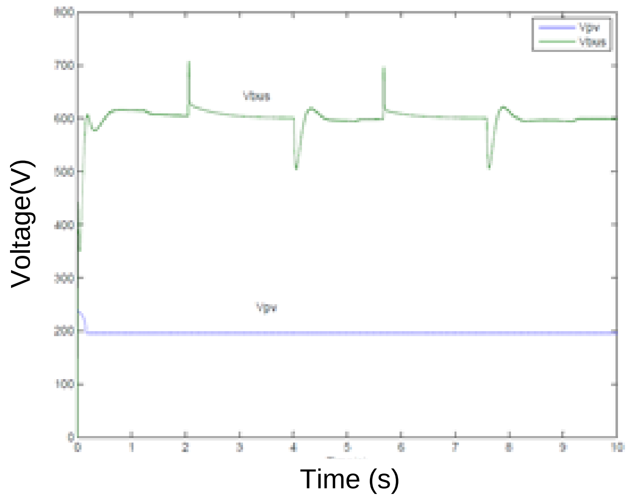


Figure 4.12 Variation of DC bus voltage and the PV voltage with time

Since the irradiance is maintained constant at $\beta = 900W/m^2$ the PV voltage is constant, but also the voltage at the DC bus is also maintained approximately constant except few minor transient variations during the sudden load change. Hence the battery is capable of maintaining the voltage at a constant value even when the load is changing rapidly either by injecting or absorbing the power from the grid. This can be observed from the Figure 4.13.

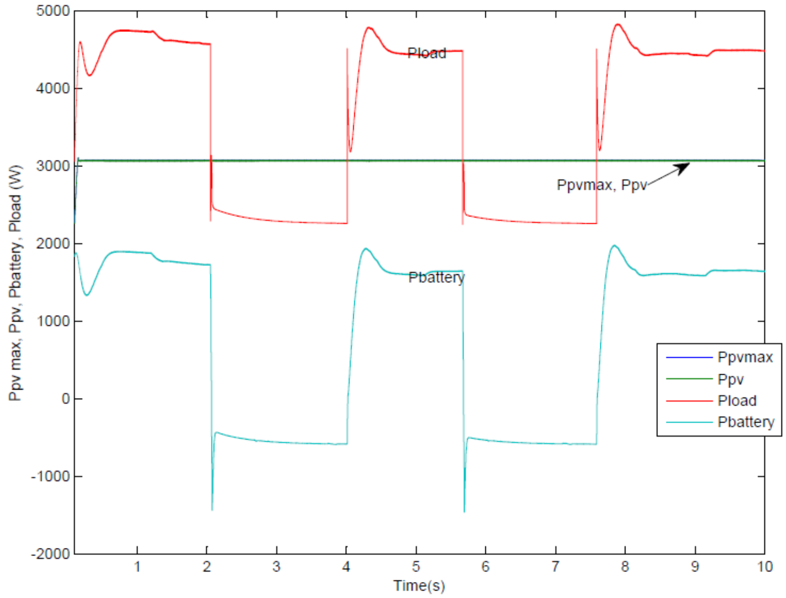


Figure 4.13 P_{load}, P_{pv}, $P_{battery}$ variation with time

From the Figure 4.13, the variation of the power of the load, battery and the PV array is shown. The negative value of the power by the battery is that it is being charged or the power is injected into the battery and the positive value of power indicates that it is being discharged or the power is being injected by the battery.

It can be noted that when the PV power produced is more than the load power, the excess power makes the voltage of the DC bus increase above the required level, then to compensate that the buck mode is operated and the excess power in the grid is transferred to the battery and we can observe the battery power being negative. And similarly when the load power is less than the PV array power, the voltage at the DC bus drops, to compensate that the boost mode is operated and the voltage is maintained at the required value.

In the Figure 4.13, for the time from 0-2 sec the load power is more than the power produced by the PV array (case 1), hence the boost mode is operated and we can observe that the difference of the power is supplied by the battery. From 2-4 sec, the load power is less than the power produced by the PV array (case 2), hence the battery is operated in the buck mode and the battery is charged. In the case 1 battery is supplying the additional power, so it is discharging and in the case 2 the battery is being charged by the additional power, this can be observed from the Figure 4.14 where from time 0-2 sec the current is negative implying that it is being discharged and the power is injected by the battery.

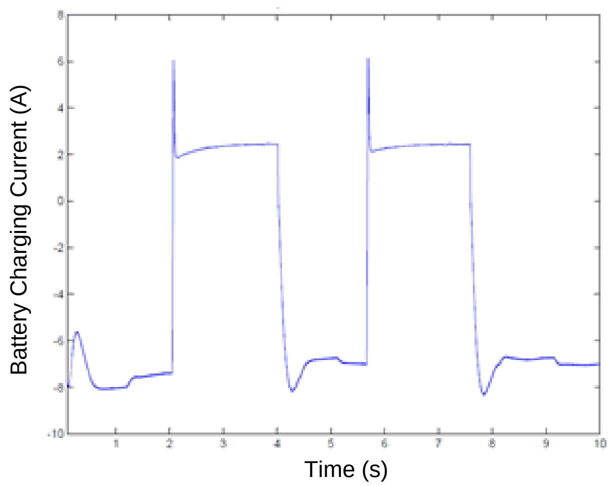


Figure 4.14 Battery current

The same can be observed from the State of Charge of the battery, during the charging period the battery gets charged and SOC% increases and during discharging SOC% decreases as shown in Figure 4.15

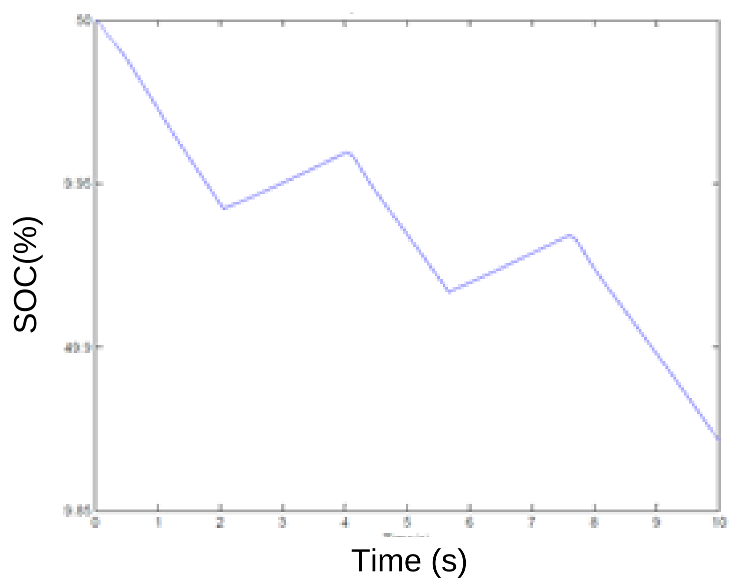
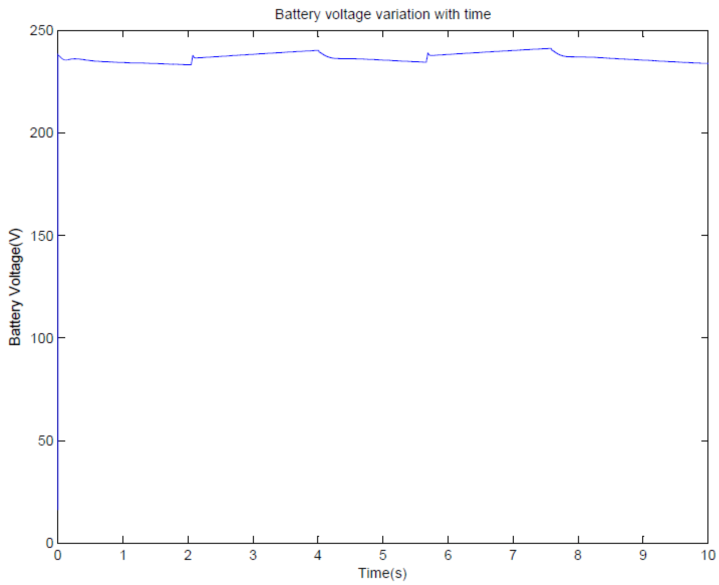


Figure 4.15 Variation of State of Charge of the battery with time



4.16 Variation of battery voltage with time

In the Figure 4.16 the variation of the battery voltage is shown, with the variation in the SOC%, the voltage of the battery also changes. Since the current discharged is low, and the SOC is not affected much, the variation of the voltage of the battery is less.

