DESIGN OF A GRID CONNECTED ROOF TOP SOLAR PV SYSTEM AND ANALYSIS OF ITS EFFECT ON GRID IN CONTEXT OF BANGLADESH

MUHAMMAD SHAMSUL AZAM AL FAROOK SHIBLEE (SN. 1016160025)

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M.Sc. Engineering Thesis

By

M S A A F Shiblee (SN. 1016160025)

Approved as to style and content by the Board of Examination on 07 March 2023:

Dr. Md. Ziaur Rahman Khan Professor of EEE Department BUET, Dhaka	Chairman (Supervisor) Board of Examination
Md Ali Azam Khan Assoc Professor of EECE Department MIST, Dhaka	Member (Co-Supervisor) Board of Examination
Dr. Enamul Bashar Professor of EEE Department UAP, Dhaka	Member (External) Board of Examination
Dr. Md. Hossam-E-Haider Professor of EECE Department MIST, Dhaka	Member (Internal) Board of Examination
Brig Gen Md Mahfuzul Karim Majumder Dean of Faculty of ECE MIST, Dhaka	Member (Ex-officio) Board of Examination

Department of EECE, MIST, Dhaka

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DECLARATION

I hereby declare that the study reported in this thesis entitled as above is my own original work and has not been submitted before anywhere for any degree or other purposes. Further I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged or cited in the reference Section.

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M S A A F Shiblee

ABSTRACT

Design of a Grid Connected Roof Top Solar PV System and Analysis of Its Effect on Grid in Context of Bangladesh

The grid-connected PV system with net energy metering is viewed as one of the best potential possibilities to improve Bangladesh's generation of renewable energy. In this study, a rooftop solar PV system for a residential building in Mirpur DOHS, Dhaka, is constructed using net metering. The findings demonstrate the extremely high energy output and yield of a rooftop PV system with net metering for residential use. The system has a low Levelized Cost of Energy (LCOE) and a positive Net Present Value (NPV), which makes it both economically and technologically appealing. It has also been investigated how much PV energy the DOHS community area could generate via net metering. In addition, a mathematical model is developed to observe the energy output variation using different tilt and azimuth combinations. Moreover, the grid stability analysis after integrating PV in the distribution feeder is also assessed for the cases like load variation, irradiance variation, three different short circuit fault condition. According to the study's findings, the rooftop PV net-metering system for residential load is practical and can be encouraged to implement as per Bangladesh's current net-metering guidelines.

সারসংক্ষেপ

Design of a Grid Connected Roof Top Solar PV System and Analysis of Its Effect on Grid in Context of Bangladesh

নেট এনার্জি মিটারিংসহ গ্রিড সংযুক্ত পিভি সিস্টেমকে বাংলাদেশ নবায়নযোগ্য জ্বালানি উৎপাদনে উৎকর্ষ সাধনের ভবিষ্যত বিকল্প হিসেবে বিবেচনা করা হয়। এই গবেষণায়, ঢাকার মিরপুর ডিওএইচএস-এ একটি আবাসিক ভবনের জন্য নেট-মিটারিং-ভিত্তিক একটি ছাদের পিভি সিস্টেম একটি রুফটপ পিভি সিস্টেম ডিজাইন করা হয়েছে। ফলাফলগুলিতে দেখায় যে আবাসিক লোডের জন্য নেট মিটারিংসহ একটি ছাদের পিভি সিস্টেমে খুব উচ্চ শক্তির আউটপুট এবং ফলন রয়েছে। অর্থনৈতিক বিশ্লেষণ দেখায় যে সিস্টেমের একটি নিম্ন স্তরের শক্তির খরচ (এলসিওই) একটি ইতিবাচক নেট বর্তমান মূল্য (এনপিভি), এই ধরনের একটি সিস্টেমকে আর্থিক এবং প্রযুক্তিগতভাবে খুব আকর্ষণীয় করে তোলে। ডিওএইচএস আবাসিক সম্প্রদায় এলাকার মোট নেট মিটারিং ভিত্তিক পিভি উৎপাদন সম্ভবনাও অধ্যয়ন করা হয়েছে। উপরন্তু, একটি গাণিতিক মডেল বিভিন্ন কাত এবং আজিমুথ সমন্বয় ব্যবহার শক্তি আউটপুট বৈচিত্র পর্যবেক্ষণ কারর জন্য তৈরি করা হয়। অধিকন্তু, ডিস্টিবিউশন ফিডারে পিভি সংহত করার পরে গ্রিডের স্থায়িত্ব বিশ্লেষণও লোডের ভিন্নতা, বিকিরণ পরিবর্তন, তিনটি ভিন্ন শট সার্কিট ফল্ট অবস্থার মতো ক্ষেত্রে মূল্যায়ন করা হয়। গবেষণায় উপসংহারে বলা হয়েছে যে আবাসিক লোডের জন্য ছাদের পিভি নেট-মিটারিং সিস্টেমটি সম্ভবপর এবং এটি বাংলাদেশের বর্তমান নেট-মিটারিং নির্দেশিকা অনুযায়ী স্থাপনে উৎসাহিত করা যেতে পারে।

