

SIMULATION OF A PV BASED MICROGRID ASSISTED BY FUEL CELL IN INDIAN SCENARIO

A Dissertation submitted in fulfillment of the requirements for the Degree
of

MASTER OF ENGINEERING *in* **Power Systems**

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DECLARATION

Certified that the dissertation entitled, “SIMULATION OF A PV BASED MICROGRID ASSISTED BY FUEL CELL IN INDIAN SCENARIO”, which is being submitted by **Ashutosh Nayan Dey**, in fulfillment of the requirements for the award of the M.E. in Power Systems, to Thapar University, Patiala, is a bona-fide record of the candidate’s own work carried out by him under my supervision and guidance. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other university or institute for award of any degree.

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NOMENCLATURE

R_{se} = Equivalent series resistance of PV system.

R_{sh} = Equivalent Shunt resistance of PV system.

N_{se} = No. of series cells in PV system

N_{sh} = No. of parallel cells in PV system.

I_{pv} = Current generated by the incident light in the cell.

I_0 = Reverse saturation current of diode

I = Output current

V = Output voltage

V_t = thermal voltage of the PV array

a = Diode ideality constant = 1.3

V_f = Fuel cell voltage.

E_n = Fuel cell Nernst voltage.

V_{act} = Activation losses

V_{ohm} = Resistance losses due to internal resistance.

V_{con} = Concentration losses.

G_f = Gibbs function constant for liquid = - 228170 J/mol.

F = Faraday constant = 96485.33 coulomb/mol

R = Ideal gas constant = 8.314 J/mol.K

t_k = Fuel cell temperature in kelvin.

t_c = Fuel cell temperature in degree Celsius.

P_{H_2O} = Water pressure (saturated)

P_{H_2} = Hydrogen partial pressure.

P_{O_2} = Oxygen partial pressure.

p_{air} = Air inlet pressure

p_{h_2} = Hydrogen inlet pressure

I_f = Fuel cell current

I_l = Limiting current = 1.4 Amp

I_0 = Exchange current = $10^{-6.912}$ Amp.

NOMENCLATURE (continued)

α = Transfer coefficient= 0.5

α_l = Amplification constant= 0.085

k= Mass transport constant=1.1

E_0 = Constant voltage (V).

K= Polarisation constant (Ohm)

i = Battery current (A)

i^* = dynamics of low frequency current (A)

i_t = Battery capacity extracted (Ah)

Q= Maximum battery capacity (Ah)

A= exponential voltage (V).

B= exponential capacity (Ah).

ABSTRACT

The first part of dissertation begins with introducing the concept of microgrid based on renewable energy resources, its relevance in Indian context with respect to application areas, benefits and challenges faced while building any microgrid plan. There is also a small brief regarding Govt. of India's movement towards smartgrid initiatives and related programs which are in pipeline.

In the next part of the thesis, we move towards modeling and simulation of a proposed photovoltaic based microgrid model assisted by fuel cell and battery to secure the load demands of Thapar University hostel building. The simulated model achieves effective synchronization of the renewable energy source with grid and is able to study the exchange of bi-directional power flow with the grid, throughout 24 hours of a given sample day. This model is robust in nature considering the fact that the proposed system was simulated with dynamically varying input irradiance level and temperature throughout the day based on real ground data of the site.

The modeled system is able to show satisfactory behavior while operating in grid connected as well as islanded mode and is able to meet the load demands of hostel. The simulation results are found satisfactory at this preliminary level of planning and design and this approach would be useful as a base to simulate and study various aspects of microgrid operation prior to actual future on-site installation.

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Growing global warming, concerns over environmental effect and depleting fossil fuel reserves has compelled everyone to look for alternative sources based on renewable energy. According to a report by IEA [1] without new policies, the growing energy demands all over the world will double the polluting emissions by 2050. This necessitates for stepping up our efforts to increase energy efficiency by reducing losses and integrating microgrid/ smartgrid concepts with renewable energy technology.

Unlike western countries having access to reliable and quality power at all times of the day, most of developing countries in Asia and African regions face power outage regularly and frequently. Though India has 3rd largest T&D (Transmission and Distribution) network in the world [2], but at the same time it suffers from an aging power infrastructure because of under-investment in modernizing its grid network. This along with poor management has led to a notorious grid which is unreliable, suffers from poor power quality, has inadequate grid coverage and massive losses in almost every aspect of power distribution. All this calls for our transformation towards smart microgrids which will provide more reliable and efficient power .

1.2 MOTIVATION

Implementing renewable energy based microgrid concept inside a university campus as compared to applications at other commercial places has lots of advantages, especially since these microgrid testbeds can act as a live project for interaction between researchers/ industry and the lessons learnt from these installations shall prove beneficial in future while building smart cities. From business prospects, building of university microgrids has huge untapped potential, given the massive number of institutions that India has along with the country's favorable geographical location which makes it a hotspot for solar energy potential [3].

This motivation led to the idea of working towards modeling and simulation of a proposed microgrid to meet the load demands of one of the hostels inside Thapar University campus.

1.3 OBJECTIVE OF DISSERTATION

- i) Preparation of a survey report on relevance of microgrid in India's perspective.
- ii) Study and design of a PV system equipped with appropriate MPPT and boost converter which will be robust enough to include the effects of climatic conditions and give a dynamic power output.
- iii) Design of fuel cell which can be integrated to assist the PV system.
- iv) The designed system must synchronise with grid and should be able to exchange power bi-directionally at all times of the day.

The designed system will be built as a case study for proposing a PV based microgrid for meeting load demands of Hostel-J inside Thapar university campus.

The output of the designed model should help in real-time estimation of solar potential and subsequent power exchange with grid. Since the model would be analysed based on-site data, hence this model should serve as a precedent for further studies to propose a microgrid system in near future in our university campus.

1.4 OUTLINE OF DISSERTATION

The motivation and objectives of this dissertation are presented in Chapter 1 while Chapter 2 deals with review on the background theory of renewable energy and microgrid from Indian perspective. This chapter ends with identification of research gap in PV based modeling and the approach of this dissertation towards it.

Chapter 3 provides description of the proposed microgrid and details about the model's constituent components. Chapter 4 begins with planning and methodology on how input climatic data and other details required for simulation were obtained besides briefing about the principal of operation. The same chapter 4 then moves towards discussion and analysis of simulation results. Conclusions and scope of future work are discussed in Chapter 5. Towards the last page of this dissertation work, there is an Appendix which contains the complete MATLAB model of the designed system.

2.1 STUDY ON MICROGRID

2.1.1 REVIEW ON CONCEPT AND ARCHITECTURE

Microgrids are basic building blocks of a futuristic smart super grid ,which in coming decades will revolutionize the power sector by ushering an era of energy revolution just like the internet. In absence of any particular standard definition, there has been a lot of literature with varied definition of microgrids which keeps evolving but the most cited definitions are of [4],[5]. Making a similar effort, the author of this dissertation defines microgrid as a self-sustaining energy model able to generate, distribute and control bi-directional flow of power within its small boundary of operation in a coordinated way with focus on integration of non-conventional sources for power generation like solar panels, wind turbines, geothermal power, biomass power, tidal power etc. An important point to note is that we donot have control over climatic conditions for most of the above mentioned renewable resources and hence along with them, we need to have energy storage systems like fuel cell, super conducting magnetic storage systems, flywheel, supercapacitor, battery bank etc. Details on these can be studied in [6]. To manage the complex operation we need to have a microsource controller which will control the parameters of the individual microsources while another central controller will control the overall system parameters. Issues and details related to microgrid control are covered as in [7],[8]. Also a microgrid will need to protect itself from probable disturbances in main grid during grid connected mode as well as be stable enough to handle the internal disturbances. Accordingly, protection need of a microgrid in grid connected mode as well as islanded mode is different and complex. Literature concerning the protection issues in microgrid can be seen in [9]. Point of common coupling (PCC) serves as a junction between microgrid and the utility grid. A microgrid can function in either of two modes: “Grid connected mode” in which the microgrid can import or export power with the main grid as per its requirement or in the “Islanded mode” when it senses any disturbance in the main grid and isolates itself by switching on to islanded mode of operation thereby continuing to feed power to its critical loads only. Issues related to control, protection and stability of microgrid operation has been covered in [10].

2.1.2 NEED FROM INDIAN PERSPECTIVE

A. Basic access to electricity:

Power is one of the key infrastructural backbone for any country's economy. But even after so many years of independence, around 300 million people [11] in the country still don't have access to electricity either due to inhospitable terrains or administrative issues and bottlenecks. Standalone microgrids based on renewable energy potential of an area can provide an alternative solution.

B. Vulnerability:

Most areas in India are vulnerable to natural calamities like cyclone and floods during which large no. of areas suffer blackout for many days. "Sendai Microgrid" in San Diego, Japan [12], has successfully shown that it can operate in islanded mode and supply continuous power even when the entire town's power supply was disrupted during the Japan tsunami.

C. To Replace the aging power infrastructure:

Due to lack of absence of any big investment to revamp the decades old power infrastructure of the country, a lot of inefficiency has crept in resulting in massive losses. Thus we need to focus on distributed resources in the power sector which reduces losses as compared to modern day centralized generation.

D. To Reduce dependence on polluting energy source:

India generates more than 56% [13] of its power from coal and other polluting sources. Lately Govt. of India has started lots of initiatives as discussed later in this chapter to encourage renewable energy generation with aim of reducing greenhouse gas emission and thereby reducing pollution.

2.1.3 BENEFITS OF MICROGRIDS

Literature and details pertaining to benefits of microgrids can be found in [14],[15] based on which the following points have been summarized.

- i)* It will help to reduce feeder congestion and help in managing peak load demand on grid network with options like direct load control and pricing incentives for customers.
- ii)* It will reduce T&D (Transmission and Distribution) losses by approximately 3% because in conventional system, power generation is centralized and lots of power is lost in transmitting and

distributing power. In case of microgrids, generation sources are closer to loads and within community boundary, so these T&D (Transmission and Distribution) losses can be eliminated to a great extent.

(iii) Grid faults can often result in cascading effect and result in blackouts as was seen in India a few years ago. Such blackouts can have tremendous negative impact on country's economy and they also stall all other essential services. In such cases, microgrid can help improve the situation by operating in autonomous mode thereby preventing cascading blackout.

(iv) With most areas facing power cuts throughout the year, microgrid provides a better opportunity with reliable and better quality power leading to less fluctuation in voltages and hence improving the lifecycle of most domestic appliances.

(v) In microgrid concept, the "Consumer" becomes "Prosumer (Producer + Consumer), by having the decision making power according to which he can import/export power to the grid enabling two-way power transfer and having better control of energy access and consumption.

(vi) Consumers in remote areas, where grid extension is not possible can gain access to electricity by standalone microgrids.

(vii) By moving away from conventional fuels based power plants like coal or nuclear, we can reduce many of the environmental issues.

2.1.4 CHALLENGES INVOLVED AND WAY FORWARD

i) Indian market is generally cost sensitive, so the high cost of installing distributed energy resources makes the establishment of microgrid a cost prohibitive affair with long repayment period. But with recent technological advancements, these prices have decreased exponentially.

ii) Since Microgrid is an emerging concept hence it faces shortage of skilled hands for its installation, operation and maintenance.

iii) Protection and operational issues are quite challenging and complex ones as compared to conventional power system [16]. In conventional power plants, we can control output voltage by controlling input supply of raw material, but in microgrid we don't have any control over climatic conditions and thus there may be wide fluctuation in output. To solve this, we implement energy storage technologies but though these storage systems provide us flexibility of storing and

delivering energy depending on requirements, but due to high costs, addition of these extra components makes the whole system very cost prohibitive. But the cost of energy storage technologies are coming down quickly and in near future it's definitely a viable alternative.

iv) There is lack of technical regulations and standards in country which the government quickly needs to step up so as to needed to ensure uniformity in operation of individual microgrid market enterprises.

2.1.5 INDIAN MICROGRID MARKET SCENARIO

Though exact statistics are not available about no. of microgrid powered households or business units in India, but a rough approximation puts that number around 125,000 [17]. But most of these small Microgrid entities are generally based on solar panels and mostly concentrated to the villages of Uttar Pradesh and Bihar where private organizations like “Nature tech Infrastructure, Mera Gao Power, Kuvam, Husk Power Systems” and others are operating economically viable microgrid models, details of which can be obtained from their respective websites. Similarly few state governments like West Bengal, Chhattisgarh and Bihar have sponsored projects like “Sagar Island microgrid” in WestBengal. As per data collected from [18], the expected distribution of smart microgrid market components in Indian market is expected to reach \$ 1.9 billion by 2015 and its shown in Fig. 1

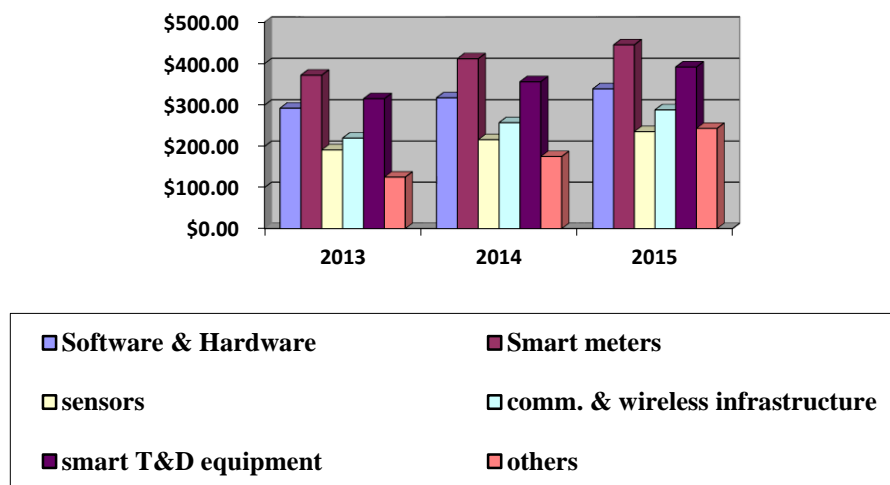


Figure 1. Smart Microgrid market distribution in India [18]

2.1.6 INITIATIVES TOWARDS SMART MICROGRIDS IN INDIA

HIGHLIGHTS OF SMART GRID VISION OF INDIAN GOVERNMENT

The vision of Ministry of Power for Indian power sector, is to “Transform the Indian power sector into a secure, adaptive, sustainable and digitally enabled ecosystem that provides reliable and quality energy for all, with active participation from all stakeholders”. To meet the above objectives, ISGTF (Indian smart grid task force) has prepared a roadmap for India in the document [19] and this contains the highlights of Indian govt.’s smart grid vision for future along with a comparison of plans & activities envisioned during 12th, 13th and 14th plan with respect to generation, transmission, distribution, policy, regulations and new technologies to be implemented as in [2].