In this chapter, the emphasis is given to the importance of the storage unit in the Microgrid. Without the storage unit, the problem with the fluctuating voltage is solved when the Microgrid is connected to the storage. The importance of the storage unit is more seen when the additional power produced by the PV array and improving the efficiency of the system. In the next chapter, the Microgrid is connected to utility grid, by which it can share its energy.

CHAPTER 5

GRID INTERACTIVE MICROGRID OPERATION WITH STORAGE

The grid connected operation of Microgrid is an important aspect to be considered when the power quality aspects are considered. The grid condition can be said to be in critical state when the frequency or the voltage is out of limits. This chapter deals with the power quality aspect of the utility grid [7],[19].

5.1 Grid connected Microgrid model

The micro grid is connected to the main grid using an inverter. With the limitation of the number of DC link voltage used, a leg inverter is used for the analysis. The power flow into or out of the utility grid is decided by the reference currents as the voltage is maintained as that of the utility grid.

The reference value of current are tracked using hysteresis current control, and the reference values of the current are obtained by Instantaneous Symmetrical Component Theory, which will be discussed subsequently.

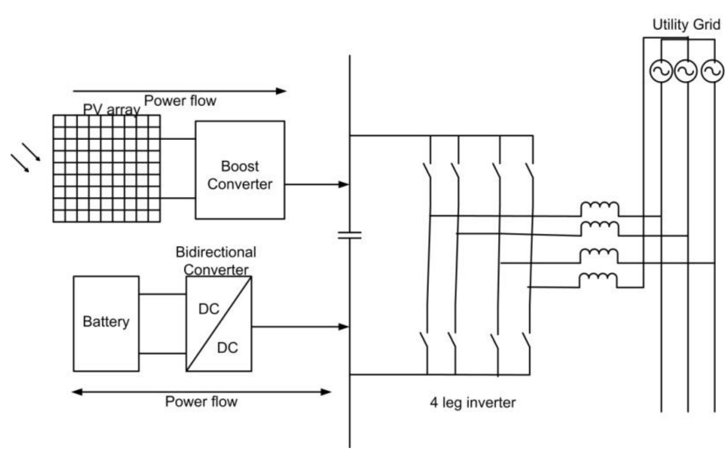


Figure 5.1 Diagram showing Microgrid connected to utility grid

5.1.1 Control of Microgrid Model

The utility grid connected is connected to many micro grids and share active and reactive power with each of them. Due to many nonlinear loads, the maintenance of the voltage and frequency in the certain limit is always a challenge to the utility grid. The Microgrids connected to the utility share the responsibility to maintain the values of voltage and frequency of the utility grid by supplying the required P and Q. The required value of the active and reactive power is sent to the local Microgrid so as to be injected into the utility grid for improving the power quality.

The Energy Management System calculates the real and reactive power required from each of the local power centers and communicates this information. The local controller controls the inverter in order to have to satisfy the power requirement from the EMS.

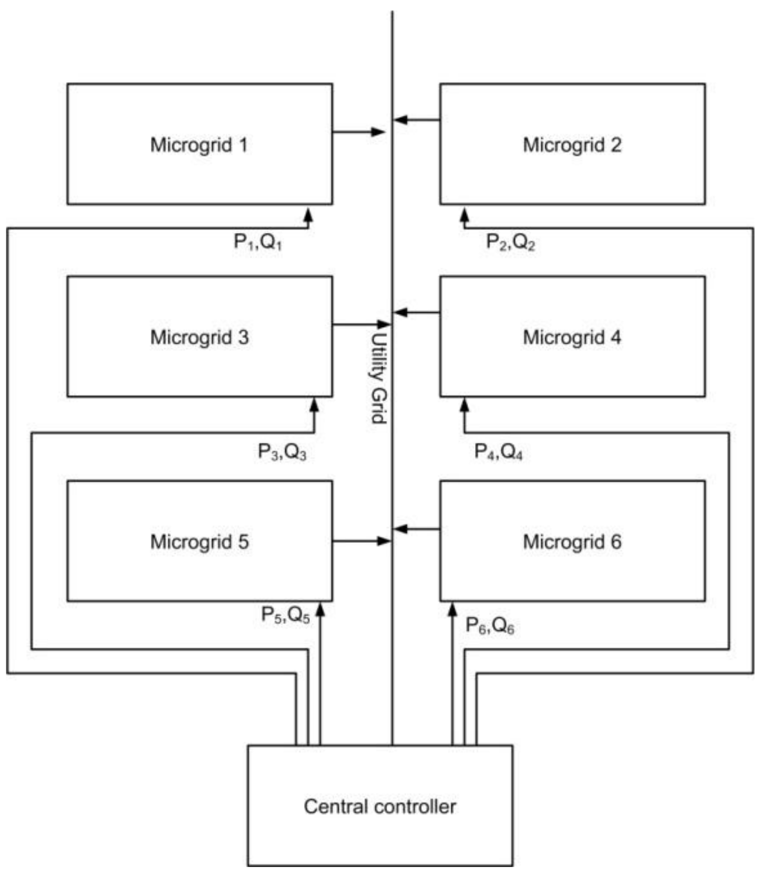


Figure 5.2 Central controller giving reference to local controllers

5.1.2 Instantaneous symmetrical component theory

Instantaneous symmetrical component theory helps in calculating the reference values of currents required by the inverter in order to provide the required active and reactive power. Since the inverter is connected to the grid; the power into or out of the grid can be controlled by the current value. Thus, it is current control which will also control the power into or out of the Microgrid [20].

$$i_{fa}^{*} = i_{la} - \left[\frac{v_{sa} + \beta(v_{sb} - v_{sc})}{v_{sa}^{2} + v_{sb}^{2} + v_{sc}^{2}}\right] P_{lav} \tag{5.1}$$

$$i_{fb}^{*} = i_{lb} - \left[\frac{v_{sb} + \beta(v_{sc} - v_{sa})}{v_{sa}^{2} + v_{sb}^{2} + v_{sc}^{2}}\right] P_{lav} \tag{5.2}$$

$$i_{fc}^{*} = i_{lc} - \left[\frac{v_{sc} + \beta(v_{sa} - v_{sb})}{v_{sa}^{2} + v_{sb}^{2} + v_{sc}^{2}}\right] P_{lav} \tag{5.3}$$

Here, $i_{fa}^{*}, i_{fb}^{*}, i_{fc}^{*}$ are the reference currents in order to achieve the required P and Q, β is calculated from the Q value which is $\beta = \frac{tan\emptyset}{\sqrt{3}}$. $v_{sa,} v_{sb,} v_{sc}$ are the central grid voltages and the load currents are $i_{la}, i_{lb,} i_{lc}$.

The reference voltages are tracked using hysteresis current control, by which the switching of the inverter is carried out and the required P, Q are transmitted by the Microgrid.

5.2 Grid connected operation of Microgrid model

Microgrid can be either islanded mode or grid connected mode. The project considers DC loads as the man loads, hence the previous chapter, where the PV array is connected to the storage device is the islanded mode of operation of the Microgrid.

The grid connected mode of is carried out using a 4 leg 3 phase inverter and the switching to the inverter is executed by hysteresis control of the reference currents mentioned above. The inverter is connected to the grid and the required power is transmitted to the grid.