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LIST OF ABBREVIATIONS

BESS	Battery energy storage system
CEC	Californea Energy Commission
DESCO	Dhaka Electric Supply Company Limited
PV	Photovoltaics
RE	Renewable energy
SREDA	Sustainable renewable energy development authority
SAM	System advisory model
MPPT	Maximum power point tracker
NEM	Net energy metering
NPV	Net present value
LCOE	Levelized cost of energy
MATLAB	Matrix laboratory
NSRDB	National solar irradiation database
STC	Standard Temperature and Pressure
PCC	Point of Common coupling
SHS	Solar Home System

LIST OF MAIN SYMBOLS

Eout	AC energy output
a, b, c	Observations parameter
kWp	kilo watt (peak)
Voc	Open circuit voltage
Isc	Short circuit current
L-G	Line to ground
L-L-G	Line-line to ground
$/Wp	USD/unit production
Hz	Frequency
MW	Megawatt

CHAPTER 1

INTRODUCTION

1.1 General

This chapter describes the background of the research and literature reviews on PV solar system, net-energy metering policy and comparative study. The research aims and objectives are set, and motivation and contributions are described in the following sections.

1.2 Background

The global electricity demand is expected to reach 38,700 TWh by 2050 to ensure substantial economic development where renewable energy (RE) contribution specially from wind and solar will be 50% [1]. It will save the earth from detrimental effects coal, oil, natural gas and other depleting fossil fuel burning at the power plants. In Bangladesh, the renewable energy production scenario is not good at all in comparison with global scenario. The rising electricity demand of Bangladesh approximated 34,000 MW by 2030, where 15% will be from RE resources - mainly by solar plants according to present target of the government. Currently, electricity demand in Bangladesh is met by fossil-based plants such as oil, natural gas, coal which are limited and exhausts are detrimental to environment [1].

Bangladesh is in northern hemisphere between 20.30° and 26.38° north latitude and 88.04° and 92.44° east longitude and shows tropical climate which is an ideal location for PV solar implementation. In reality, a little portion of energy demand of Bangladesh is filled by solar PV system though Bangladesh receives enough solar irradiance ranges from 215 W/m^2 in the northwest to 235 W/m^2 in the south-east per day which varies between 4 to 6.6 kWh/m^2 /day. Hence, the government of Bangladesh plans to get 40% of its energy from renewable sources by 2041 and reduce 22% of carbon emissions by 2030 [2]. So far, mentionable progress is only stand-alone solar home systems of about 5 million which is predominantly for off-grid areas. On the other hand, lack of available land and high costs are considered as main barriers to building large-scale PV plants. Bangladesh power development board has set up solar PV electrification project in the Chattogram hill tracks region. But, for scarcity of land mass installation of PV solar all over the country cannot be possible where rooftop solar PV system will be the best solution to utilize the solar energy.

However, at present renewable energy contributes only 0.19% of total installed capacity in Bangladesh and out of this, hydro, solar and wind energy share 60%, 39.5%, and 0.5% per cent respectively. Table 1.1 presents the renewable energy production scenario in Bangladesh [3].

Table 1.1 Renewable energy production scenario in Bangladesh [3]

Techlology	Off-grid (MW)	On-grid (MW)	Total (MW)
Solar	356.75	367.98	724.73
Wind	2	0.9	2.9
Hydro	0	230	230
Biogas to Electricity	0.69	0	0.69
Biomass to Electricity	0.4	0	0.4
Total	**359.84**	**598.88**	**958.72**