In the past few years, Govt. of India has started lots of initiatives in these directions, prominent among them are mentioned below—

- i) *Institutional framework* [2]: Setting up of ISGTF (Indian smart grid task force) and ISGF (India smart grid forum) consisting of representatives from various organizations like Dept. of Science and Technology, Central Power Research Institute, Central Electricity Authority, Ministry of Renewable Energy.
- ii) *Alignment of ongoing activities with smart grid vision*: Programs like R-APDRP [20], Gramin Vidyutikaran Yojana, JNNSM solar mission, GIS mapping, consumer indexing, Smart billing system etc. which are presently in progress can be modified according to state specific policies within a uniform broad framework of standards, so that they those could be aligned with smartgrid mission.
- iii) *Launch of national smart grid mission*: A National smart grid mission (NSGM) has been targeted by govt. to be launched by end of this fiscal year and for this a National Board For Smart Grids has already been formed for holding consultation with all stakeholders and its likely to be given statutory powers for handling the entire process of developing and managing the necessary regulatory framework.

2.2 STUDY ON RENEWABLE ENERGY

2.2.1 PHOTOVOLTAIC SYSTEM STUDY

The basic building block of PV system are solar cells which can be further grouped to form modules and arrays. Basically a solar cell is a P-N junction which is fabricated as a thin wafer made up of two layers of semiconducting material, predominantly silicon. One side of the layer is doped with boron and other side with phosphorous, thereby producing excess electrons on one side and deficit on other side.

2.2.1.1 WORKING PRINCIPLE:

When sufficient sunlight hits on solar cell and incident energy is greater than band gap energy of semiconducting material then electrons are released creating a electron-hole pair for conduction. A current proportional to the incident radiation is developed and this is known as photovoltaic effect. A schematic figure showing the basic principle of working of a solar cell is given in Fig. 2

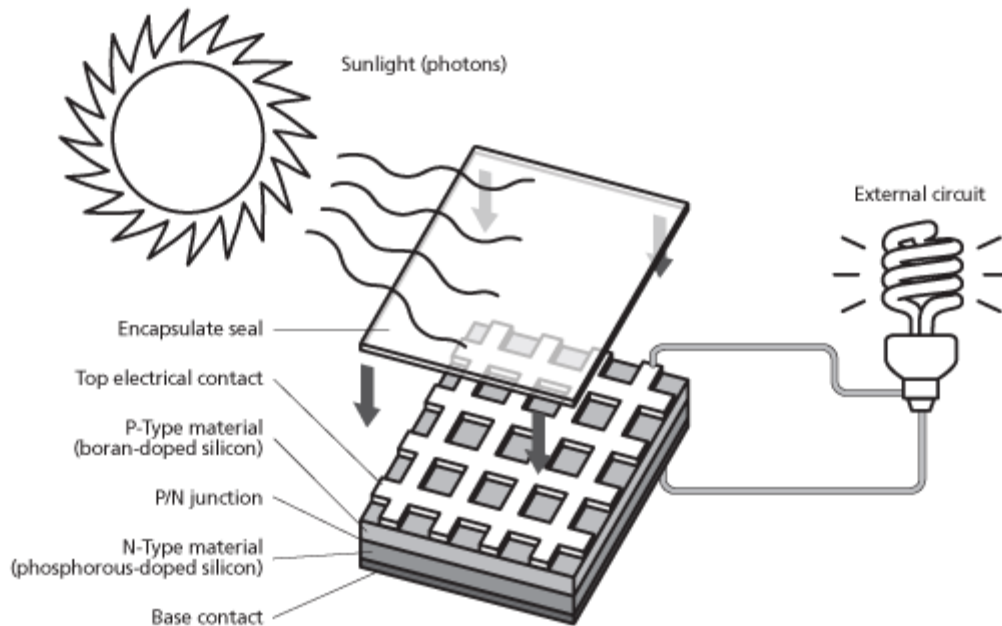


Figure 2 Schematic figure of how solar cells work [21]

Many PV cells can be grouped together and connected in series/ parallel to form a module i.e panel. Similarly to fulfill our desired voltage or current ratings , several modules can be wired in

series or parallel connection to form large PV-Arrays. The difference between PV cell,. module and array has been shown in Fig. 3

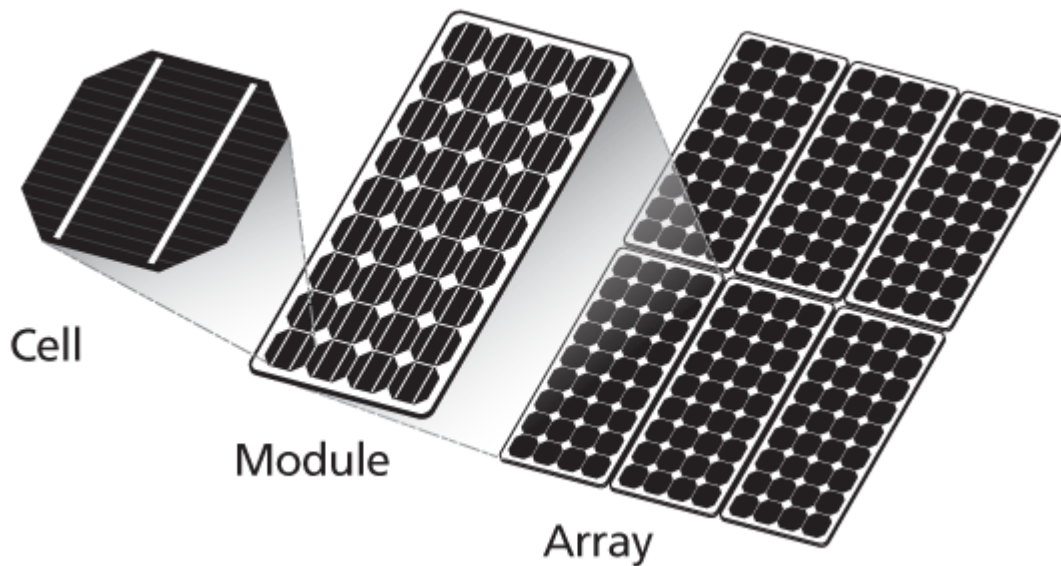


Figure 3 Difference between PV Cell, Module And Array.

Photovoltaic systems exhibits a non-linear I-V and P-V characteristic curves, varying with respect to solar irradiance and temperature. The electricity available at the end terminals of PV Array is in DC form and can be used to feed small loads but given the uncertain nature of environmental condition we need to add many additional components for a robust PV system like MPPT controller, Boost converter and battery storage. These are discussed later on, where they appear in the dissertation work.

2.2.1.2 EQUATIONS AND STANDARD CURVES

Ideal Photovoltaic cell

The basic diagram representing the generalised model of PV system consists of a photo-current source with a diode in parallel alongwith a series resistance R_{se} and a shunt resistance R_{sh} is given in Fig. 4.

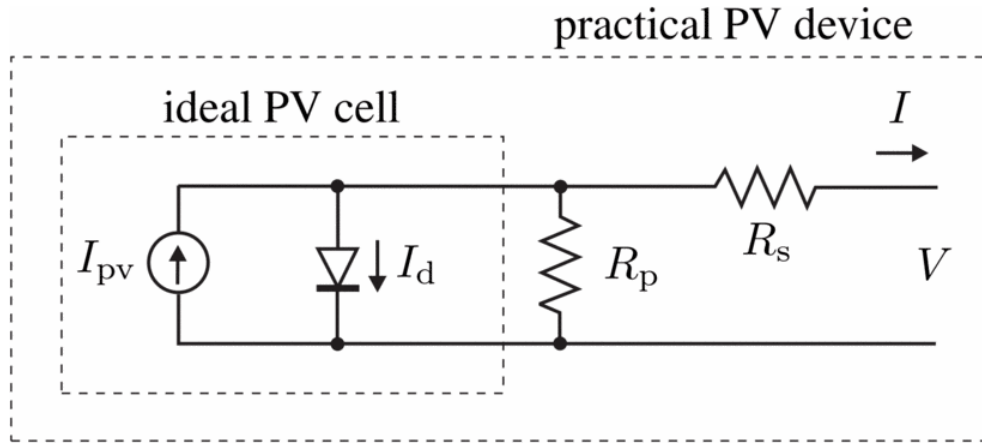


Figure 4. Circuit diagram of single diode Photovoltaic cell [22]

The basic equation of a PV cell presented below in equation 2.1 is taken from the work of [22]

$$I = I_{pv} - I_0 \left[\exp \left(\frac{V + R_{se} \cdot I_0}{V_t \cdot a} \right) - 1 \right] - \left[\frac{V + R_{sh} \cdot I_0}{R_{sh}} \right] \dots \dots \dots (2.1)$$

Cells/ modules are connected in parallel when increased current rating is required and they are connected in series when increased voltage rating is required. The series resistance represents an internal resistance to current flow and the parallel resistance represents leakage current.

For a given Array of $N_{se} \times N_{sh}$ modules, the modified form of basic circuit diagram is given in Fig. 5 and the corresponding equation 2.2 involved is as given below

$$I = I_{pv} \cdot N_{sh} - I_0 \cdot N_{sh} \left[\exp \left(\frac{V + R_{se} \left(\frac{N_{se}}{N_{sh}} \right) \cdot I_0}{V_t \cdot a \cdot N_{se}} \right) - 1 \right] - \left[\frac{V + R_{sh} \left(\frac{N_{se}}{N_{sh}} \right) \cdot I_0}{R_{sh} \left(\frac{N_{se}}{N_{sh}} \right)} \right] \dots \dots \dots (2.2)$$

Where

R_{se} and R_{sh} = Series resistance and Shunt resistance respectively

N_{se} and N_{sh} = No. of series cells and No. of parallel cells respectively.

I_{pv} = current generated by the incident light in the cell.

I_0 = reverse saturation current of diode

I = Output current

V = Output voltage and V_t = thermal voltage of the array

a = diode ideality constant = 1.3

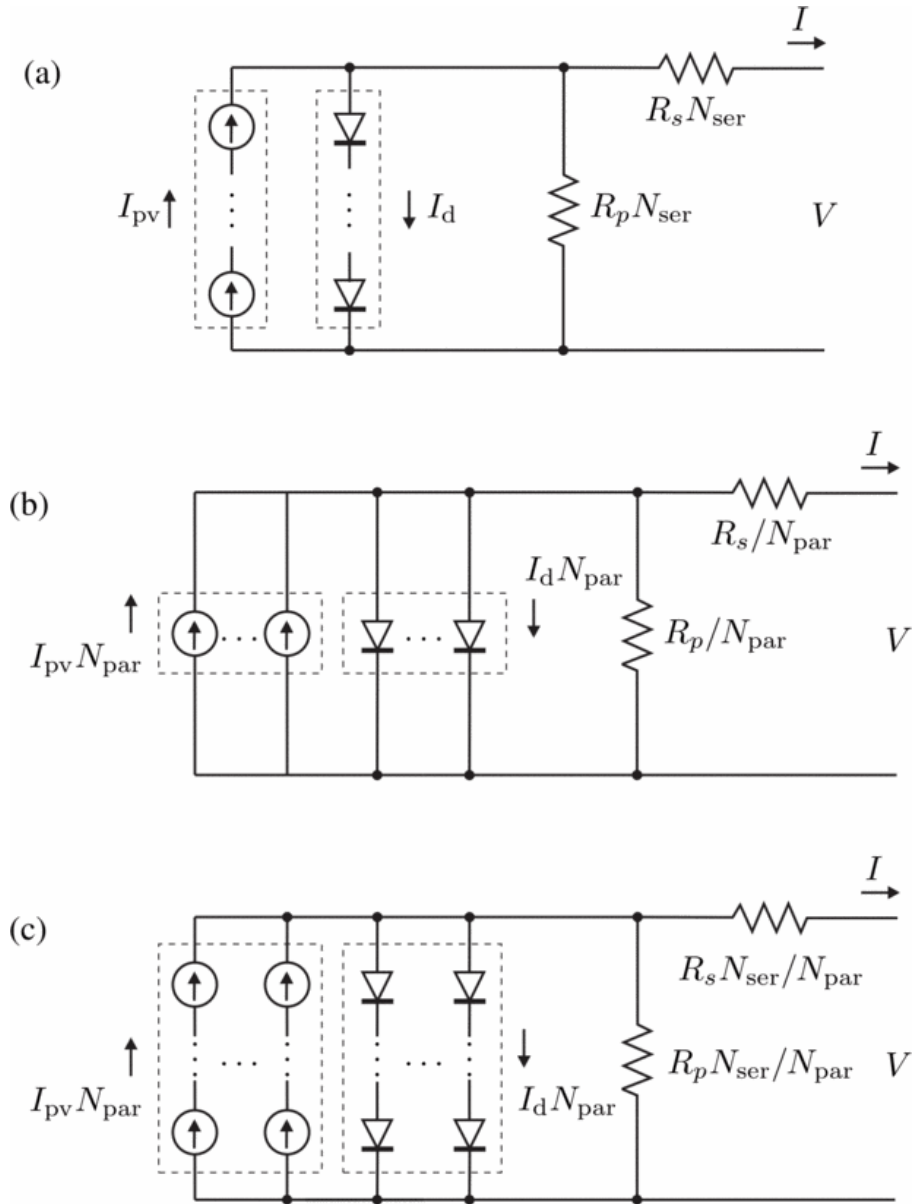


Figure 5. Equivalent Circuit diagram of Photovoltaic Module (a) Photovoltaic Array of N_{se} modules connected in series, (b) Array of N_{sh} modules connected in parallel, and (c) Array composed of combinations Of $N_{se} \times N_{sh}$ modules. [22]

The typical I-V characteristic curve as shown in Fig. 6, has three important points i.e short circuit point at $(0, I_{sc})$, Maximum power point at (V_{mp}, I_{mp}) and open circuit $(V_{oc}, 0)$. All these information along with other characteristic values are generally provided in the data sheet of manufacturers and these values are always with respect to the standard test conditions (STC) of temperature and irradiance level (i.e 1000 W/m^2 and 25 degree Celsius). The I-V and P-V Characteristic curves

are not static and will vary with changing irradiance level and temperature. These variations have been discussed in chapter 4 in simulation results.