5.2.1 Case 1: Only Active Power Requirement

The following are the results when the simulation is carried out at P_{ems} =1000W and ø=0^o

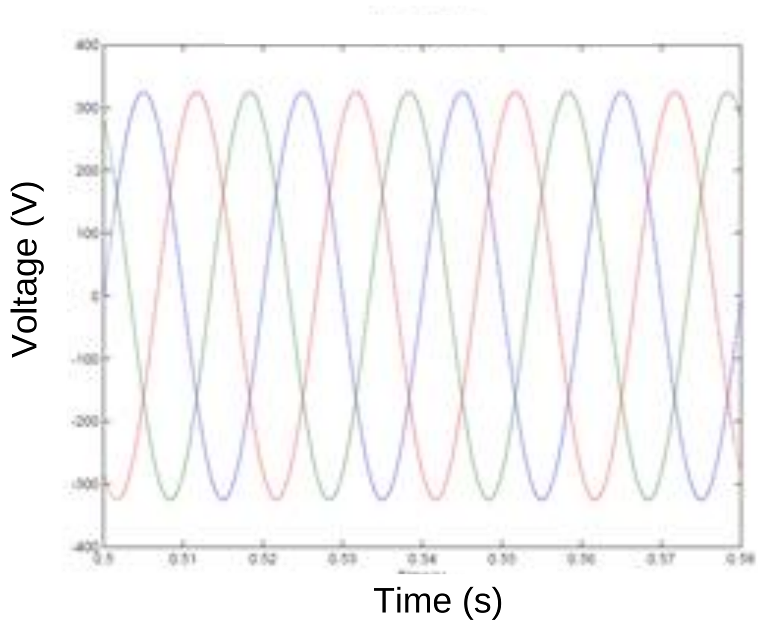


Figure 5.3 Grid Voltages

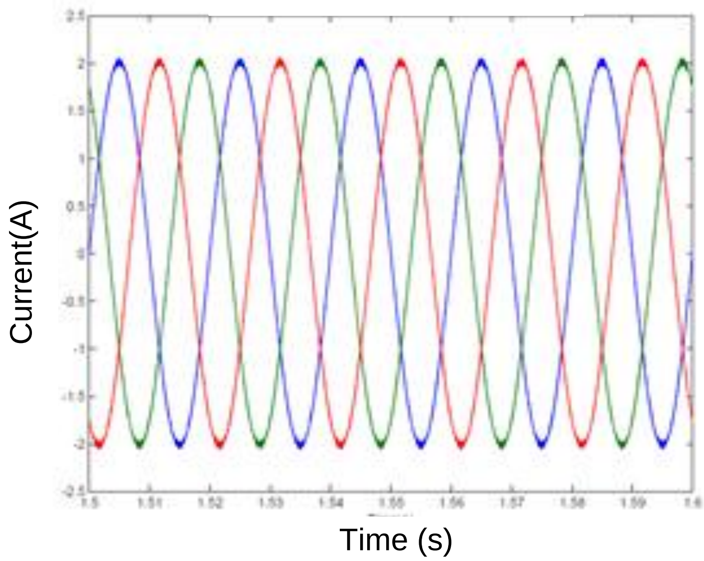


Figure 5.4 Tracked Current

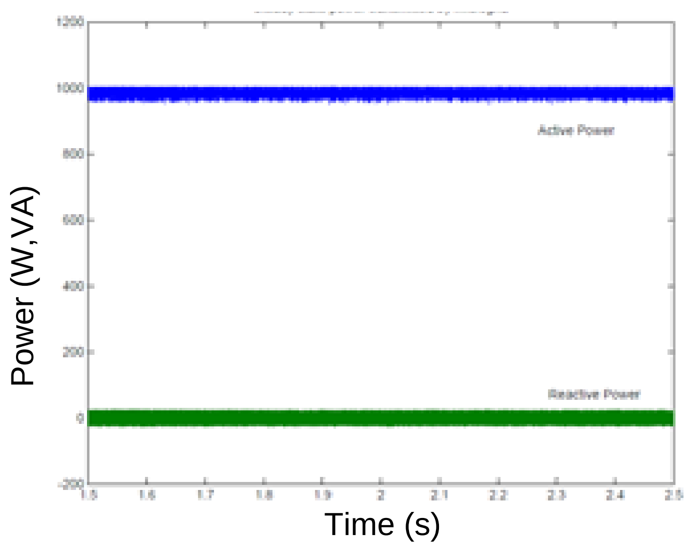


Figure 5.5 Power transmitted by the Microgrid

We can observe from the Figure 5.5 that the power of 1000W is being transmitted by the Microgrid with no reactive power. The current is tracked to the reference value and is shown in the Figure 5.4 and the grid voltages are shown in the Figure 5.3

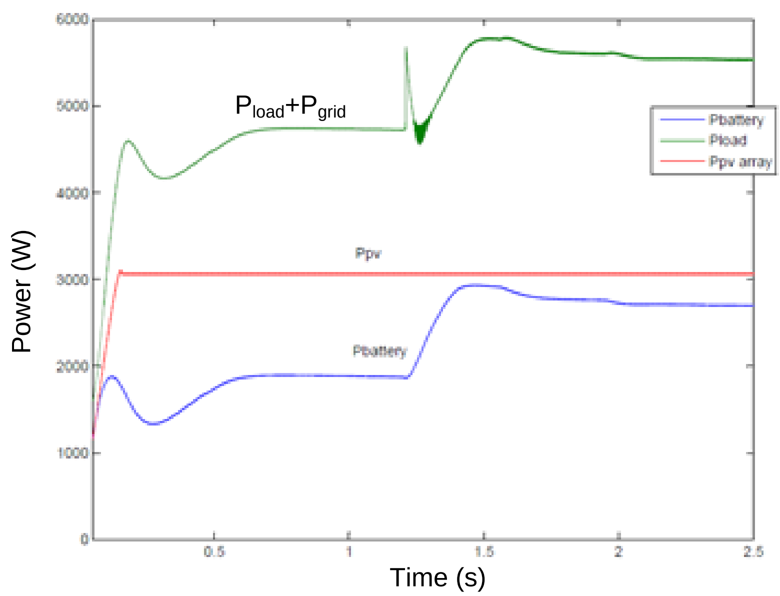


Figure 5.6 $P_{battery}$, P_{load}+P_{grid}, P_{pv} variation with time

From the 0-1.25s the Microgrid was working under islanded mode and the power balance is the same as shown in the previous chapter. After the Microgrid is connected to the utility grid, the additional power is supplied by the battery, so there is a sudden rise in the power supplied by the battery in Figure 5.6. Since the battery in the islanded mode was working under the boost operation, with the addition of the new load, the stress on the battery increases.

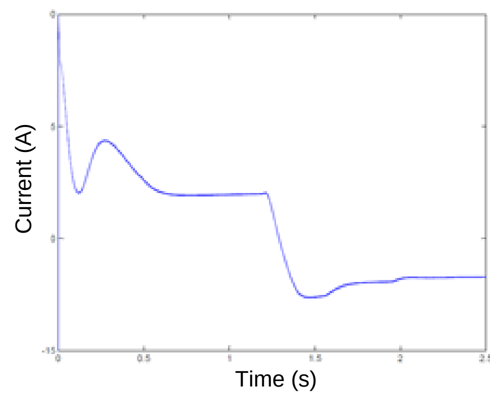


Figure 5.7 Variation of Battery current with time

As previously explained in the, the stress on the battery will increase as it supplying power into the grid, which can be observed from the Figure 5.7. Initially during the islanded mode the current required get stable around 8A, when an additional 1000W is to be injected into the utility grid, the current discharged further increases and settles around 12A.