The residential sector in Bangladesh is responsible for 50% of electricity consumption. Due to the increase in primary fuel and retail electricity prices in the past ten years, electricity has become costly for consumers. Therefore, many countries have incorporated rooftop PV production by utilizing unused building roof space. Moreover, the installed PV systems also require a battery energy storage system (BESS), which is less cost-effective because of the installation, periodic maintenance, and high capital cost. Bangladesh adopted the Renewable Energy Policy in 2008, which mandates the sourcing of 10% of electricity from renewable sources by 2020 [4]. The Bangladeshi government's current renewable energy policy calls for the specialization of renewable energy generation budgets in order to reduce global pollution while promoting the sector's use of biomass, solar, hydro, wind, and tidal power. Recently, Sustainable Renewable Energy Development Authority (SREDA) of Ministry of power, energy and mineral resources has provided net metering guidelines focusing urban area to encourage distributed RE development, mainly by solar PV installations at free open spaces like rooftops of residential, commercial and industrial complexes by allowing the customers to generate their own electricity and use it to offset the amount of energy they draw from the grid and also, to export excess amount to the grid [5]. Again, the PV system's output should have low distortion, thus other equipment connected to the utility system is not adversely affected. Besides, the installation should comply with the relevant national and international safety standards like earthing, lightning protection etc. that are to be considered for the safe operation of the system, presently missing in many such installations. In context, SREDA from the government of Bangladesh has articulated a PV net metering policy in 2018 to enhance the electricity production from solar PV systems. According to this policy, a customer produces electricity from a PV system and can export excess energy to the grid if the generation is more than the demand. In opposite, if the generation is less than the load, customers can import additional energy from the grid to meet demand. Therefore, the customers work as the "prosumers" who are producing and consuming electricity at the same time. Currently, 1677 net metering-based systems are installed across the country with a total capacity of 45 MWp, mainly in industry and KEPZ alone has almost 15 MWp of installed capacity. As of today, residential consumers are not allowed to participate in the net-metering scheme according to the existing policy, designed by SREDA. Therefore, net-metering technical and economic feasibility for residential consumers needs to be investigated to incorporate them in the current policy [6].

In Bangladesh despite having great potential of PV solar energy sources, the sector currently consists of only 1% share of the energy portfolio. Absence of proper regulated tariff and incentive structure, lack of regulatory and institutional framework play a vital role for discouraging the third-party owner to invest in installation of IPP projects. Other countries have established some incentive mechanism to promote the deployment of such IPP solar projects. There is lack of nationally recognised technical standard for large solar PV projects [7]. There is no such study that evaluated the overall IPP solar tariff scheme by considering installation cost, debt-equity ratio, interest ratio, net present value, loan tenure effect on LCOE for different PV solar tariff mechanism in perspective of Bangladesh. Bangladesh has a huge prospect on PV solar energy due to its geographical location. For the enhancement of solar IPP projects an assessment is required to evaluate Net-Energy Metering (NEM) to understand their impact on economic parameters and derive the most promising tariff alternatives to be applied in solar PV system [8].

1.3 Related Works

Several research works on the viability of net-metering solar PV systems in Bangladesh have been carried out, mainly for commercial and industrial buildings. For example, a study explores the feasibility of a solar energy net-metered easy-bike charging station in

Bangladesh and its cost effectiveness after applying the NEM policy [9]. On the other hand, for a commercial building with 10 stories, Bangladesh's net metering applicability is assessed to calculate the annual net savings and payback period [10]. At a building with net metering, a 2 kWp rooftop PV system was built, and it was determined to be profitable with a 12-year payback period [11]. A recent study conducted in an educational building in Bangladesh found that PV system investment was feasible in terms of electricity cost [12]. In addition, few studies are conducted on industrial PV systems. For example, a study compared net billing and net-metering schemes for industrial loads to identify the grid limiting factor[13]. In another study, the economic sustainability of net billing and feed-in-tariff (all energy buy/sell) methods for industrial PV systems in Bangladesh is compared to current net-metering based on plant capacity factor, excess energy transfer, Levelized cost of energy (LCOE), net present value (NPV), payback period, and profitability index (PI). The study found that the adaptation of other schemes in the present guidelines can enhance industrial PV production in Bangladesh [14] Interestingly, there have been a limited number of studies found to assess the residential net metering systems in Bangladesh. A study conducted on the residential net metering assessment found that the PV net metering system is profitable with a payback period of 6.85 years [15]. A research article addressed the limitations of current net metering guidelines. It recommends modifying the policy with updated features like connecting residential consumers, providing a carbon credit facility for the utility, mitigating the 10 MW capacity limit, and using excess electricity at any place apart from the grid by giving the wheeling charge [8]. Therefore, a prevalent knowledge and research gap are found in the assessment of PV net metering for residential consumers in Bangladesh in context of both technical and economic feasibility.

1.4 Motivation of the Work

From a broader perspective, the motivation of the proposed research work is the assessment of residential roof top PV system technical and economic viability and, identify the energy production capacity of community area. In this work, assessment of Net-Energy Metering, for a residential building in carried out. Bangladesh government has established a net metering policy which is still on test for large scale deployment. So, we are going to analyze the net present value, LCOE, payback period, annual net savings for different PV installation, net energy delivered to the grid and cost analysis for different scheme for a residential building. Moreover, a mathematical equation has also been developed to assess the output energy variation with the change of tilt and azimuth. The grid impact is also analyzed if a significant volume of PV energy is integrated with grid. The systematic review of related research works persuades that there is much scope for improvement in the performance metrics of the existing work.