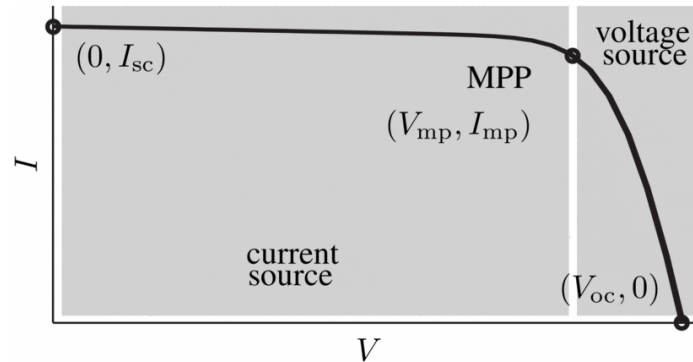


Figure 6. Typical Characteristics I-V Curves.

2.2.1.3 APPLICATIONS OF PV SYSTEMS

- i) PV systems mounted on rooftop & integrated with buildings grid connection.
- ii) PV systems is an important power in spacecrafts and now-a-days also used in many transportation modes like hybrid electric vehicles on road and boats which has catapulted it into an alternative energy source for automobiles..
- iii) PV systems in small standalone devices like calculators and toys, traffic signal lamps, street lights etc.
- iv) PV also plays a role in agriculture especially to pump water.

PV is increasingly being considered as an important constituent source for application of distributed energy resources for off-grid rural electrification and also grid connected smart microgrid projects.

2.2.2 FUEL CELL

Fuel cell is fast emerging as a preferred source of renewable energy technology due to its high operating efficiency in the range of 40-60%. It can be installed anywhere either in standalone mode or coupled with other renewable systems like PV to improve system reliability.

A fuel cell is a device that converts energy from the chemical reaction of fuels into electric power. Since it's basically an electrochemical process with no involvement of combustion process of fuel, so there is no harmful emission of gases and it's environment friendly. Just like battery cells many individual fuel cells can be combined to form a fuel cell stack.

2.2.2.1 WORKING PRINCIPLE

Each individual cell consists of a cathode, an anode and an electrolytic membrane. When we feed any hydrogen rich fuel into the stack there is an electrochemical reaction with surrounding air (oxygen) which produces DC power across the terminals accompanied by small heat and water as by-products.

The basic reactions are given by Equations 2.3 to 2.5

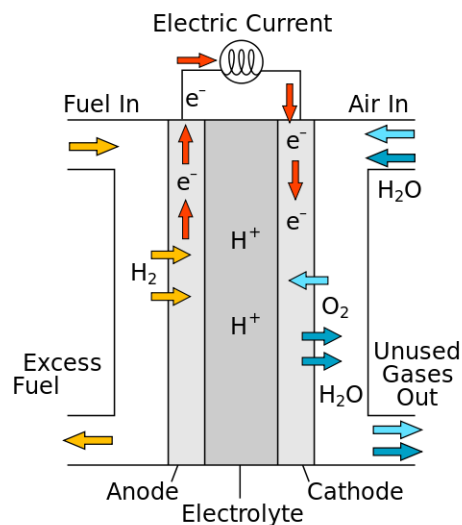
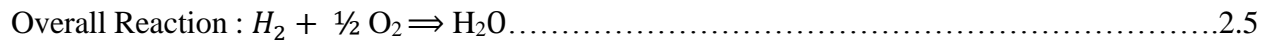
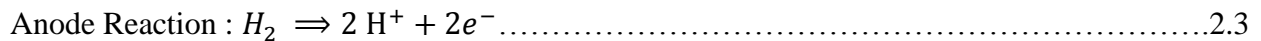


Figure 7. Basic working schematic of fuel cell [23]

Fuel cells are classified according to their type of electrolyte used like PEMC (Proton Exchange membrane fuel cell), AFC (alkaline fuel cell), SOFC (solid oxide fuel cell) etc. But out of all these PEMC is the most preferred one due to its high power density and low operating temperature which makes it safer for humans to operate. Therefore we have choosed PEMC model in this dissertation work.

Proton exchange membrane fuel cell

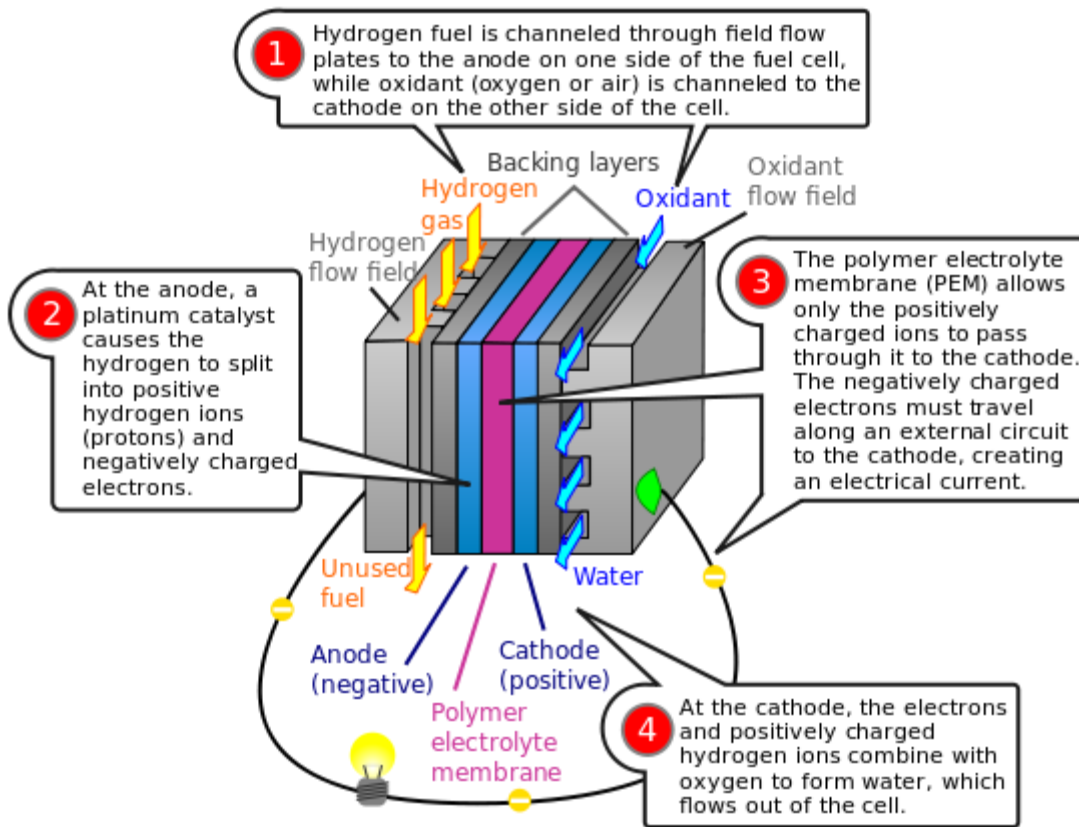


Figure 8. Schematic diagram of PEMC fuel cell prototype [24]

2.2.2.2 EQUATIONS AND STANDARD CURVES

Fuel cell voltage V_f is expressed in Eqn 2.6 and other constituent equations necessary for modeling purpose are given from equation 2.7 to 2.14

$$V_f = E_n - V_{act} - V_{ohm} - V_{con} \dots \dots \dots 2.6$$

$$E_n = \frac{-G_f}{2F} - \frac{R.t_k}{2F} \left(\frac{P_{H_2O}}{P_{H_2} \sqrt{P_{O_2}}} \right) \dots \dots \dots 2.7$$

$$P_{H_2O} = 10^y \dots\dots\dots 2.8$$

$$y = (1.445 t_c^3 \times 10^{-7}) - (9.183 t_c^2 \times 10^{-5}) + 0.0295 t_c - 2.1794 \dots\dots\dots 2.9$$

$$P_{H_2} = 0.5 \left\{ \frac{p_{h_2}}{\exp\left(\frac{1.653 I_f}{t_k^{1.334}}\right)} \right\} - 0.5 P_{H_2O} \dots\dots\dots 2.10$$

$$P_{O_2} = \frac{p_{air}}{\exp\left(\frac{4.192 I}{t_k^{1.334}}\right)} - P_{H_2O} \dots\dots\dots 2.11$$

$$V_{act} = \frac{Rt_k}{2\alpha F} \log_{10} \left(\frac{I}{I_0} \right) \dots\dots\dots 2.12$$

$$V_{ohm} = I_f \cdot R_{int} \dots\dots\dots 2.13$$

$$V_{con} = -\alpha_l \cdot I^k \cdot \ln \left[1 - \frac{I}{I_l} \right] \dots\dots\dots 2.14$$

Where ,

V_f = fuel cell voltage.

E_n = fuel cell Nernst voltage.

V_{act} = Activation losses

V_{ohm} = Resistance losses due to internal resistance.

V_{con} = Concentration losses.

G_f = Gibbs function constant for liquid= - 228170 J/mol.

F= faraday constant= 96485.33 coulomb/mol

R= Ideal gas constant= 8.314 J/mol.K

t_k = fuel cell temperature in kelvin.

t_c = fuel cell temperature in degree Celsius.

P_{H_2O} = water pressure (saturated)

P_{H_2} = hydrogen partial pressure.

P_{O_2} = oxygen partial pressure.

p_{air} = air inlet pressure

p_{h_2} = hydrogen inlet pressure

I_f = Fuel cell current

I_l = limiting current= 1.4 A.

$I_0 = \text{exchange current} = 10^{-6.912} \text{ A}$

$\alpha = \text{transfer coefficient} = 0.5$

$\alpha_l = \text{amplification constant} = 0.085$

$k = \text{mass transport constant} = 1.1$

STANDARD CURVE

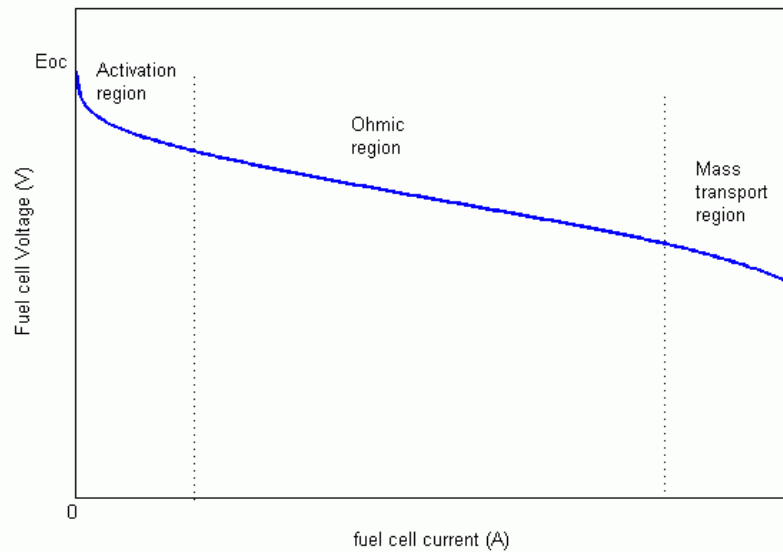


Figure 9. Standard curve of fuel cell [25]

The first region in the figure depicts the voltage loss due to slow rate of chemical reaction and is represented by activation drop U_{act} occurring at electrode surfaces. This varies with respect to type of electrode, catalyst used and the operating pressure/temperature. The second region depicts losses because of internal resistance of fuel cell stack i.e U_{ohm} . The last region depicts the concentration losses or the mass transportation losses due to change in concentration of reactants as the fuel gets depleted due to its use.

2.2.2.3 APPLICATIONS OF FUEL CELL

- i) Power back up in commercial and industrial complexes.
- ii) Auxiliary power in spacecraft and planes.
- iii) Automobiles like buses and cars.
- iv) Integration with distributed energy resources.

2.2.3 BIOMASS TO FUEL CELL [26]

For establishing large scale fuel cell systems, we need to have a least expensive source of hydrogen. Though it can be run with natural gas but this need can also be derived from the biomass which are often discarded as wastes in agricultural residues, hostel food wastes, sewage etc. Thus not only clean power generation but using biomass to feed our fuel cell will reduce waste disposal problems.