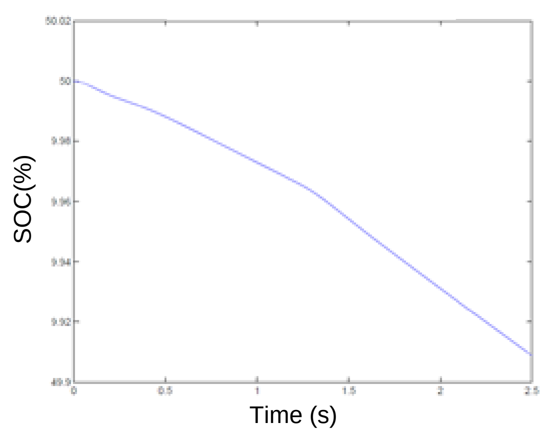


Figure 5.8 SOC of battery

From the Figure 5.8 a small change in slope is seen at 1.25 s where the grid is changed from islanding mode to grid connected mode. The battery voltage is shown as in Figure 5.9.

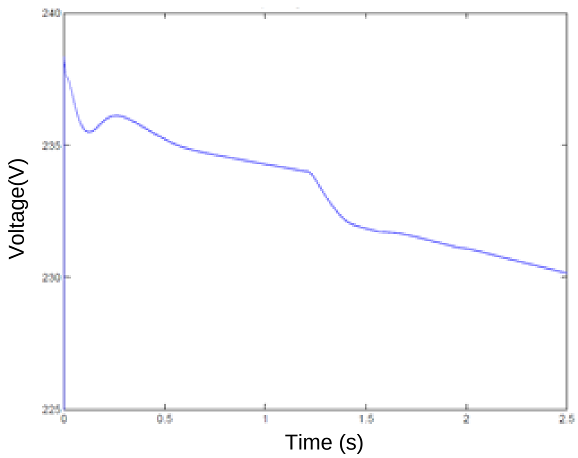


Figure 5.9 Battery voltage

5.2.2 Case 2: Both Active and Reactive Power

The EMS power requirement can be both take active and reactive power, to analyze the following, we consider P and Q values at two different values of ø and the results are analyzed.

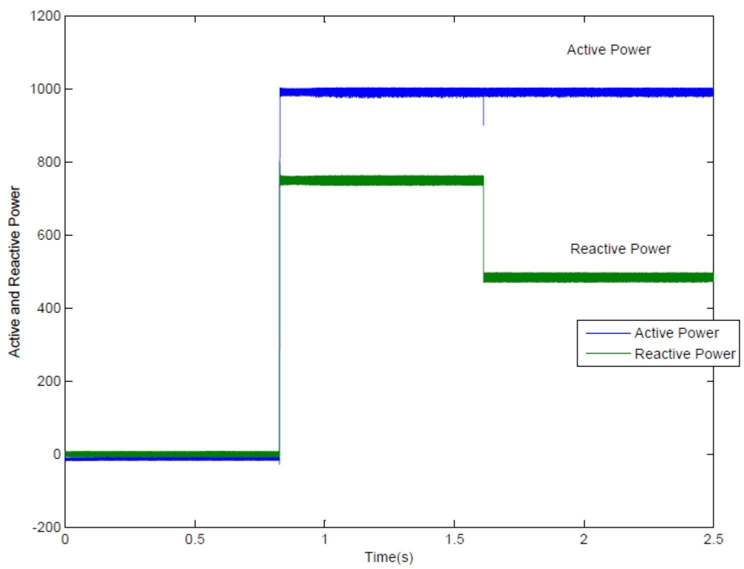


Figure 5.10 Power Variation with time

From the Figure, it can be observed that the grid is in islanded mode from 0-0.8s and then an EMS command of P=1000W and ø=36.86^o is communicated with the local controller from 0.8-1.55s then the command to the local controller is change from previous value to new ø=25.84^o. The current waveforms are as shown in the Figure for the following P and Q requirements from the EMS.

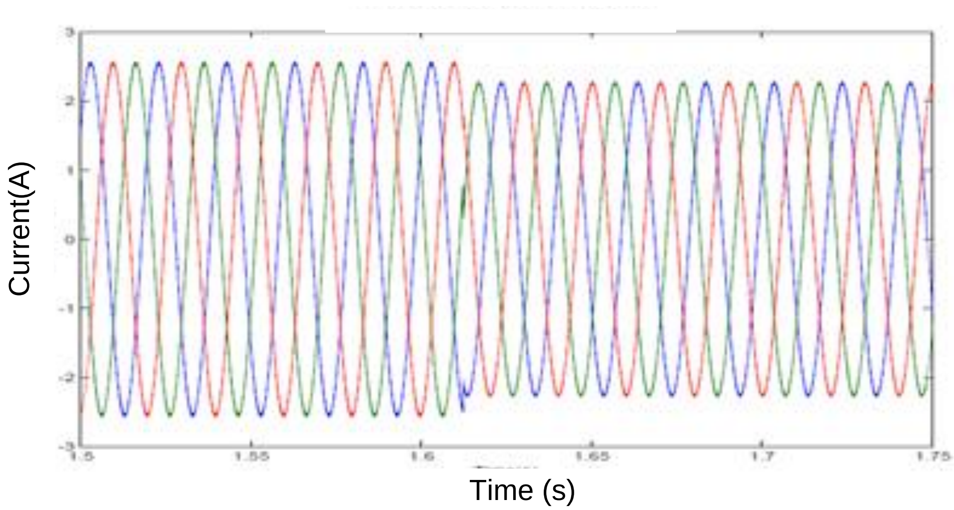


Figure 5.11 Current injected into the utility grid

From the Figure 5.11, it can be observed that the current magnitude varies when the requirement of Q decreases. Initially the current required for operating at the required ø is more when compared to that to the later value, which can be observed from the Figure 5.11. Since the value of the Q needed is being reduced, the amount of current required to transmit the same will also decrease, in this case a drop of 0.2A is observed.

The power balance of system will remain the same as the active power is the same as in the previous case as shown in the Figures 5.6 and 5.12

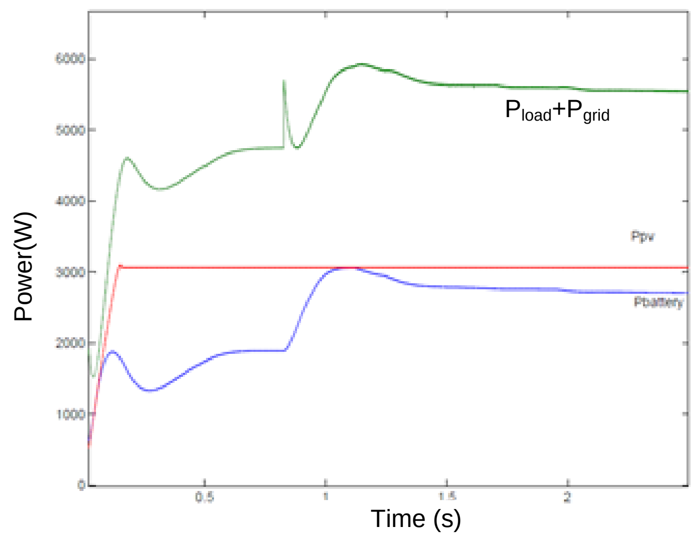


Figure 5.12 $P_{battery}$, P_{load}+P_{grid}, P_{PV} variation with time

The other waveforms will be same as to that of the previous case when the active power injected is zero. In this chapter the effective integration of the Microgrid with the utility grid is explained.

5.3 Energy Management Algorithm

With the fluctuating input power from the power source, and the varying state of charge of the battery, the choice between the buck mode of operation and boost mode of operation is important, also the amount of power that is to be transmitted into the grid. The following algorithm in the chapter analyses few parameters and a decision is taken on the mode of conversion of the buck converter and also the power to be transmitted to the grid.