1.5 Research Objectives

The objectives are:

(i) To assess rooftop solar potential by contour mapping of a residential area.

(ii) To find out a mathematical model of PV yield of solar panel at different roof orientation and tilt angle.

(iii) to make a complete design of a grid-tied PV system following net-metering guidelines of Government.

(iv) To determine various effects on grid when huge solar power will be connected to it.

1.5 Research Contribution

In pursuit of fulfilling the distinctive objectives, this research contributes to a number of novelties, some of which are already published at international conferences and the rest are drafted for the possible publications. The major contributions of this research are summarized below:

(i) Techno-economic assessment of residential PV systems with net-metering in terms of LCOE, payback time and Net present value (NPV) which identifies the system profitability.

(ii) Identify the net energy trading value of by importing and exporting from the grid for a residential building.

(iii) Estimate the annual energy production for the residential community.

(iv) Develop the mathematical model of the annual energy production by varying the tilt and azimuth.

(v) Grid impact analysis is conducted if significant volume of PV is integrated to the grid in terms of load variation, irradiation variation, short circuit analysis.

1.6 Research Organization

The research embodied in this thesis is divided into six chapters, organized as follows:

(i) **CHAPTER 1 - INTRODUCTION:** At first, this chapter introduces the general overview. Next, the related works are briefly described, followed by the motivation of the work. Henceforth, the research objectives are included. The research contributions are summarized afterward. Finally, the research organization is represented.

(ii) **CHAPTER 2 - LITERATURE REVIEW:** Initially, the general overview of this chapter is considered. Later, the different components of PV system design and net-energy metering is discussed. Then, the comparative study on different literature on net metering is presented. Finally, the challenges and mitigations of grid impact to integrate large scale PV is briefly discussed.

(iii) **CHAPTER 3 – METHODOLOGY:** This chapter represents the general overview. Subsequently, the solar irradiation analysis, load modelling, PV system design and tariff design is described in detail. Then, the mathematical model is developed to determine the output energy variation with tilt and angle. After that, the grid with PV systems is designed in Simulink to assess the grid impact.

(vi) **CHAPTER 4 – RESULTS AND DISCUSSIONS:** Primarily, the general overview of this chapter is focused. After that, the simulation set up are illuminated. Techno-economic assessment of residential PV systems with net-metering in terms of Levelized cost of energy (LCOE), payback time and Net present value (NPV) are presented which identifies the system profitability. Then, the net energy trading value is estimated for a residential building and annual energy production for the residential community is calculated. Then, a mathematical model of the annual energy production by varying the tilt and azimuth is presented. Finally, grid impact analysis is conducted if significant volume of PV is integrated to the grid in terms of load variation, irradiation variation, short circuit analysis.

(iv) **CHAPTER 5 - CONCLUSION AND FUTURE RECOMMENDATIONS:** Firstly, this chapter sums up the conclusion. Thereafter, the limitations of the work are addressed, followed by the future recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter presents a comprehensive analysis of the existing literature related to the proposed work. The overview of PV system in Bangladesh with the analysis of technical PV system design is presented in section 2.2, 2.3 and 2.4. The comparative study of net-metering policy applied in many countries illustrates in section 2.5 and 2.6. Finally, section 2.7 and 2.8 discusses the PV grid integration challenges and different ways to mitigate this.

2.2 Overview of PV System in Bangladesh

Bangladesh has introduced PV solar system as an alternative option to address the basic energy crisis in the off-grid rural area first in 2003[16]. Solar home system was introduced in the areas where grid expansion was challenging. Infrastructure Development Company Ltd (IDCOL), a government-owned company, assisted with the Solar Home System (SHS). The SHS Program's main objective was to provide Bangladesh's rural residents' fundamental power needs. 18 million individuals now have access to solar power thanks to the installation of 4.13 million SHSs. Bangladesh has very good monthly average solar radiation all over the country [17]. The daily average insolation varies between 4 and 6.5 kWh/m^2 and thus, Rooftop Solar Project has been introduced for the rapid development of solar PV sector on a massive scale in Bangladesh. IDCOL has approved 11 Rooftop Solar Projects of which 4 are in operation with a cumulative capacity of about 3.07 MWp. The Government has developed Net Metering Guideline on August 2018 to encourage the use of vacant spaces and rooftops in solar power generation. To boost up the installation of solar energy in our country, the net metering policy focused on the industrial sectors, largest power consumer in Bangladesh. It is mandatory that any new building must use 3% renewable energy. The rooftop capacity limit is 70% of the load according to the net metering policy [4].