Integrating biomass-fuel cell as a renewable energy source in DERs (Distributed energy source) will allow communities to reduce their dependence on diesel generators, thereby providing economical benefits as well as an environmental friendly option.

In regions having high agricultural residues, we have access to low cost biomass sources which makes it economical and suitable for business case for establishing fuel cell plants. Since in this dissertation we are proposing a microgrid system for a location based on a agriculture dominated state hence availability of biomass is cheap and easy.

Also , the type of waste generated inside the Thapar University campus includes kitchen leftover of hostels and spent cooking oils, food wasted in hostel mess, sewage waste and horticultural wastes from the vast college plantation gardens. Even if biomass to fuel cell is around 30% but if cogeneration application concept is applied by capturing waste heat and reusing it for other auxiliary purposes, then this efficiency can be increased upto 80-90% and similar technology for biomass to fuel cell has been developed by Ballard Power and business case study for such a system has been presented in [26] .

2.2.4 BATTERY SYSTEM

Energy storage blocks are an essential part of designing any renewable energy based systems because we don't have control over mother nature. Though many energy storage systems like flywheels, super capacitors etc. are available now-a-days but the most simple and cost efficient solution is battery system. Many different battery types are available like lead-acid, lithium ion, nickel-cadmium etc. but in our dissertation we have choosed lithium-ion. Though nickel-cadmium has low energy density but offers high life cycle and low cost option so it was earlier used widely but since it contains toxic metals which is not environment friendly hence most organisations are phasing them out. Lead acid has the best cost per Watt hours but is much more heavier and larger

in size than Lithium ion which offers a good trade-off between high energy density and being light weight though slightly costly than lead acid. Lithium ion is being increasingly preferred for renewable energy applications.

Preferred criteria of battery to be used in long term storage are high power, high energy density , higher efficiency , low specific kWh-cost, long life cycle time, low self-discharge, less maintenance cost, light weight, easy installation & operation and low maintenance expenditure. The above details were obtained from [27], [28].

Matlab/Simulink has inbuilt battery blocks which can used directly and by clicking the battery block we can select the type of battery and for this dissertation work, the author has choosed Lithium-ion.

The generic dynamic battery model which represents most of the rechargeable batteries is as shown:

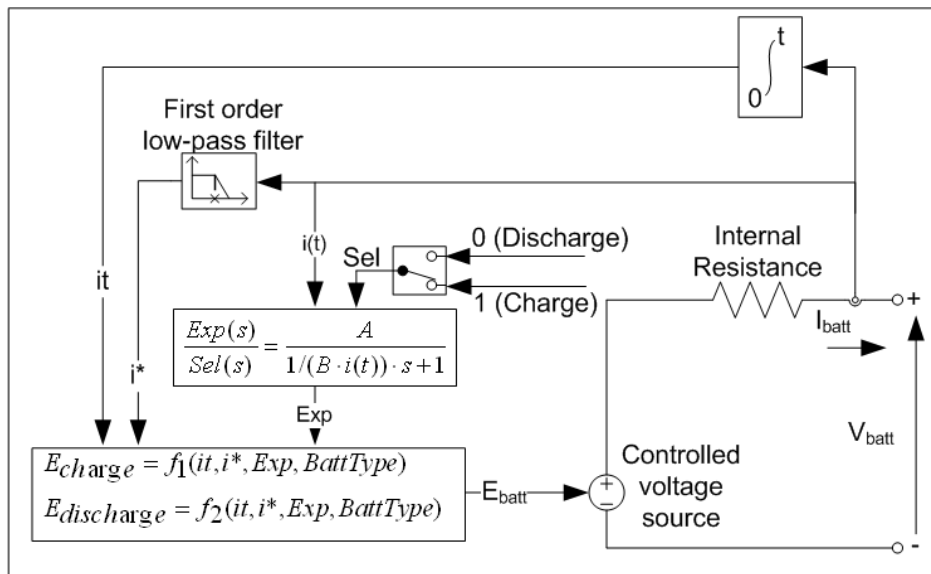


Figure 10. The Generic dynamic battery model as given in Simulink

The standard equations are given in equation 2.15 and equation 2.16 :

Discharge Model ($i^* > 0$)

$$f1(it, i^*, i) = E_0 - K \cdot \frac{Q}{Q-it} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \dots\dots\dots 2.15$$

Charge Model ($i^* < 0$)

$$f2(it, i^*, i) = E_0 - K \cdot \frac{Q}{0.1 Q+it} \cdot i^* - K \cdot \frac{Q}{Q-it} \cdot it + A \cdot \exp(-B \cdot it) \dots\dots\dots 2.16$$

Where,

E_0 = Constant voltage (V).

K = Polarisation constant (Ohm).

i = Battery current (A).

i^* = dynamics of low frequency current (A).

i_t = Battery capacity extracted (Ah).

Q = Maximum battery capacity (Ah).

A = exponential voltage (V).

B = exponential capacity (Ah).

2.3 INFERENCE AND IDENTIFICATION OF GAP IN RESEARCH

As per the best knowledge of authors, there are not many papers which takes into account the bell shaped curve of PV irradiance variation along with temperature variation throughout a 24 hour period of day for studying the dynamic power exchange with grid along with feeding of load. Most of the work done on such PV system models whether grid connected or standalone are modeled only at specific irradiance/temperature levels or at standard testing conditions (i.e 1000 W/m² and 25 degree Celsius). But unlike them, this dissertation work presents a simple and unique approach to fulfill the gap mentioned in above line.

Though variation of characteristics I-V, P-V curves of Photovoltaic system model with respect to changing irradiance and temperature has been presented by many authors but there are hardly any dynamic model showing the exchange of power with grid at various times of day when the system is fed from dynamically changing input of irradiance and temperature variation as per real onsite data.

An important note here, which the author wants to highlight is the fact that many approaches are available for PV panel modeling like single diode model described in [22] or two-diode model, empirical model etc. as described in [29]. While single diode model is the simplest, has least computation time and it has almost the same ability as two diode model to extract values but under varying temperature condition accuracy of two diode model is much better [29]. But both of these traditional approaches of using single-diode or two diode models is very cumbersome in handling dynamically varying input climatic parameters and these previous models also have varying degree of inaccuracies arising from different design parameters used by different users. Thus, for studying the power exchange in grid integrated system, a robust Simulink model of a PV system was prepared using the inbuilt PV modules in latest version of Simulink, so that varying environmental conditions & different parameters can be fed as input values and corresponding output power can be obtained, matching that of manufacturers data sheet value. Also we have the option of choosing between various manufacturer module types. Hence, the author of this dissertation decided on using the inbuilt solar modules available in new 2014 Matlab /Simulink version in the present work.

CHAPTER 3: DESIGN OF PROPOSED SYSTEM

3.1 INTRODUCTION OF THE PROPOSED SYSTEM AND ITS BLOCK DIAGRAM

Main features of building any successful microgrid model are

- i) Identification of renewable energy sources feasibility as per site conditions.
- ii) Design and Integration of the renewable energy sources with grid.
- iii) Ability to allow bi-directional power exchange with grid (as per deficient/surplus power generation).
- iv) Ability to ensure uninterrupted supply to meet its own critical load during grid blackout in islanded mode of operation.

All the above conditions have been met satisfactorily at initial level of modeling in this dissertation work of a proposed microgrid for hostel building in University campus.

The Overall system model designed in Matlab/ Simulink during this dissertation work is given in Fig A.1 of APPENDIX.

The block diagram for the same is given below in Fig. 11

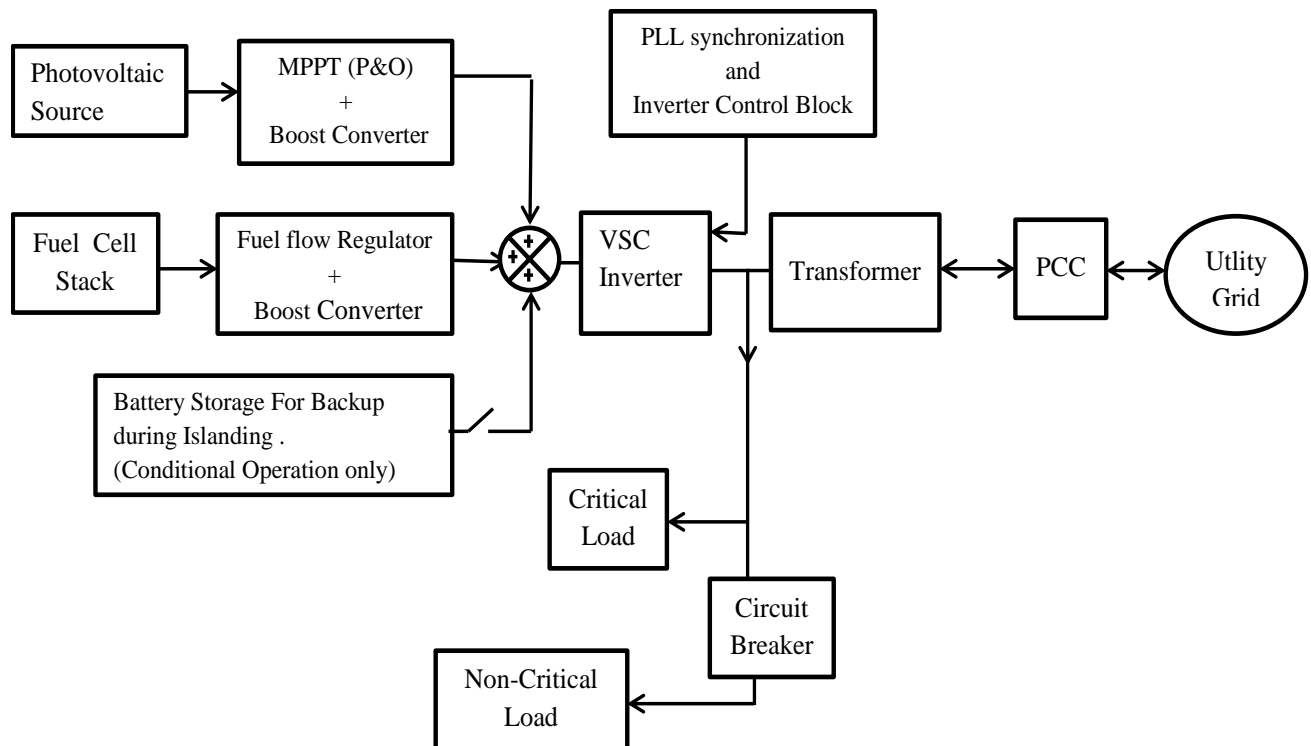


Figure 11. Block diagram of proposed system

3.2 PROPOSED SYSTEM COMPONENT DETAILS

3.2.1 PHOTOVOLTAIC SYSTEM

3.2.1.1 PV PANEL

Our proposed system model contains two Photovoltaic arrays connected in parallel, which can deliver a combined load of 200 kW (each can deliver 100 kW) at standard testing conditions i.e. 1000 W/m² irradiance and 25 degree Celsius but the actual generated power would be less than 200 kW depending upon actual irradiation level which varies from 0 to a maximum of around 840 W/m² at 12 pm noon. For simulation we would be using the Simulink 2014 version, Inbuilt blocks of PV array and select SunPower-SPR305 module from the “module type” pop up menu. The PV array is based on the simulation block of solar array developed by Pierre Giroux, Gilbert Sybillie. This block was fed with two signal builder blocks one mimicking the varying irradiance level input & other varying the temperature (The data fed in these signal builder blocks were based on actual site data). The PV array block then generates corresponding values of voltage/current/power as per the manufacturer manual sheet. Each of these array comprises of sixty-six strings of five series connected modules in parallel (66*5*305.2 W=100.7 kW). On opening up array block menu, we can find the module parameters as indicated below. Fig. 12 shows the Simulink model of the PV system

For one module, the manufacturer specifications are—

No.of series cells=96,

V_{OC} = 64.2 V,

I_{SC} = 5.96 A,

V_{mp} =54.7 volt.

I_{mp} =5.58 Amp.

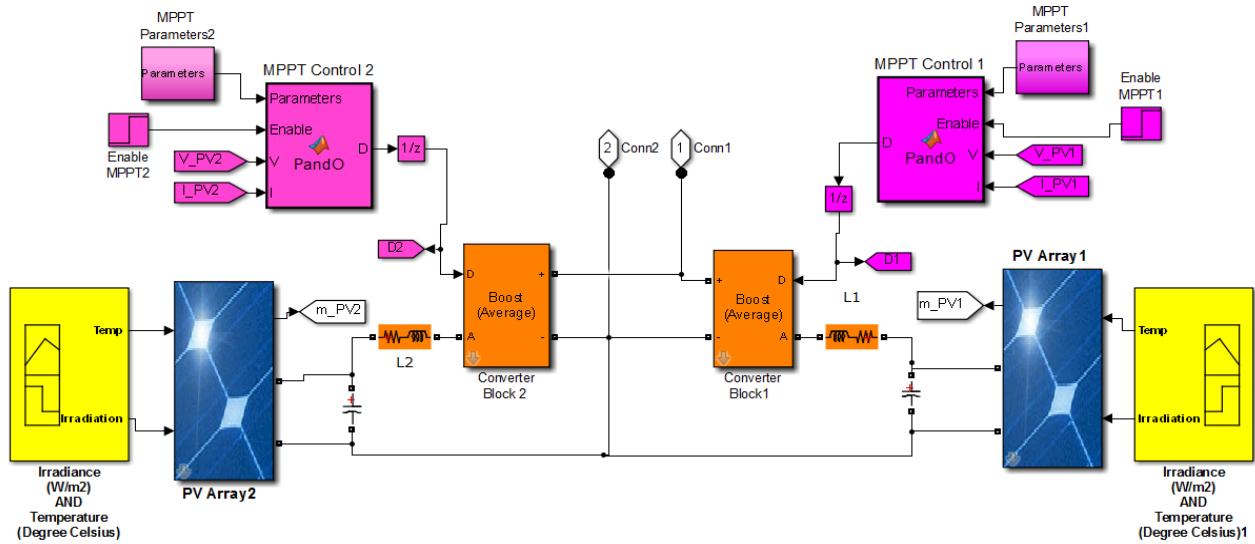


Figure 12. Simulink Model of the designed PV system.