5.3.1 Energy management

For the effective usage of the energy, the following algorithm is implemented

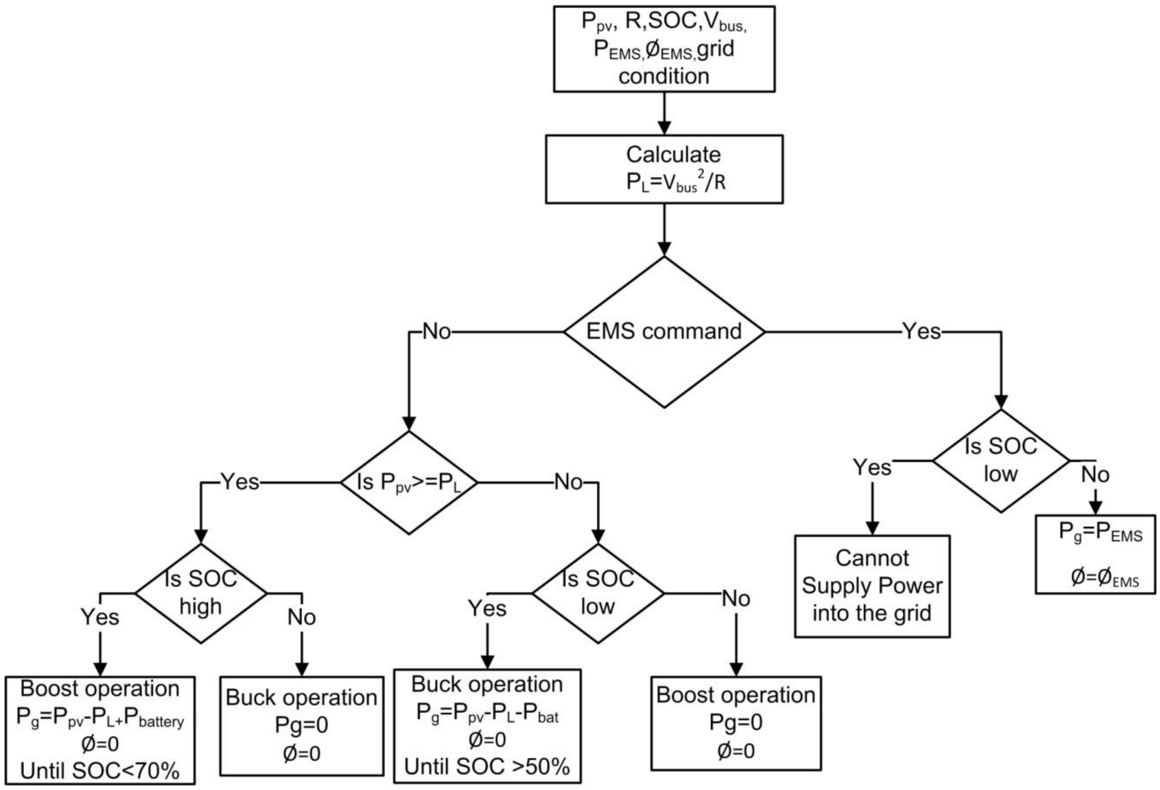


Figure 5.13 Algorithm for energy management in the Microgrid connected to utility grid

The algorithm is proposed in the basic view of the localized energy usage in an area. Initially the grid condition is checked, if the grid is operating in a condition where the voltage and the frequency are within the permissible limit, the normal operation of Microgrid is carried on. If the voltage or the frequency requirement is out of the permissible limits, the command from the EMS is analyzed and the required amount active and reactive power is transmitted into the grid.

If the grid is in normal operation, if the power produced by the PV array is more than the required power by the load, usually without storage unit the voltage of the DC bus would rise above the required value, but the additional power produced is absorbed by the battery by buck operation and the voltage is maintained at a constant value. In the algorithm the SOC is taken into consideration. If the power produced by the PV array is more than that of the load, the state of charge of the battery is checked. If the SOC of the battery is greater than a limit(usually 80-90%), the battery starts discharging until the SOC is 70% and later since the SOC is less than the limit, it acts like a buck converter and absorbs the additional power to maintain the DC voltage constant.

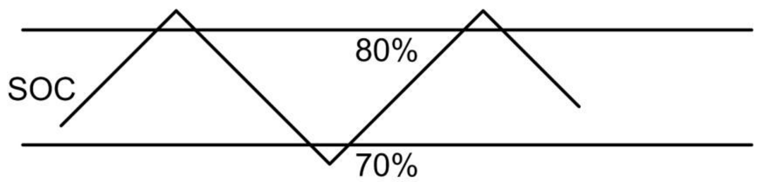


Figure 5.14 SOC upper band

If the grid is in normal operation, and the power produced by the PV array is less than the load required, the battery operates under the boost operation and the required power is injected into the grid so as to maintain the grid voltage. The battery cannot be operated below certain limit (usually 30-40%), so when the SOC is less than a certain limit the battery, the battery boost operation should stop so as to not discharge above a permissible limit. Thus, if the SOC is less than the permissible limit, the boost operation is stopped and battery is charged by absorbing the power from the utility grid. If the battery is charged until the SOC reaches 50%, then the SOC is greater than minimum value, hence the boost operation can be continued in order to maintain the required voltage.

The algorithm can be observed to be more localized and interacts with the utility only if it energy deficient and the energy source is undercharged or when energy surplus and the battery is fully charged. It is to be noted that the utility grid is assumed to be always available. The concept of brownout can be used in to make the utility grid always available.

5.3.2 Simulation and Results

The above mentioned algorithm is simulated and the following results are observed. It is to be noted that the battery charge capacity is decreased in order to have better observation on SOC variation during simulation.

5.3.2.1 Upper Limit Mode

In the first case battery reaching the upper limit of SOC is analyzed. The SOC is initialized at 79.99 so that the observation is easier during the simulation. The upper limit of SOC is at 80%. Initially the Power from the PV array is more than that of load power, hence the buck operation is carried out and the battery gets charged. The SOC is limited to certain value, if the SOC crosses the upper limit, the buck operation and the battery is discharged. The discharge is carried out until a specified point (usually a band is assigned if SOC>80% discharge until 70%). For the simulation convenience, 1Ah battery is used. The upper limit is taken to be 80% SOC.

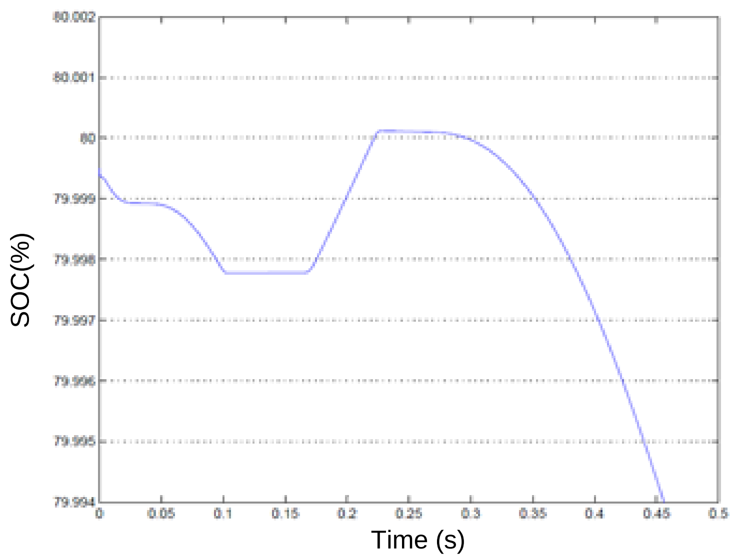


Figure 5.15 Zoomed in version of SOC variation

It can be observed from the Figure 5.15; the SOC initially decreases due to the MPPT takes time to reach its maximum power position, later on when the power produced by the PV array is more than the lad power, the battery charges by buck operation, the moment the SOC reaches 80% the boost operation is triggered and the additional power is transmitted into the grid. From the Figure 5.15, it can be observed that the when the SOC reaches 80% the boost operation is started at around 0.25s and the battery gets discharged by the additional power being transmitted into the grid.(In this case ~1200W). An EMS command is sent to the local controller so as to transmit a power of 2000W at ø=25.84. The Power transmitted by the Microgrid is shown in the Figure