In solar PV systems, cells are utilized to transform solar energy into electrical energy. One or two layers of silicon or another semi-conducting material comprise the PV cell. When light shines on a cell, electricity flows through the layers of the cell, creating an electric field. When solar cells are exposed to full sunlight, they can produce up to a kilowatt peak, or kWp, of electricity. The flow of electricity increases with increasing light intensity. The solar cell is the key building block of solar photovoltaic (PV) technology. People are commonly familiar with calculators that are powered by PV solar cells. These cells are linked together to form a module. PV modules absorb solar energy from the sun and convert it into direct current (DC) electricity. An inverter can convert this DC power to alternating current (AC power, which is the type of electricity used in your home). Several PV modules form a PV solar panel system. Large PV systems can be integrated into buildings to generate electricity [11]. Figure 2.1 shows the operating principle of solar PV system.

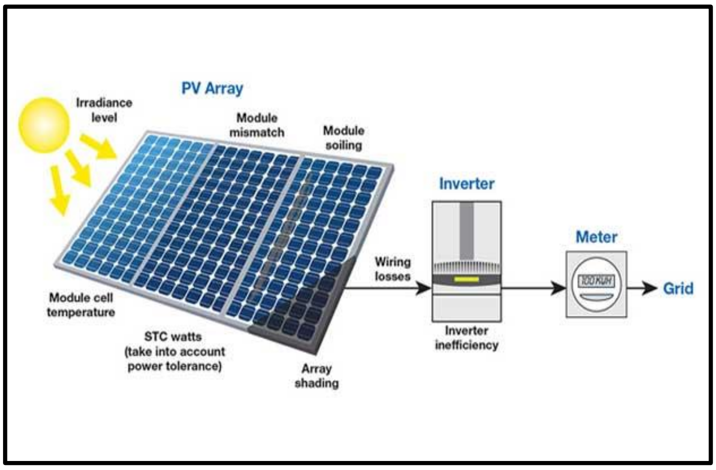


Figure 2.1: Operational principle of Solar PV system

2.3 Types of PV Solar System

The essential principles of operation are the same for all solar power systems. Solar panels first convert solar energy, or sunlight, into DC power via the photovoltaic (PV) effect. After being either stored in a battery or converted to it by a solar inverter, the AC electricity can then be used to power home appliances. Depending on the type of system, excess solar energy can either be fed into the electrical grid in exchange for credits or stored in a variety of battery storage devices. There are three different types of solar PV systems: grid-tie or on-grid, stand-alone or off-grid, and hybrid-grid connected solar systems with battery storage.

2.3.1 On-grid System

On-grid or grid-tied solar systems are most ubiquitous and frequently used in homes and businesses. These systems use solar inverters or micro-inverters rather than batteries and are connected to the public energy grid. The electrical grid receives any excess solar energy the system generates, and customers are often rewarded with credits or feed-in tariffs for the energy exported. In contrast to hybrid systems, on-grid solar systems are unable to function or generate electricity during a blackout for security concerns. If the solar inverter was still supplying electricity into a damaged grid, blackouts would likely occur, which would put the safety of the employees repairing the network fault(s) at jeopardy. Most battery-powered hybrid solar systems have the ability to instantly cut off from the grid (a maneuver called islanding), continuing to deliver some electricity even during a blackout. Batteries may eventually be added to on-grid systems if necessary.

2.3.2 Off-grid system

Battery storage is required because an off-grid system is not hooked into the electrical grid. Off-grid solar systems must be carefully designed to be able to generate enough electricity all year long and have enough battery storage to meet the needs of the home, even during the shortest months of the year when there is often much less sunlight. Off-grid systems are typically needed in more rural areas that are not connected to the energy grid.

2.3.3 Hybrid System

In a variety of designs, modern hybrid systems combine solar electricity and battery storage. Battery storage is becoming more affordable, allowing systems that are already wired into the electrical grid to start using it. There must be a means to store solar energy during the day and use it at night for this to function. Since the grid serves as a backup in case the energy in storage runs out, customers benefit from the best of both worlds. Hybrid systems also have the option of using less expensive off-peak electricity to charge their batteries.

2.4 PV System Design Criteria

Many factors affect how much electricity a solar installation produces. They include the system's design and installation (tilt, orientation, stringing configuration, etc.), as well as environmental variables like sunlight, soiling, and snow. In order to guarantee that a PV system design will generate enough energy to meet consumers' needs, an accurate estimation of that amount is necessary. There are a few key factors to take into account while using solar PV systems [18], [19].

2.4.1 Solar Irradiance

The average daily sun radiation in Bangladesh varies from 4 to 6.5 kWh per square meter. If the insolation was 6 kWh per square meter on a certain day, a 1 kW solar PV system would produce 6 kWh of power. It should go without saying that increased sunlight increases the amount of electricity generated by solar PV systems. But other factors also have an effect on the system's output.