3.2.1.2 MPPT CONTROL AND BOOST CONVERTER FOR PV SYSTEM

The output from the PV arrays are connected to the MPPT controller and in this dissertation we have used the logic of “perturb and observe” for MPPT tracking whose flowchart is given in Fig. 13 and the output was then fed to an average model of Boost Converter for increasing the output voltage of PV arrays from about 260 volt to 500 volt dc. By this combination of MPPT controller and boost converter, the duty cycle is varied automatically so as to generate the desired voltage for extracting maximum power. The maximum power point tracking is done by a MATLAB function block and the “perturb and observe” code was then embedded inside a simulink block. For details on the MPPT techniques, the following paper [30] was referred. Also a capacitor needs to be placed between PV array and the grid side converter, needed for reducing high frequency harmonics. The flowchart for the MPPT code that was used and embedded in our simulation purpose is given in Fig. 13

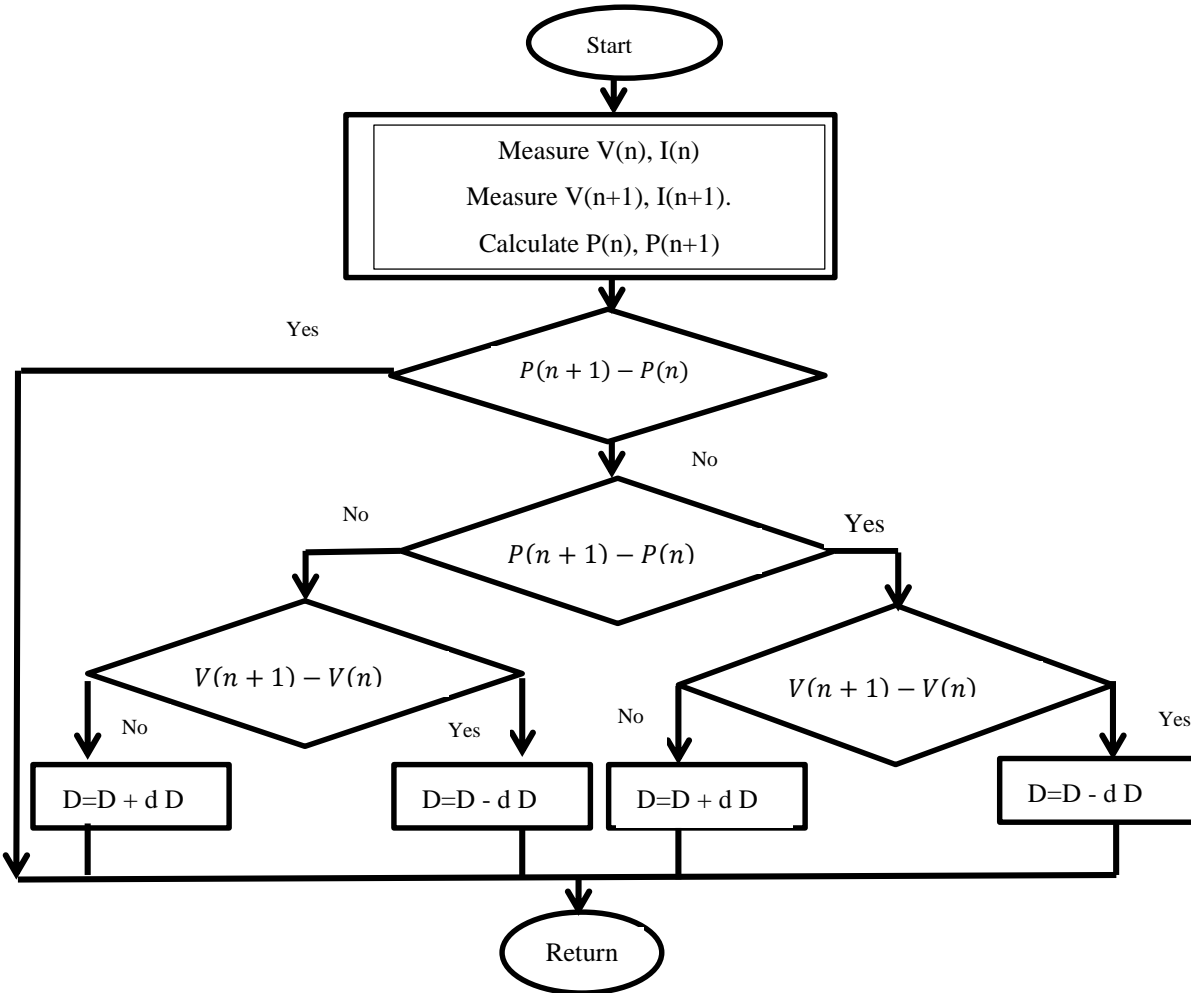


Figure 13. Flowchart for MPPT

In the Flowchart given in Fig 13,

$V(n)$, $V(n+1)$ are the voltages at Nth and (N+1)th instances of time respectively.

$I(n)$, $I(n+1)$ are the current at Nth and (N+1)th instances of time respectively

$P(n)$, $P(n+1)$ are the power obtained at Nth and (N+1)th instances of time respectively.

D = Duty cycle of converter

dD =Difference in duty cycle at Nth and (N+1)th instances of time

3.2.2. FUEL CELL SYSTEM

Simulink 2014 version has an inbuilt block of fuel cell stack and we selected the 6 kW, 45 volt PEMC type model which feeds a DC/DC converter with a constant output of 100 volt DC. A regulator block implementing PID control is necessary to control the flow rate of fuel and air because variations in flow rate can effect efficiency. The converter is essential so as to step upto 45 volt DC to 100 volt DC. This whole arrangement was converted into a single subsystem with 6 kW, 100 volt dc output and five such subsystems were connected in series (Thus, $5 \times 6 = 30$ kW and 5×100 Volt = 500 volt dc). This was done keeping in mind, our requirements of approximately 30 kW critical load and also the need to connect these 5 fuel cell in series so as to obtain 500 volt DC output which will match with PV system's 500 volt dc output and thereby enabling both of their parallel operation as well as their connection to grid side VSC inverter which will receive a constant DC input of 500 volt and produce AC output in grid side. Simulink model for the fuel system that was modelled is given in Fig. 14

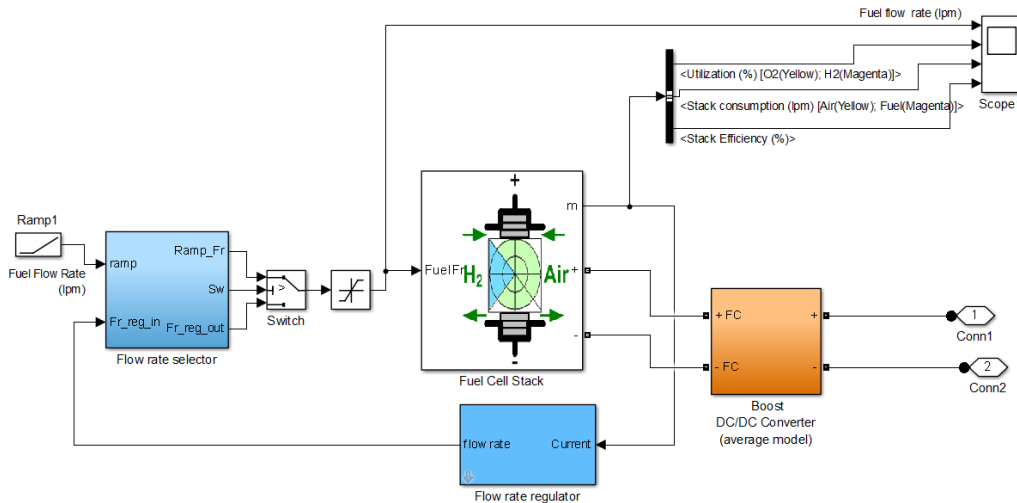


Figure 14. Fuel cell model in Simulink

The fuel can be obtained by converting biomass to fuels and the steady input of biomass required can be sourced from the 8 big hostels of university where each hostel has a food/oil waste of approx. 70 kg daily i.e ($70 \times 8 = 540$ kg). This data was arrived after discussion with mess managers of the hostel who maintains a list of daily edible food, used oil etc. being thrown as waste.

Additional raw material required for biomass converters can be easily obtained from nearby regions and Punjab being an agricultural state has easy and cheap availability of agricultural waste/

husks etc. which can be recycled and used by the biomass converters as a fuel. These husks otherwise end up being burnt and that smoke often chokes air leading to environmental pollution as documented by NASA satellite images and multiple studies. Thus, proposals such as this have the potential to obtain useful energy from being wasted.

Biomass based fuel cell systems have already been designed in [26] and we propose to use this commercial product in our system.

3.2.3 BATTERY BACKUP SYSTEM

We need not use battery during normal operation as they are quite costly and hence they will remain in floating condition & will not be involved as long as our system is in grid connected mode because any deficiency to meet our load demand will be met by drawing power from grid. But still we require a battery back-up for emergency cases so that in case of islanding purpose we are able to secure our critical loads.

For providing a battery backup of about 3-4 hours for our critical loads, we have calculated our battery capacity required at 600 mah capacity Lithium ion type. Battery charging-discharging and its scheduling in microgrid scenario is beyond the scope of study of this paper & hence for our simulation purpose we have assumed the battery to be fully charged during our simulation of islanded condition. Details regarding battery scheduling in grid connected PV using a microcontroller can be studied in [31].

3.2.4 VSC INVERTER BLOCK AND ITS CONTROL

The power obtained at the output side of PV source & fuel cell are DC which has to be converted to AC for integrating our proposed system for Grid Connection as well feeding the loads in hostel which run on AC. In this dissertation, we have used the inbuilt average model of VSC available in Simulink which converts 500 volt DC to 240 Volt AC.

This three level VSC maintains a constant DC bus voltage of 500 volt supplied from the hybrid renewable sources so as to obtain a steady power. While the system is running under normal grid connected mode, the inverter should preferably be operated in current controlled mode whereas during standalone operation, it is preferred to be operated in voltage control mode. From PCC (point of common coupling), current and voltage vector values are being sensed and then

transformed into d-q reference frame thereby becoming DC quantities. Adoption of PI controller is used to set reference current tracking with zero steady state error. For controlling the active and reactive power injected into the grid, PLL or phase locked loop concept is used which was adopted from [32], [33]. The required phase angle for abc-dq transformation was obtained by using this PLL Method. Also, modulation index for inverter control was obtained by transforming the control signals in dq frame back to abc frame.

Control of power flow was done by adopting the technique of synchronous reference frame concept and parks transformation was used to convert three phase “abc” components into two phase “dq” frame. Due to the component’s synchronous rotation with respect to reference frame, the control variables become equivalent to DC quantities allowing us to use PI controllers for current control. Individual controlling of real and reactive power, depends upon the use of d-q components of voltage and current. Control system for VSC uses two loops—one is the outer control loop which is used for regulating DC voltage and the inner control loop which is used to regulate the active and reactive component of grid current. Since in our simulation we have considered average models of dc-dc boost converter and average models of VSC converter, hence there shall be no representation of harmonics here in this paper but still the dynamics occurring due to interaction between control system and power system is preserved.

3.2.5 FILTER

An output LC filter of 20 kVAr is also introduced to remove the components of high switching frequency from the output side of inverter. This 20 kVAr capacitor bank is connected after VSC block to filter the harmonics produced by the VSC converter block.

3.2.6 LOAD

The Hostel building has a total connected load of 120 kW and load variation can be known from the substation of university at regular intervals. During islanded mode of operation, the maximum connected load of 120 kW is split into critical load (30 kW) & non-critical loads (90 kW) so that with help of battery backup, we can secure critical loads first. The critical load of hostel will include lights placed in corridors, security cameras and safety alarms, motors used for water supply, main office of hostel and the kitchen equipment in hostel mess.

3.2.7 TRANSFORMER

A three Phase Transformer of ratings 200 kVA, 240V/ 25 kV, is used for coupling our system with grid. This transformer plays many roles i.e stepping up the output voltage of inverter to the level of grid values, it serves for the purpose of isolation and also helps by preventing injection of DC current into the grid. We generally prefer Delta-Star configuration in grid connected energy systems since third harmonics will circulate inside delta connection and it wont be able to enter grid.

3.2.8 POINT OF COMMON COUPLING (PCC)

Circuit breaker may act as PCC and it plays a vital role in microgrid because its responsibility is to isolate its own system from the grid connected mode to islanded mode incase of failure of grid or when it can sense fluctuations in the grid side having potential of blackout. During real life implementation we need to combine sensors at PCC to track the grid parameters for islanding purpose.

3.2.9 GRID

Grid's modeling was done assuming a 25 kV feeder line fed by a 120 kV transmission network. Simulink model of the same can be seen in Fig 15.