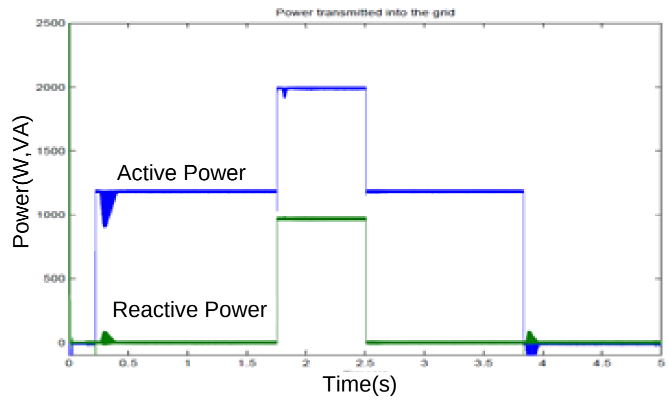


Figure 5.16 Power transmitted into the grid

The communication by EMS occurred at around 1.75s to transmit the required power, and again communicated at 2.5s to stop the power transmitted. It can be noted from the SOC value in the Figure 5.17 that the drop in the curve after 1.75s is more than the previous value, and after 2.5s as the power transmitted is less than the previous value of 2000W required by the EMS, hence the slope becomes less negative. Even after 2.5s, the Power of the PV array is more than the load power, and the SOC didn't reach the upper bands minimum value, hence the battery still discharges. At 4s the load power is increased in order so that it is greater than that of the PV array power production, since the consideration of the local loads are given importance, the power transmission into the grid is stopped as shown in the Figure 5.16. The power needed to compensate and maintain the voltage is greater than to the previous case; hence the SOC rate falls faster from 4s from the previous value.

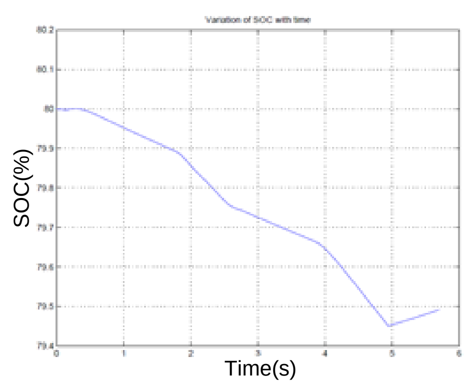


Figure 5.17 Variation of SOC with time

The lower limit for the upper band is maintained at 79.45% of SOC (for easier simulation), hence after reaching the lower limit of the band, then at around 5s the load is changed to previous value and the lower limit is reached, hence it acts in normal mode, as the power produced by the PV array is more than that of the load power, the excessive power is stored in the battery and the it can be observed from the Figure 5.17 that the SOC increases after 5s

Table 5.1 Timeline of Upper Limit Mode Simulation

Time	Actions/Conditions	Effect
0-0.2 s	System is started(P_L<P_{PV})	Initially discharged and then charged
0.2 s	% SOC > 80 %	Upper limit mode activated
0.2-1.75 s	Upper limit mode active	Transmits power into the grid
1.75-2.5 s	EMS contacts with requirement	2000W, 1000VA Power is transmitted
2.5 s	EMS contacts to stop transmission	Power transmission stopped
2.5-4 s	P_L<P_{PV}, Upper limit mode active	Transmits power into the grid
4-5 s	P_L>P_{PV}	Power into grid stopped
~5 s	% SOC < 79.45 % , P_L<P_{PV}	Upper limit mode deactivated, charges battery

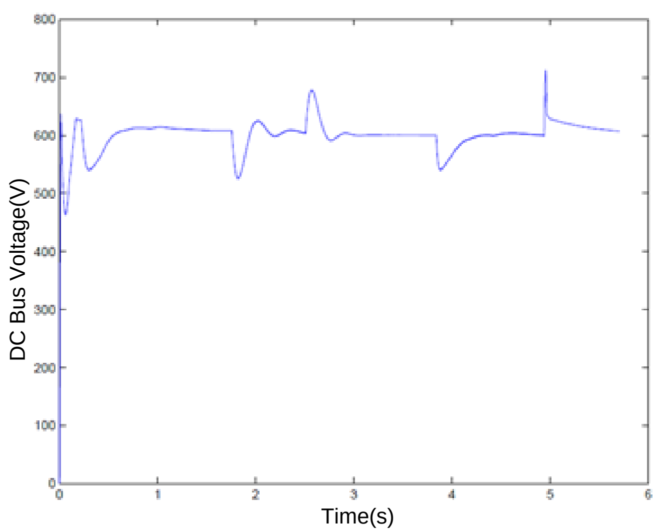


Figure 5.18 Voltage of DC bus

The voltage of the DC bus is maintained constant with variations during the switching from one power requirement to another. The current of the battery follows the pattern and behaves as shown in the figure.

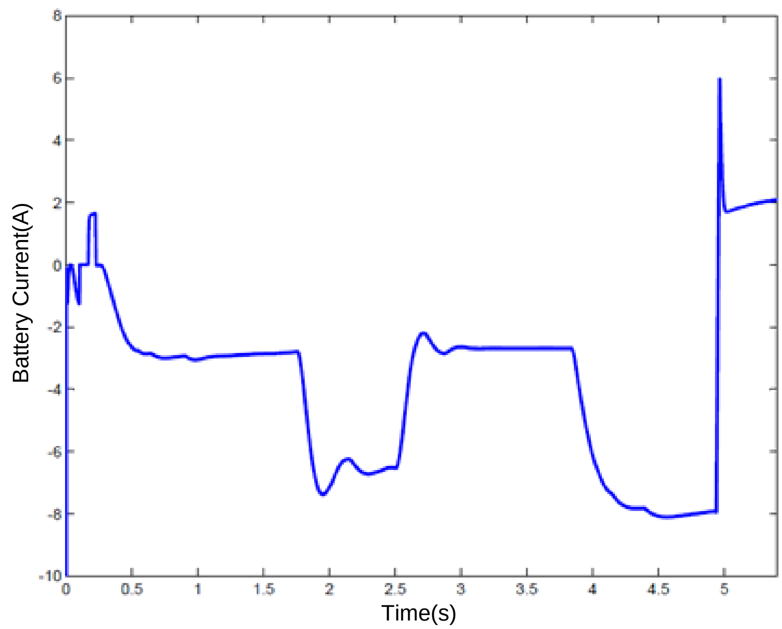


Figure 5.19 Variation of battery current with time

Hence, the following observations are made. Similarly the same process is done for lower limit band so as to validate the model.

5.3.2.2 Lower Limit Mode

The simulation is carried out at the lower limit band the observations are noted, the SOC initially is 50.04%. Initially the power from the PV array is less than that of the load power; hence the battery is used in boost condition in order to maintain the required voltage by supplying the power into the DC side bus. As the battery is discharging the current, the SOC value decreases. When the SOC value reaches to the minimum value of the lower limit band (in this case 49.94%), the lower limit mode is activated and the battery is in critical state and cannot be discharged more. Note that the EMS requirement is zero always when the SOC is low as the grid itself is supplying power to make it charged, but after the battery is in normal mode the EMS can contact the local controller for the required power as before.