2.4.2 Optimal Sizing of PV Module

It is critical to size solar PV systems effectively because they demand capital investments. It starts by figuring out how much electricity the consumer uses. It is advisable to start with energy-efficient equipment so that the amount of energy required is kept to a minimum because the daily electricity demand will determine the size (and price) of the solar system. A successful design requires an accurate estimation of the daily electrical load. As a result, energy efficiency concerns should be taken into account while building and installing the solar system. A charge controller, an inverter, and batteries are among the wired parts of a solar PV system. All of these are just partially successful.

For instance, the battery needs to be charged for around 115–120-amp hours for every 100-amp hour that are used from it. Both inverters and charge controllers are often only 85% effective. Because of the relatively low DC voltages involved, cables provide electrical resistance to the flow of current that is significant. People strive to keep it low by using higher DC voltages where it is feasible while still maintaining low wire costs and resistance losses (let's say less than 3%). Hence, the modules must contribute more energy to the system than just the daily watt-hour load in order to account for all such losses.

2.4.3 Solar Panel Efficiency

The efficiency (wattage per unit panel area) of the panels becomes a critical issue due to the limited rooftop space. Lower efficiency panels occupy more area than those with greater efficiencies. The solar PV facility's size will be constrained. On rooftops with limited space, the solar panels with the maximum power per square foot must be chosen. A 1 kW solar PV system typically needs 100 square feet of space, depending on the panel efficiency. Efficiency of a panel is expressed as Panel kWp per sq meter of the panel, expressed as a percentage. Another important consideration is tilt or angle in reference to the horizontal.

For fixed panel systems, it is frequently considered to be the same as the relevant site's latitude. In case of confusion, the best option is to consult a solar PV system installer.

2.4.4 Inverter Sizing

An inverter is used when the PV system wants to produce 220V-AC electricity. The DC input voltage must be the same as the battery bank's voltage (12V, 24V, or 48V), and it must never be less than the total rating of all the appliances. In general, the inverter size should be 25–30% bigger than the sum of the appliance wattages. If the load contains a motor or compressor, the inverter's size should be at least three times that of the load to be able to handle the initial surge current.

2.4.5 Temperature Co-efficient

The temperature coefficient determines how well solar panels will perform under less-than-ideal conditions. Solar panels perform best when kept cool, ideally at or below 25 °C (77 °F), just like other electrical equipment. The temperature coefficient reveals how the panel's performance will be affected by hot summer days. For every degree above 25° C (or 77° F), the temperature coefficient results in a reduction in the electrical output of solar panels. A smaller temperature coefficient is preferable. The temperature of the panel affects its output. The solar panels should be positioned to encourage increased air circulation rather than being in enclosed spaces because the local temperature cannot be adjusted.

2.4.6 Power Output of Solar PV Plant and Shading

A shade-free space is necessary for solar PV power plants. Shadows may be cast by nearby structures such as other buildings, cell phone towers, billboards, and trees. A row of panels may even create a shadow on the rows behind it, causing the shadow to come from the PV plant itself. Longer shadows at higher latitudes necessitate a wider roof area for the plant. Not only can shadows lower the output of the panel, but they also run the risk of damaging it. Shadowed parts begin to heat up and change from being a conductor to an insulator; eventually, this might cause those areas to burn. The warranty does not cover such damages. The complexity of a solar PV plant's actual power output is dependent on a number of factors, including insolation, panel orientation, tilt angle, temperature, and others. Traditionally, the capacity utilization factor is used to measure the performance of PV plants (CUF). The CUF is the ratio of a plant's actual output to its maximum feasible output under ideal conditions, represented as a percentage (assuming that the sun shone every day of the year).

2.4.7 PV Solar Loss

Several factors might lead to energy generation loss in solar PV systems. There are three typical types of DC losses: nameplate, mismatch, and degradation brought on by light. When we talk about DC losses, we're referring to conditions that lessen the quantity of direct current (DC) energy generated by solar panels before that energy is transformed into alternating current (AC) by the inverter for usage in the house and on the electric grid. The output of the PV modules will be decreased by these % values because they are all applied to the system as fixed-percentage DC-side losses. Electrical wire losses on the AC side of the system are covered by the AC losses. Transformer loss is the electrical loss caused by a distribution or substation transformer that is accounted for in the yield of an extensive photovoltaic system. "System availability losses" are reductions in system output brought on by operational needs such as maintenance outages or other occurrences that prohibit the framework from functioning as planned.