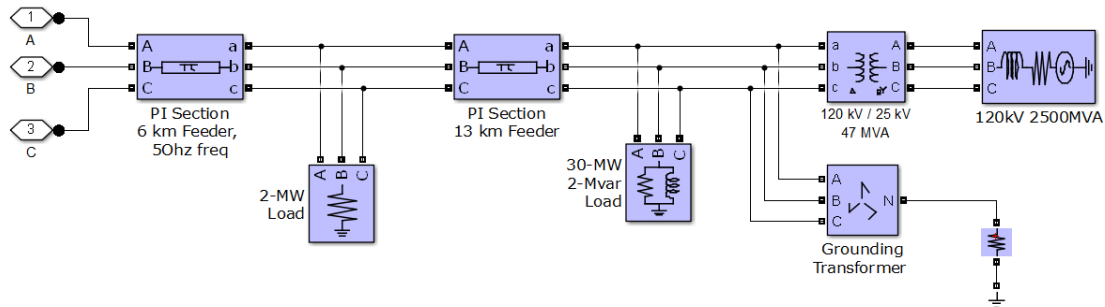


Figure 15. Simulink model of designed Grid system

DISCUSSION ON DATA COLLECTION AND SIMULATION RESULTS

4.1 BACKGROUND PLANNING AND DATA COLLECTION METHODOLOGY

Before building any microgrid plan, there is a need to analyse the energy potential of the location. In this dissertation work, the model being simulated is primarily intended as a case study of a proposed microgrid system for a hostel inside Thapar university which is located in Punjab state of India, which has great solar potential but poor wind potential. Also it's a state rich in agricultural bio-waste which can be utilized to generate biomass powered fuel cell and these two facts were obtained from the website of Punjab govt. (ENVIS Centre, 2014). Based on these facts, a PV based microgrid system assisted by fuel cell is proposed.

The maximum load of Hostel-J, Thapar University is around 120 kW and there is dynamic variation throughout the day and this data was collected from the electrical sub-station inside university campus. Based on that for simulation purpose, a variable load was modeled.

The two important input parameters on which output of our proposed system depends is irradiance variation and temperature variation.

The variation in temperature over a 24 hour period in the month of April was noted from mobile weather apps and internet weather updates for the site location.

The variation of average hourly irradiance in Thapar University campus over a given 24 hours was measured everyday at hourly time interval for various months of a year in [10] (Ganguli, 2010).

The sample data for 30 days in the month of April at different time intervals was noted and by using the above measured data, the author of this dissertation calculated an approximated average value of irradiance level for each hourly duration, as a data for our sample day. For example if at 10 am, irradiance measured was 450 W/m² on 2nd April, 490 W/m² on 3rd April and 390 W/m² on 4th April then we calculated our average irradiance value for 10 am in the month of April as $(450+490+390)/3 = 443.33 \text{ W/m}^2$. i.e $\frac{\sum Irr(i)}{i}$, where "i" represents the total no.of days of the

month and $\sum Irr(i)$ represents the value of irradiance at that particular hour in all days of the month. Such an average value was calculated over a period of 30 days for each of the 24hours duration and an approximate table of irradiance for a sample day was arrived at and this has been fed via a signal builder block as input in our modeling of photovoltaic arrays PV1 & PV2 in W/m². The following Table 1. ,summarises our input data for the sample day used in our model.

Table 1. Irradiance and temperature parameters of the sample day considered for simulation.

TIME	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm
IRRADIANCE (Watt/m ²)	0	0	0	0	0	20	45	100	300	550	650	750	840
TEMP (Degree)	28	27	25	24	24	22	25	27	28	31	32	33	36
TIME	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 am	
IRRADIANCE (Watt/m ²)	810	725	560	345	150	150	0	0	0	0	0	0	
TEMP (Degree)	38	37	36	34	34	32	32	31	30	30	28	28	

4.2 PRINCIPLE OF OPERATION.

Case 1) Grid connected mode:

As the solar irradiance & cell temperature varies throughout the day, the power output from PV array also varies. The parallel connected fuel cell also assists this system and when abundant energy from PV-FC combination is generated then after meeting its own load requirement, the system will supply or export the excess power to grid while incase of lack of solar generation the load will draw power from the grid. A point to be noted, that the battery energy will not be used

in normal grid connected mode & it will come to picture only in islanded mode or grid blackout cases.

Case 2) Islanded mode:

Sometimes, due to load shedding/power cuts as often seen in summer days, or grid blackout, or natural calamity like cyclone or storms which disrupts power supply we may have a situation when grid support fails and when the above condition happens, the microgrid sensors should be able to sense that and the CB which acts point of common coupling, will be able to isolate our system and switch over to islanded mode of operation.

4.3 SIMULATION RESULTS:

Fig. 16 shows the I-V and P-V curve of each individual PV array with respect to variation in irradiance level and its found that with increasing irradiance the curves also seem to shift upwards. Similarly, Fig. 17 shows the I-V and P-V curve of each individual PV array with respect to variation in temperature levels.

The dots in the central part of the curves in this Fig. 16 and 17, represents the maximum power points.

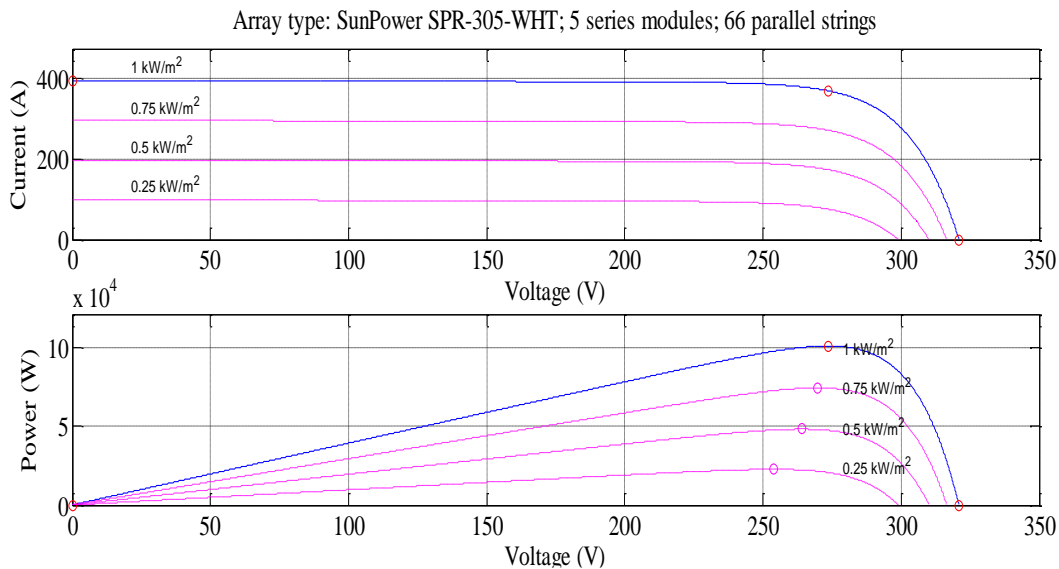


Figure 16. Variation in I-V and P-V curves at different irradiance levels.

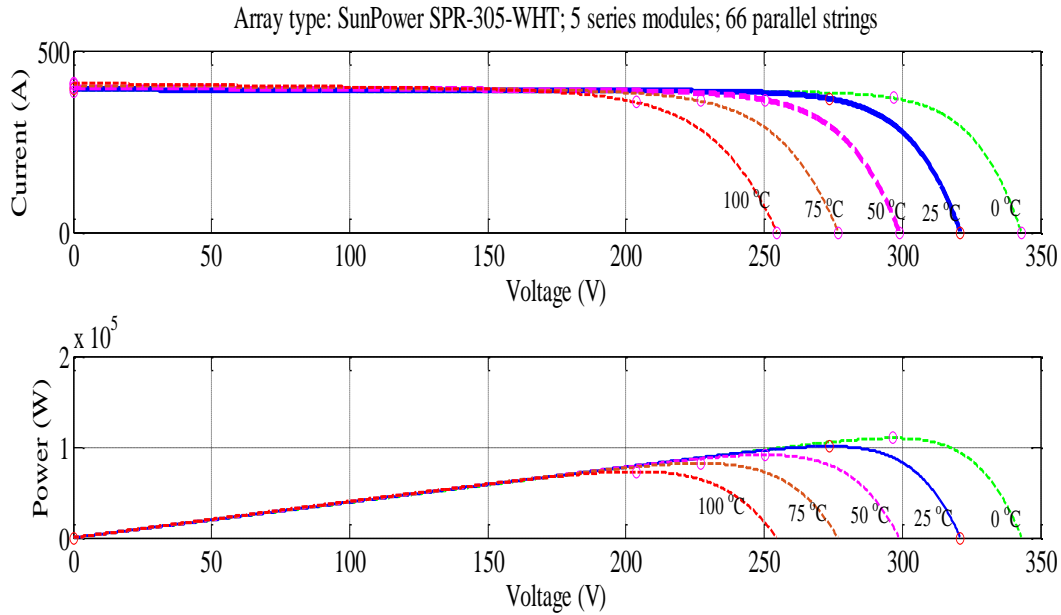


Figure 17. Variation in I-V and P-V curves at different temperature levels.

The Simulink model as given in Appendix Figure A.1, was run for a sample period of 6 seconds representing data of 24 hours of a sample day. In all the figures the X-axis is common and it represents a particular time of a day while Y-axis will be different as per intended parameter study. Fig 18 and 19 represents the varying irradiation and temperature level for our sample day which was fed via signal builder blocks to the each of the PV panel and we find that the irradiance is varying from 0 to about 840 Watt/m² while the temperature varies between 28 to 38 degree at different times of the day. Now, Fig 20, 21 and 22 represents the output power, output voltage and variation in modulation index of PV side boost converter subjected to MPPT algorithm and all these outputs are corresponding to the variable input parameters of temperature and irradiation throughout the day. The output power obtained in Fig 20 is a bell shaped curve with the maximum power being generated between 11am to 2 pm time. We should note that these values from Fig 18 to Fig 22 are only for one PV panel. Since both of the PV panels are similar so we have skipped showing output of 2nd panel which would also be the same.

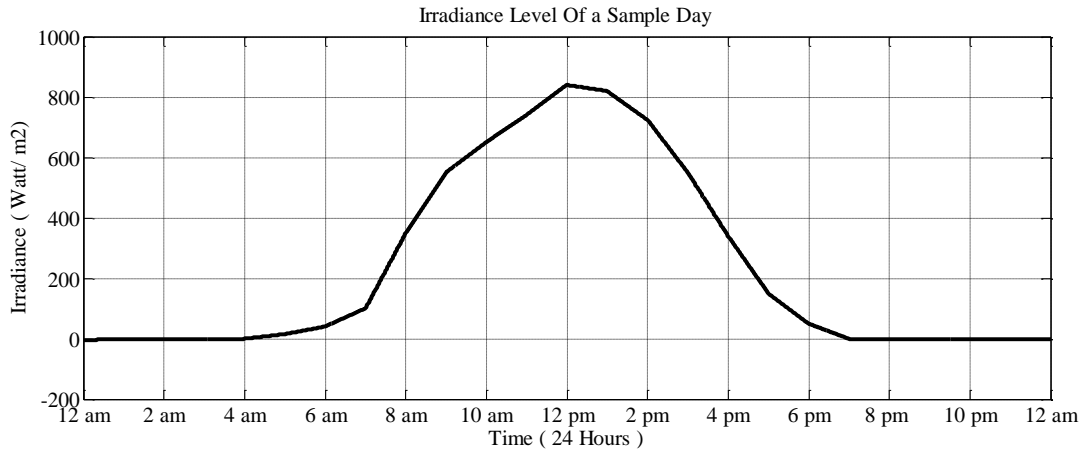


Figure 18. Variation in Irradiance level over a 24 hour sample period.

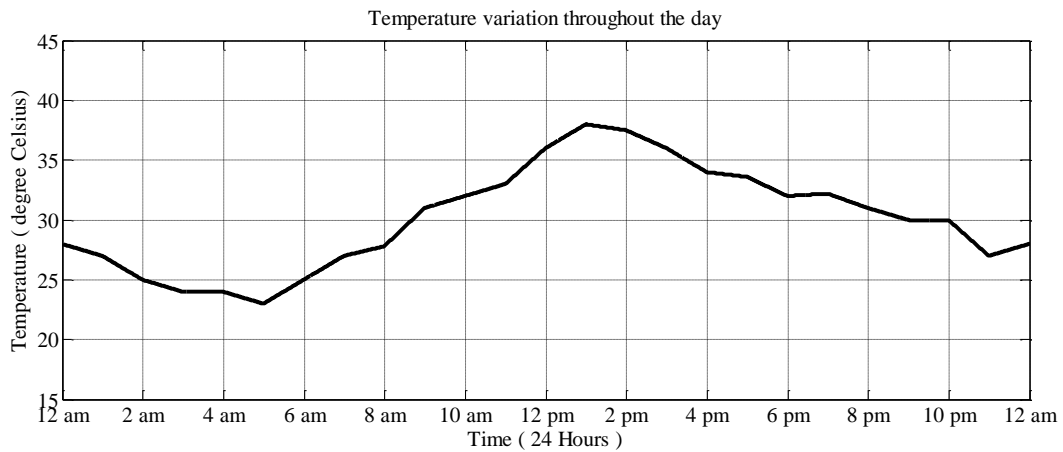


Figure 19. Variation in Temperature level over a 24 hour sample period

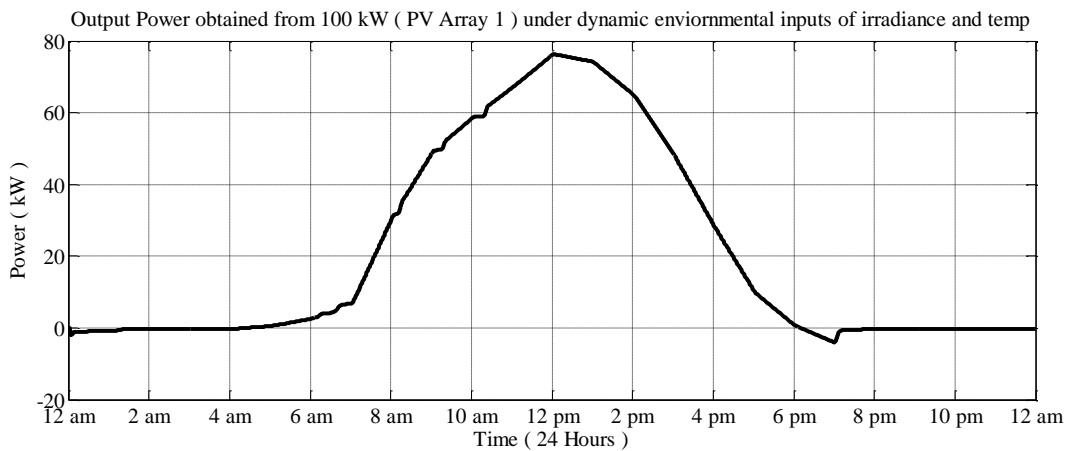


Figure 20. Variation of power output from one PV array over a 24 hour period.