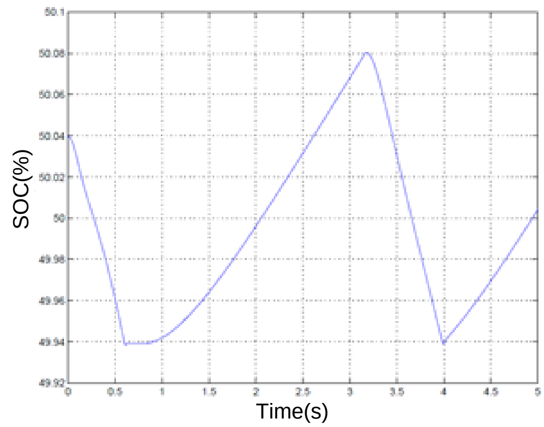


Figure 5.20 State of Charge of the battery

It can be noted from the Figure, that the SOC reaches the minimum value lower limit band at around 0.5s and now since the power cannot be supplied from the battery, the Microgrid absorbs the power from the grid not only enough to supply the additional power needed but also some power to charge the battery.

The battery is in buck mode and the grid transmits power in order to charge the battery and also to bridge the gap between the required energy and the produced energy by the PV array. The following Figure shows the amount of power transmitted to the grid, which should be negative as the Microgrid is absorbing the power, this can be observed in the Figure 5.21.

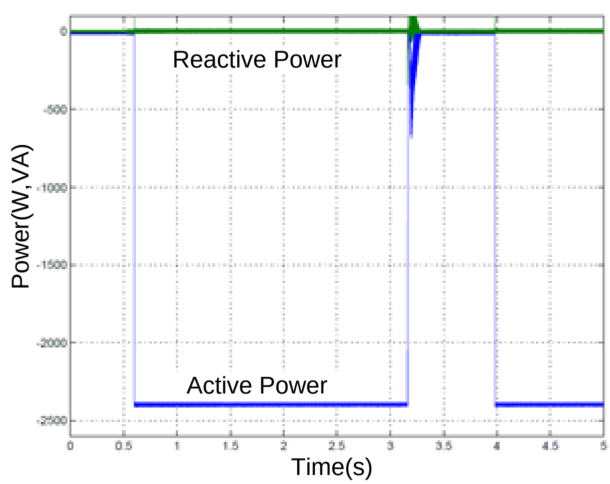


Figure 5.21 Power transmitted into the grid

As already noted, initially the power transmitted into the grid is zero as the battery is capable of supplying the additional power requirement by the load. After the battery discharges and hits the lower limit, then the power is absorbed by the Microgrid until, the battery is charged and reaches the upper band of the lower limit (in this case 49.94) . Later on after reaching the upper band of the lower limit, the battery is capable enough in supplying the additional power requirement by the load. As the load power still remains more than the power produced by the PV array, the battery is discharged again and until reaches the lower limit again.

Table 5.2 Timeline of Lower Limit Mode Simulation

Time	Actions/Conditions	Effect
0-0.6 s	System is started(P_L>P_{PV})	Battery discharges
0.6 s	% SOC < 49.94 %	Lower limit mode is activated
0.6-3.2 s	Lower limit mode is active	Absorbs power from the grid
3.2 s	% SOC > 50.08 %	Lower limit mode is deactivated
3.2- 4 s	P_L>P_{PV}	Battery discharges
4 s	% SOC < 49.94 %	Lower limit mode is activated
4-5 s	Lower limit mode is active	Absorbs power from the grid
~5 s	System is stopped	-

The current varies as shown in the Figure 5.22

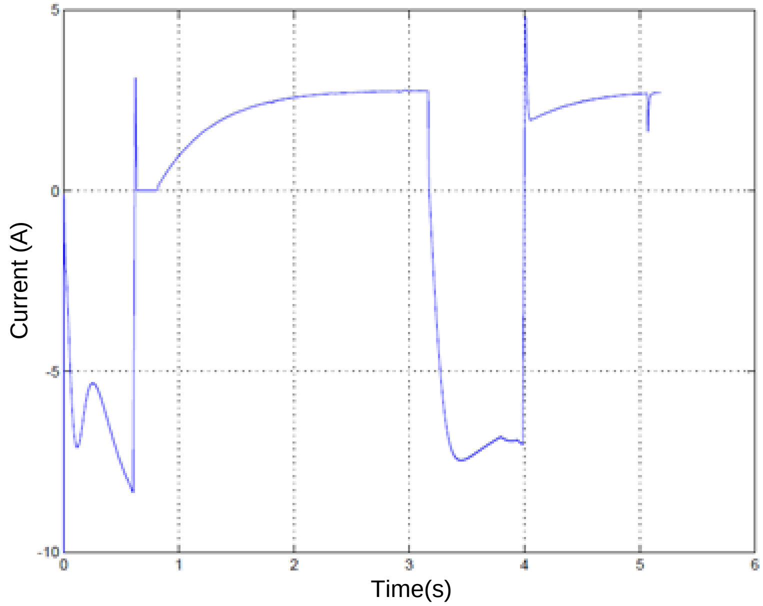


Figure 5.22 Current variations with time

As already mentioned above in the timeline, the current behaves the same way it is expected to be, initially the current discharges to hit the lower limit, then additional energy is taken from the utility grid in order to charge the battery and the compensate the additional power requirement. Then, after getting charged up to a certain extent, the SOC reaches the upper limit of the lower band, and then the current again discharges from the battery until it again reaches the lower limit at 4s, by which again the power is absorbed from the grid and the battery is charged.

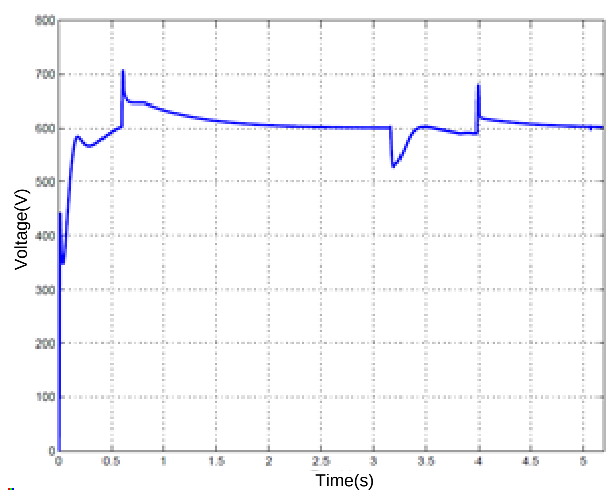


Figure 5.23 Variation of voltage with time

5.3.3 Merits of the algorithm

There are many merits for the following proposed algorithm, the main merit is that it is a localized algorithm than which interacts with the grid regularly. The grid is only contacted for power if there is any deficiency in power and the battery cannot supply the because of low SOC or if these is an excess power production and the battery is nearly fully charged and charging it more will be inefficient.

Few merits are listed below

- Localized algorithm, by which the transmission is near the load center, lower transmission losses
- Can even work under brown out condition
- Top priority loads are the internal loads
- Usage of solar power
- After the internal loads satisfy, the excess power is transmitted into grid
- The battery SOC is maintained above lower limit without fully discharging the battery
- The battery SOC is maintained below upper limit without over charging the battery
- Can provide electrical energy at remote places

5.3.4 Summary

In the following chapter, an algorithm for the effective utilization of energy is proposed and the simulation is carried out. Since, the battery cannot be overcharged or under charged, this algorithm maintains the SOC of the battery in limits. The results are discussed emphasizing on the working of the algorithm. And then, the merits of the algorithm are briefly mentioned.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

The central objective of the project is to effective utilization of the energy produced using solar array and the effectively managing the energy with the utility grid. To achieve this, an MPPT algorithm is implemented for utilizing the maximum power produced by the PV array and an algorithm for interconnection between the grid and the Microgrid is proposed.

6.1 Conclusion

The Microgrid integration with the utility grid will help in the effective utilization of the renewable sources not only improving the quality of the grid, but can be useful in remote places and helps in energy inclusion of India.