2.4.8 Accessories of the PV Plant

This is an important factor in windy areas because solar panels along with their mountings can be fairly heavy. It is not a problem for concrete roofs but asbestos and other roofs may be too fragile and pose safety problems. So, the roof should be sturdy enough to withstand the weight and wind load of the plant. It is needed to store the DC current from the panels into batteries and then convert it into AC through an inverter for end use. Type of batteries and inverter will also determine the overall efficiency of your solar PV system. In summary, energy efficiency considerations must always precede solar PV design; it further helps to know various factors that dictate the actual power output from your solar system.

Due to the weight of solar panels and their mountings, this is a crucial consideration in windy places. Roofs made of concrete are unaffected, but other roofing materials, such as asbestos, may be dangerously brittle. In order to support the weight of the plant and the wind load, the roof must be strong enough. The DC electricity generated by the solar panels must first be stored in batteries before being converted to AC for usage. The batteries and inverter you pick will also have an impact on how efficient your solar PV system is overall. In conclusion, solar PV architecture must always take energy efficiency into account. It is also helpful to understand the numerous elements that affect the actual power generated by array

2.5 Net Energy metering (NEM) policy for Grid Connected PV System

There is different policy that gives customers with solar installations credit for the electricity generated by a photovoltaic (PV) system. Different tariff scheme has been developed for on grid PV framework and practiced in many countries. In this scheme, excess generation is the difference between the system's total monthly generation and total monthly consumption. For months with excess generation, the excess is "rolled over" to the next month's bill, effectively reducing the billable kilowatt-hours in that month. Excess generation at the end of December is credited to the December electricity bill at the year-end sell rate (which can be zero). if the amount of energy consumed is more than the amount of energy generated, then it is imported from the utility grid and the owner pays only the net amount. Power utility companies more than 50 countries around the world are practising some form policy mechanism and allowing residential and commercial renewable energy (solar, wind) based plant to connect to the national grid. In 2018, the government has introduced net metering policy for mass deployment of On-grid solar PV system. NEM is a policy which permits an electricity consumer to balance some of his consumption positively through importing energy to the utility grid. Figure 2.2 presents the schematic diagram of net energy metering system [20] .

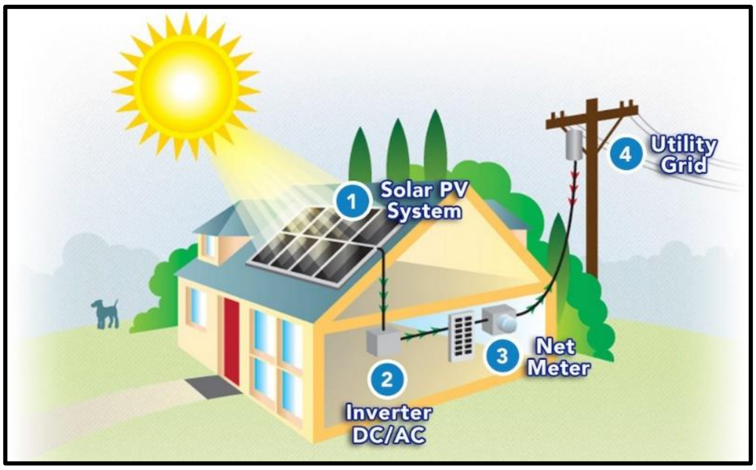


Figure 2.2: Schematic diagram of net energy metering system

According to NEM policy, the excessive electric energy is imported to the utility and the same amount of electricity can be consumed from the utility without any cost or consumers get a credit which is paid after a settlement period from utility. NEM mechanism works by installing a Bi-directional energy meter which is capable to measure net energy flows in any directions both from utility to consumer and from consumer to utility. At the end of settlement period, the consumer electricity bill is calculated according to the net energy recorded in the net energy meter [21]. If the consumer import more than export, then the extra units will roll over to the next billing period. Three different energy meters can be used in the system where two are unidirectional as solar accounting meter and self-consumption meter and one bi-directional meter as net meter. In Bangladesh, as per third party owned systems operation expenditure (OPEX) model, solar accounting meter and self-consumption meter installation is compulsory for NEM structure. A particular amount of price is provided to the renewable energy system provider according to re-accounting meter. To inter-connect with the grid connected net metering system the consumer must have 3 phase connection along with converters output not exceed 70% of the load [22]. Generated electricity must maintain nominal voltage, power factor, frequency and harmonics. Protection system scheme must be ensured strictly by the consumers so that it do not hamper the stability of the distribution utility and other consumers of this PV system Since Bangladesh has introduced the NEM guideline recently and has limited experience therefore to reduce the regulatory and technical challenges, the guideline limit the range of export energy. The prosumer cannot export energy more than 70% of total sanctioned load. Under net metering scheme, any prosumer can export maximum 3 MW of power to the grid [8].