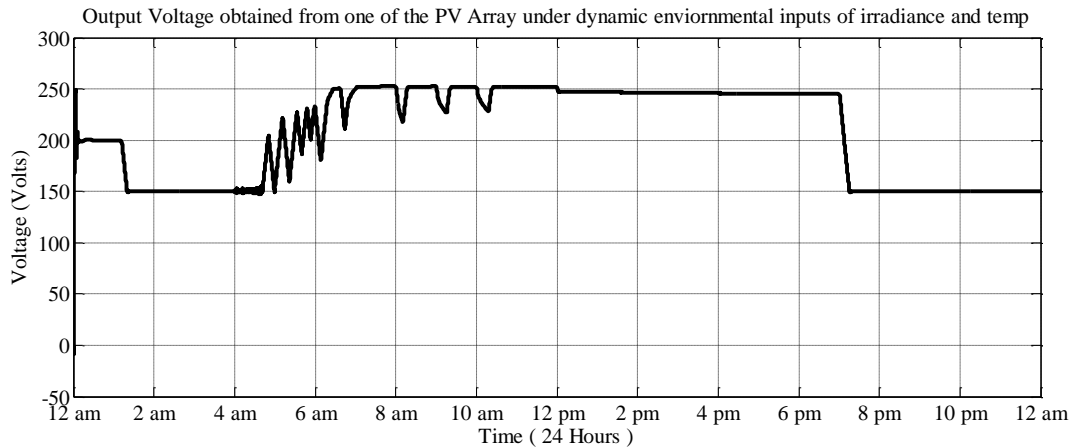


Figure 21. Variation in output voltage of one PV array.

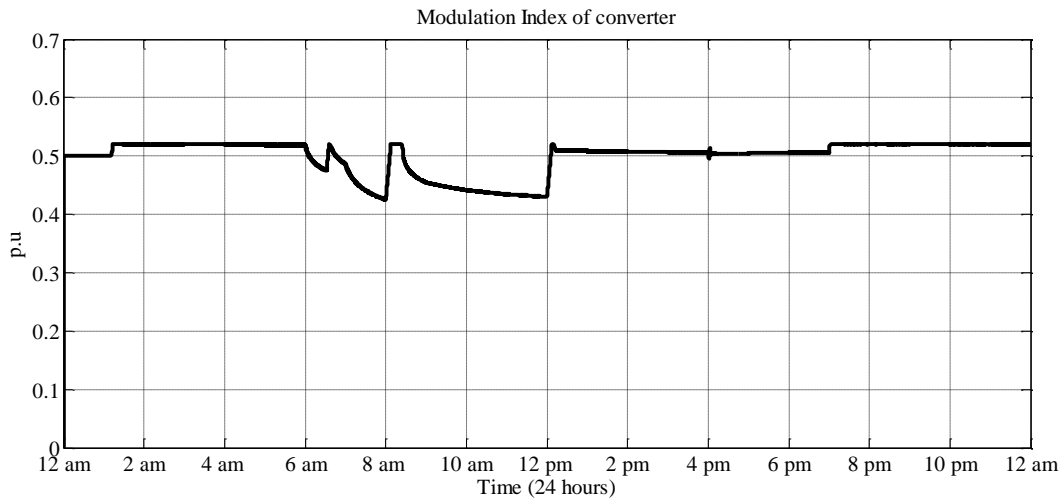


Figure 22. Variation in modulation index of Boost Converter

Fig. 23 shows the net summation of solar Power generated from both of the PV1 + PV2 panels and the combined output power varies from 0 to 150 kW throughout the day with maximum power found to be generated during afternoon period as per expectation.

Comparing the output of Fig 21 and Fig 24, it is found the output from the PV system which was around 260 volt DC in Fig. 16 has been boosted upto a level of 500 volt DC in Fig 24. Thus it can be said that the PV+FC system's output voltage has been individually boosted upto the level of 500 volt by their own respective boost converters and this constant 500 volt DC is fed to the input of VSC converter for conversion from AC to DC which is shown in Fig 24.

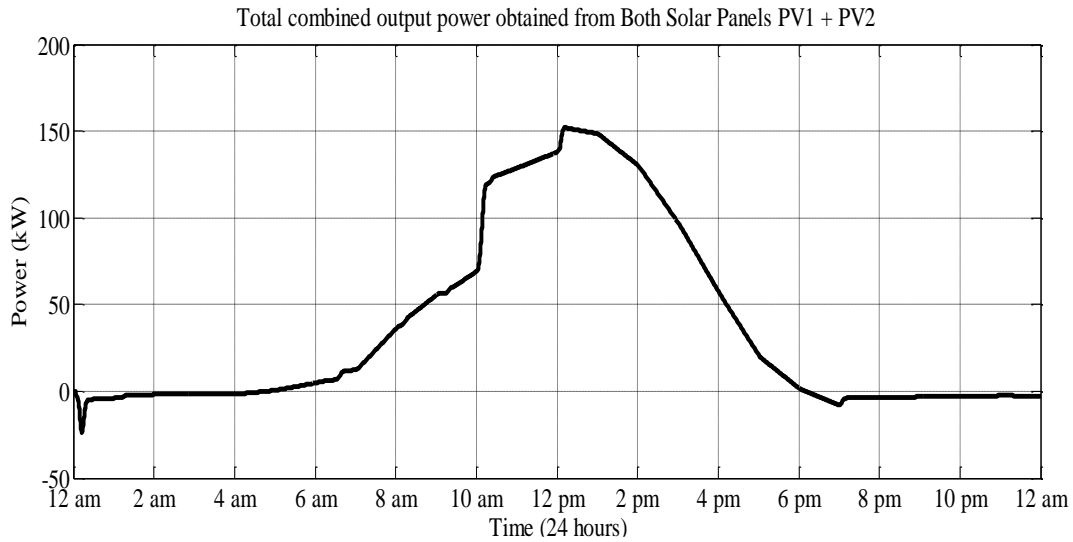


Figure 23. Total combined power being generated by both PV arrays.

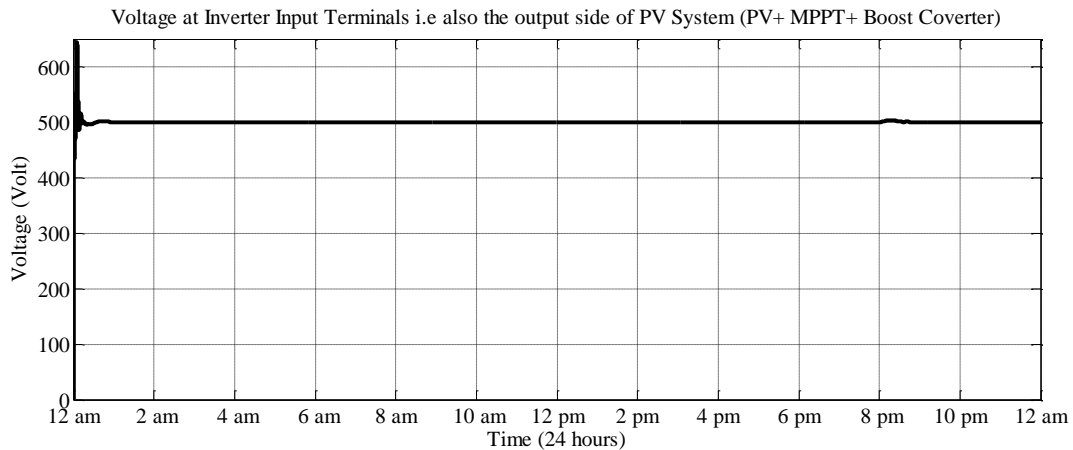


Figure 24. Voltage at input of VSC inverter terminal.

The control block of VSC converter plays the important role of controller for synchronizing utility grid side with input side generation sources and due to this synchronization, our system is able to facilitate bi-directional power exchange to meet the varying load demand with varying solar power generation. In case our load demand is more than power being generated from input sources then our system will draw power from utility grid and when there is excess generation then power can be supplied back to grid. This import/export i.e exchange of power with the grid is shown in Fig. 25 with respect to feeding a variable load. Neglecting the minor system losses in simulation, this power exchange can be simply visualized by the logic $P_{Load} - (P_{Solar} + P_{fuel\ cell}) = P_{Grid}$

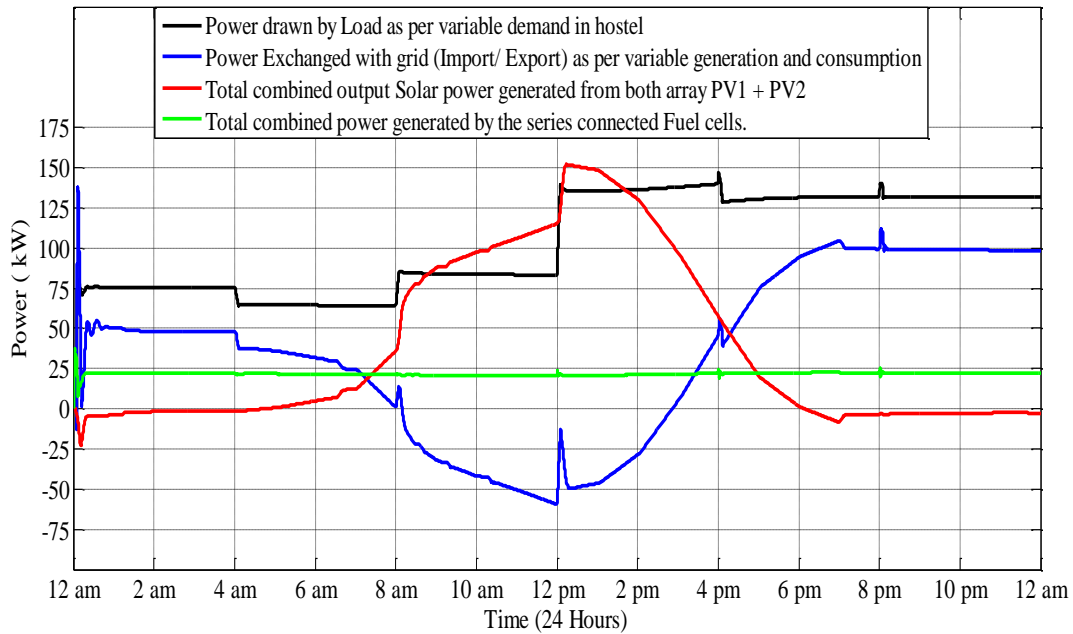


Figure 25. Bi-directional power exchange with grid as per power generated and variable demand.

In figure 25, the blue line representing power exchange with the grid traverses both negative and positive region of graph indicating bi directional power exchange with grid as per requirements. When generation is excess of load demand around afternoon of the day, the blue line which is showing a drift towards negative region, is indicating an excess power being supplied back to the grid.

Fig 26, 27, and 28 are obtained from scopes connected in the load side and it shows the voltage across load and its current variation with respect to variable load power being consumed.

An important part of good quality supply is that irrespective of variable load, voltage fluctuation should be within permissible limits and Fig. 26 confirms that our system is stable and supplies load with approximately 240 volt as required as per Indian electricity law.

Since voltage is constant, the variation in power as consumed by load in Fig 28, is met by varying levels of current drawn as shown in Fig. 27.