Initially the PV grid is simulating the equivalent circuit which acts as the primary source and the battery as the storage unit. Owing to the non-linearity of power voltage and power current relations of the PV array, a Maximum power point tracking algorithm is proposed using Perturb and Observe method. A boost converter is used to realize this operation.

A control algorithm is also proposed so as to control the voltage of at the DC bus side at a constant value with the help of an energy source. In grid connected mode instantaneous symmetrical component theory is used to track the current and the switching to the 4 leg inverter is done using hysteresis control.

In a sample simulation of 24 hours, approximately 6kWh energy is produced by the PV array on an average on January 1 of the year using MPPT. This power is essentially used for by the internal loads or transmitted into the grid. Which is said to increase the power about 50% to what is produced without MPPT [21]. Using MPPT and the control models around 6kWh of the solar power can be effectively utilized. The additional power produced by the Microgrid can be transmitted or can be shared among different Microgrids for better usage of the energy produced.

6.2 Future Scope

The main aspects to be considered for a battery is the SOC and the discharge currents, these currents have to be smooth in order to have sustainable use of the battery, hence using a super capacitor to supply the additional fluctuating current needed and a constant current with less fluctuations can be provided by the battery for having a better lifetime.

The algorithm does not take time or the grid condition when the power production is less, which means that the Microgrid can ask for more power even when the utility grid is under stress due to excess loads. The same algorithm can be made time dependent and can charge the energy sources during nights when the load values are low and buy these units at lower cost and can transmit the power at a higher cost during peak load condition.

The unavailability of the utility grid condition can be explored, and the survival of the Microgrid during that condition using the present algorithm can explore few adaptive control values to fix a certain SOC, for which the critical condition of low SOC won't occur even if the utility grid is unavailable for some time. With the penetration of Microgrids, the proposed algorithm can be extended to practical usage. Further a pilot project on the implementation of the algorithm is also an option. Based on the results, it can be extended to real Microgrid systems.

APPENDIX A

6-FMX-150B Battery Specifications

Normal Voltage	12V
Capacity	150 Ah @ 10hr to 1.80V per cell @ 25℃(77℉)
Weight	Approx. 48 kg
Internal Resistance (full charged)	Approx. 4.2mΩ @ 25℃(77℉)
Maximum Discharge Current	1090A (5sec)
Self Discharge @ 25℃ (77℉)	Less than 8 % after 90 days storage
Operating Temperature Range	Discharge: -40℃～50℃(-40℉～122℉) Charge: -20℃～45℃(-4℉～113℉) Storage: -20℃～40℃(4℉～104℉)
Recommended Operating Temperature	15℃～25℃(59℉～77℉)
Maximum Charging Current Limited	30A
Charging Voltage @ 25℃(77℉)	Float: 2.25 V/cell,Temps coefficient -3mV/ cell • ℃ Cycle: 2.35 V/cell
Container Materials	ABS
Terminal	M6 and TU_2
Capacity Affected by Temperature	105 % @ 40℃ 85 % @ 0℃ 60 % @ -20℃

Constant Current Discharge Characteristics Unit: A (25℃, 77℉)

F.V/Time	30min	1hr	2hr	3hr	4hr	5hr	6hr	8hr	10hr	12hr
1.70V	158.7	88.4	57.8	43.7	34.6	27.1	22.7	18.3	15.2	12.7
1.75V	150.0	85.6	57.1	42.9	34.1	26.8	22.5	18.2	15.1	12.6
1.80V	142.0	83.8	56.5	42.0	33.7	26.4	22.3	18.1	15.0	12.5
1.83V	135.8	80.2	55.8	41.4	33.5	26.2	22.2	18.0	14.9	12.45
1.85V	131.0	77.9	55.3	41.0	33.2	26.0	22.1	17.9	14.8	12.4

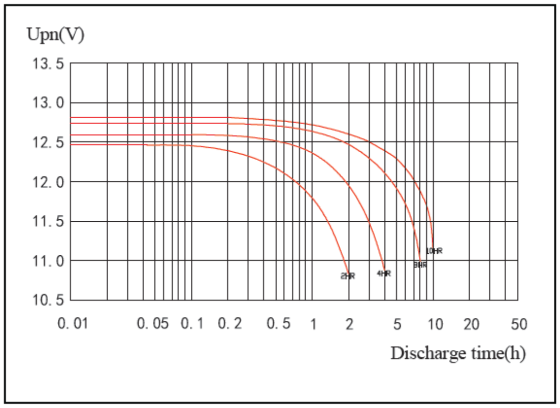
Constant Power Discharge Characteristics Unit: W/cell (25℃, 77℉)

F.V/Time	30min	1hr	2hr	3hr	4hr	5hr	6hr	8hr	10hr	12hr
1.70V	287.7	164.2	110.8	85.3	64.6	53.8	44.7	36.6	30.4	25.4
1.75V	275.7	161.3	110.1	84.1	64.0	53.4	44.4	36.4	30.2	25.3
1.80V	263.8	159.5	109.5	82.7	63.1	52.8	44.0	36.3	30.1	25.2
1.83V	255.1	154.2	108.8	82.1	62.6	52.4	43.7	36.2	30.0	25.1
1.85V	249.5	150.5	108.2	81.5	62.2	52.1	43.5	36.1	29.9	25

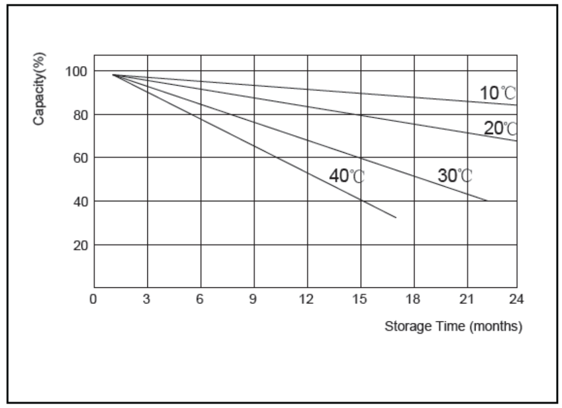
APPENDIX B

6-FMX-150B Battery Characteristics

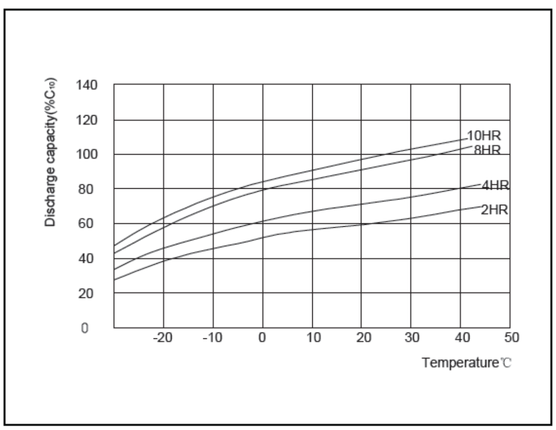
Discharge Performance at Different Discharge Rate



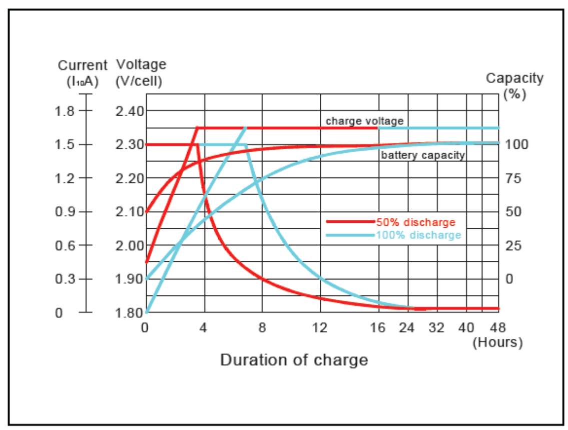
Curve of Self-discharge at Different Temperature



Capacity at Different Temperature



Constant Voltage Charge Characteristics



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