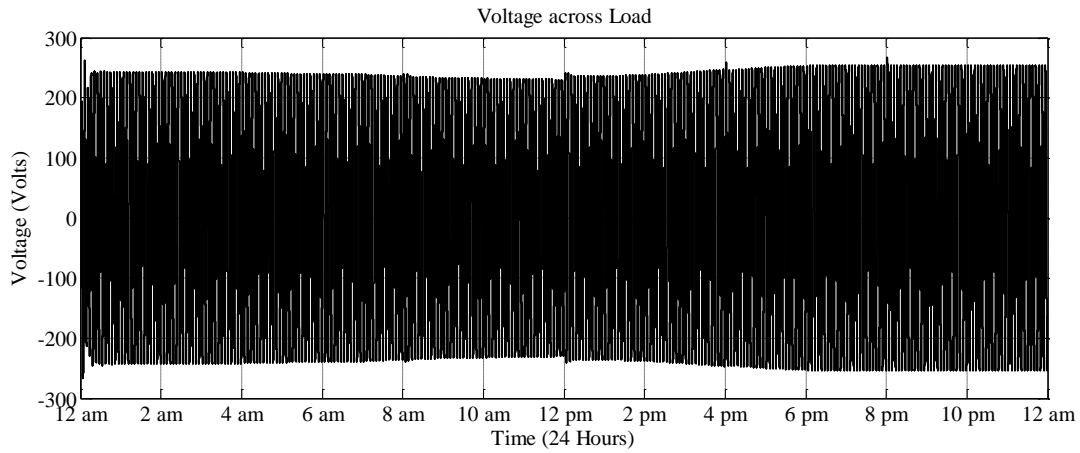


Figure 26. Voltage across load terminals at different time instances corresponding to variable load

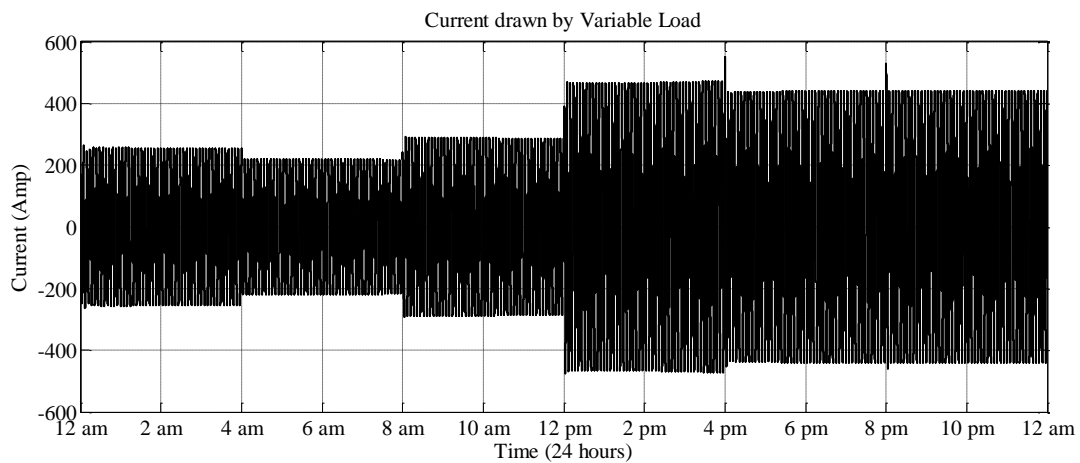


Figure 27. Current drawn by load terminal at different time instances corresponding to variable load.

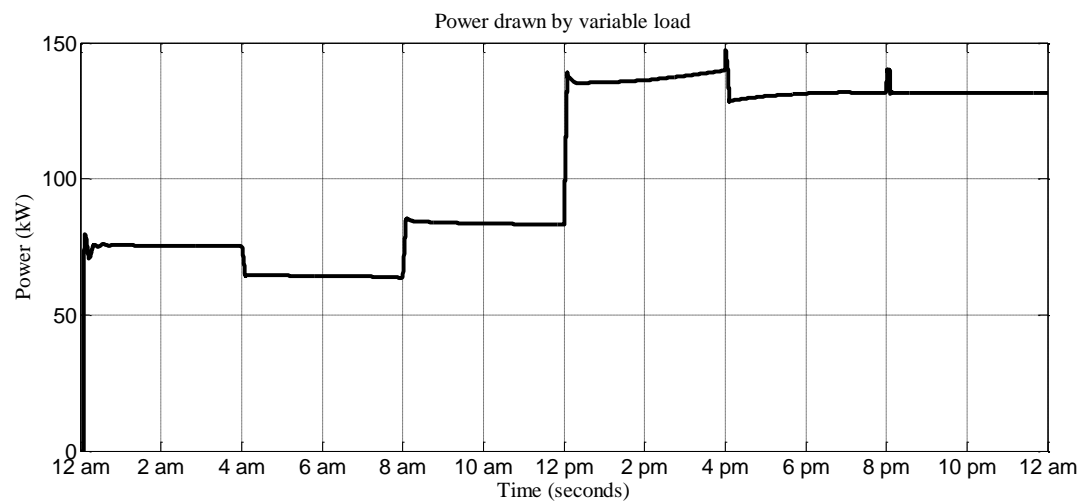


Figure 28. Variable power consumed by load at different time instances.

Sometimes, blackout may occur which will make our grid unavailable so in such case we need to check our systems stability which should be able to work in islanded mode and be able to separate out non-critical loads and then meet the critical load demand. Imagine such a worst possible scenario occurring at 2 pm on X-axis in our figure 29, 30 and 31 assuming that at 2 pm its raining so no sun is available after that and simultaneously a grid blackout also happens. This worst possible case is mimicked in the Simulink model given in Appendix Figure A.1, by opening of circuit breaker from grid side and PV side at 2 pm. In such a case our system which was initially meeting load demand of maximum upto 120 kW will not be able to meet that much with battery alone without grid or solar support so it will switch to meet only critical loads of 30 kW thereby ensuring power supply to important loads and preventing complete blackout. Though it was possible to show the islanding effect with variable load too but for easy analysis we will assume constant load of 120 kW upto 2pm after which islanding occurs and only 30 kW power will be consumed after that and this has been shown in Fig. 29. Corresponding current and voltage variation at load terminals in such a scenario has been shown in Fig. 30 and Fig. 31.

In figure 31, we can find that there is a slight dip in voltage during this islanding at 2pm but the slight dip is within permissible limits of voltage fluctuation and hence our system is able to supply a constant AC voltage of 240 volt \pm 5 volt.

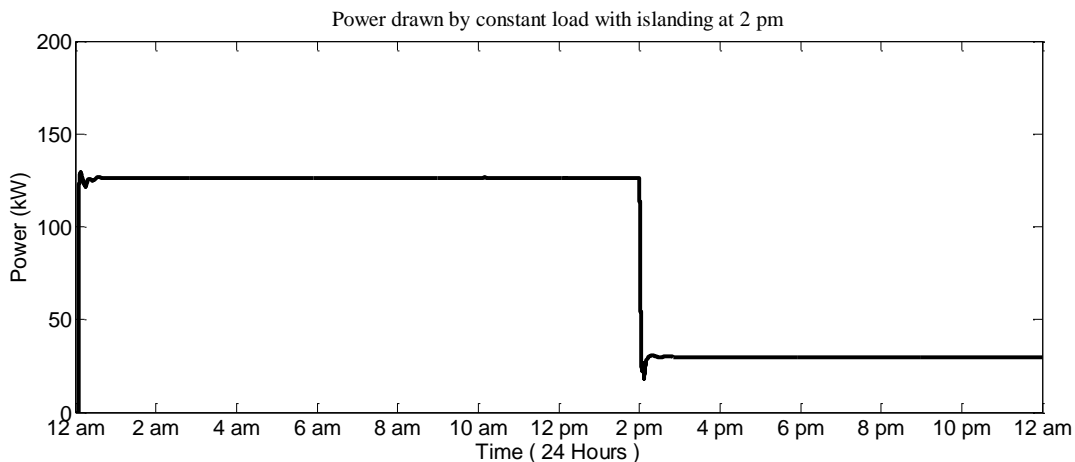


Figure 29. Power drawn by load with islanding at 2 pm on X-axis.

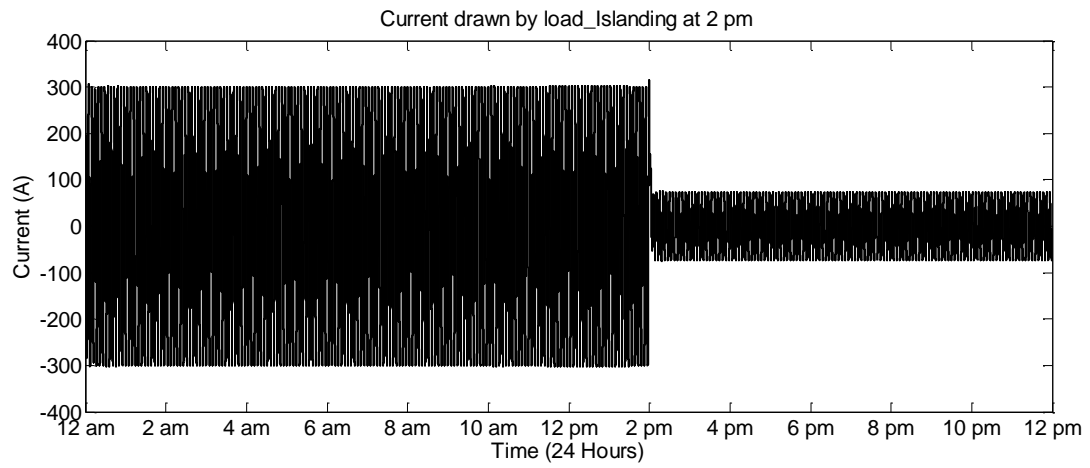


Figure 30. Current drawn by constant load with islanding at 2 pm on X-axis.

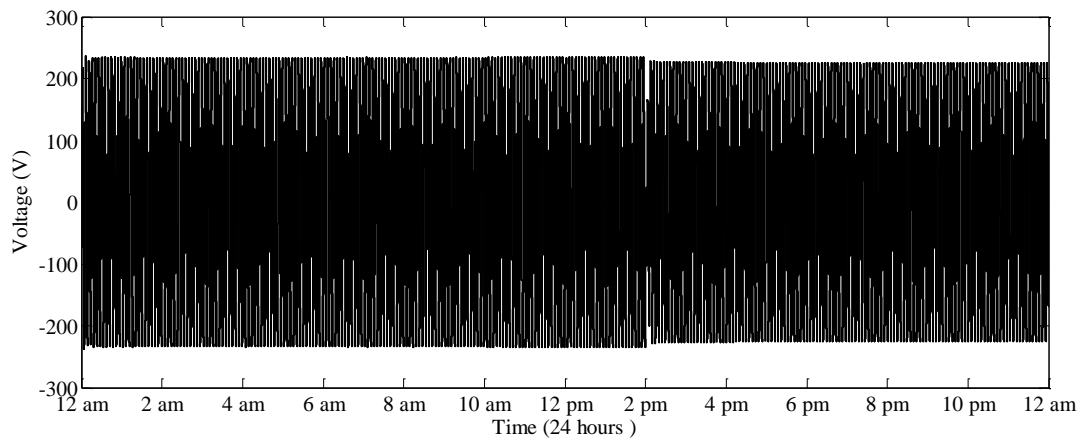


Figure 31. Voltage across the load terminal with islanding at 2 pm on X-axis.

The approach of this dissertation work had main intention of performance evaluation of a PV based microgrid at a preliminary planning and modeling stage of project. The designed model was able to show satisfactory operation results during simulation and this dissertation presented a way to utilise the renewable energy potential of any place for building microgrid models which would prove to be building blocks of future smart cities. It can be said that, prior to any ground installation of microgrid, a huge R&D (Research and Development) cost is incurred for project feasibility evaluation and its expected performance analysis but this dissertation shows how a simulation based approach of study can be a low cost alternative to replace huge R&D cost while ensuring we have fairly approximate idea about system performance output by considering climatic effects while simulating the model. Also, by utilising the biomass waste into an energy source inside the university campus and integrating it with solar energy, we have given an approach towards recycling and generating clean energy.

In future work, the robust model of this dissertation which takes into account the climatic variation effect for PV systems can be used as the base model and the work can be extended for simulating other technical issues in a microgrid like developing a suitable central microgrid controller, developing a protection scheme, studying system stability issues etc. and all these advanced performance evaluation will need a robust base model like given in this dissertation. Also in future an economic feasibility analysis of the modeled system needs to be carried in detail.

APPENDIX

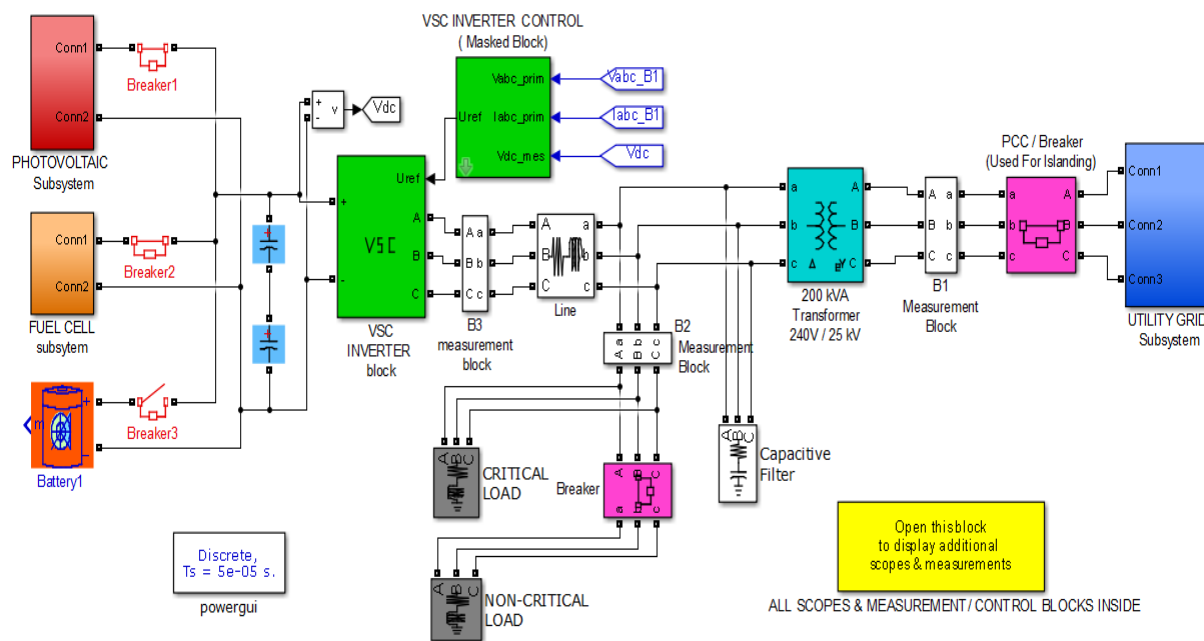


Figure A.1 Overall Simulink model of the proposed microgrid

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