2.6 Comparison of Various Net Metering Schemes

By 2017, 46 countries have net metering policy all over the world. There are some major factors that matter in the policy making as – the year of commencement, limits on installed capacity and electricity export, metering arrangements, cost allocation, credit policy, settlement period etc. In most of the cases, the settlement period is 12 months. Except in Malaysia the settlement period is 24 months and in Philippines this time is fixed by an agreement between both parties [23]. In Sri Lanka, Netherlands and Slovenia settlement period is not specified. For metering purpose, almost every country allows a bidirectional meter; only in some cases, they allow two unidirectional meters. In most of the net metering policies of different countries, there is no specification of consumer classes [24]. Only in some states of Canada, Malaysia, Slovenia, some states of India, they have classified their consumers [25]. Generally, the classification is based on residential, commercial, and industrial building. Also, in some areas, the classification is according to voltage. In every policy, a capacity limit has been specified. In California, they allow the highest capacity to limit up to 1 MW. Some countries allow up to 100 kW. In some other countries' policy, they have set up the capacity limit according to 1 phase and 3 phase system and according to consumer classes. The credit settlement rate differs from country to country. In some states of Canada, United States, and India, they credit according to prevailing retail rate. In California, they credit according to net surplus compensation. In Philippines they credit 5.658 peso/kWh [21]. In Malaysia, they credit according to net bill. In Sri Lanka, the credit settlement rate is fixed for first 7 years (Rs 22). And in Netherlands the import export has same value. So, every country has different net metering scheme due to the countries' socio-economic structure, PV installation system, the weather, the demand and capacity limit etc.

On the other hand, India has been promoting the installation of solar PV system to ensure the increasing energy demand. The government is ensuring special services for the installation of solar park [26]. The SPPD will estimate the total cost of the project and then formulate a recovery model to ensure the sustainability of the solar parks. Moreover, the investors are allowed to pay in four installments at different stages of the project duration. The authority is ensuring a large-scale solar project by lowering the tariff trends. Also, it is obligatory for the state governments to purchase at least 20% of the generated electricity through its utility companies. The project implementation deadline has also increased up to 2 years for solar PV instalment. So, India has ensured an investment friendly policy to make the process more efficient and convenient. A study in India has researched about the economic feasibility of net metering and gross metering policy for 3 types of consumers where first 2 consumers are primary residential consumers and third one is a school. The payback time is lesser for consumer 2 and 3 in net metering policy comparing to gross metering. Also, the NPV for consumer 2 and 3 has found positive for net metering scheme. In Sri Lanka, a financial evaluation was studied for three cases. Case A: optimized SPVP, Case B: optimized B-SPVP, Case C: improved cost of Battery Energy storage system (BESS) (in USD/kWh) of B-SPVP to ensure optimized NPV, payback time. For a solar PV capacity of 14.06 MW, in case A the NPV and simple payback time is 14 (USD mil) and 16 years. But due to the cost of BESS, the payback time becomes 156 years in case B. In case C, if the cost of BESS can be 135 USD/kWh, then the NPV and payback time increased to 28 million USD and 26 years in an optimum range comparing to case A. In 2008, there has been a big push in Indian policy circles called ‘go green’ to ramp up the contribution of renewable energy sources to the domestic power supply. The subsidy policy is reconstructed to encourage mass population for installation of rooftop solar PV to meet the target of 40 GW of decentralized solar rooftop PV up-to 2022. For the solar rooftop installation in building of residential, social, or institutional sector, the capital subsidy is 30 % of the project cost or benchmark cost. The push made by India to modernize electricity infrastructure has been a major source of inspiration for scaling up of solar capacities.

In Europe, Solar PV system became an emerging option in 2000. But, the mass deployment of PV solar system was not possible due to policy decision that resulted in substantially increased installed capacity [27]. All the European countries except the United Kingdom have experienced a similar pattern of behaviour in annual installed capacity where period of rapid growth is maintained for two or three years and then followed by a sharp decline. For the enhancement of policy and regulation solar PV contributes more than 7% of overall electricity demand in European countries. A study in Netherland has found that, the simple payback time is around 3 years for the net metering policy for a reference system which leads to overvaluation. On the other hand, abrogating net metering without introducing any new policy leads to a sharp increase in the simple payback time. The study has shown that full maintenance of net metering and fiscal maintenance of net metering has very less difference in the payback time. Rather in limiting net metering or Feed-in subsidy or Investment subsidy policy can achieve a stable payback time around 7 years from the year of purchase for a system [28].

2.7 Solar Grid Integration Challenges

Solar grid integration is the process of allowing solar photovoltaic (PV) power into the national utility grid. There are two main types of grid-connected solar generation: distributed generation, which refers to: Small scale generation (small residential and commercial renewable solar typically range between 5 and 500 kW) on the distribution grid (where electricity load is served,) and Centralized, utility-scale generation (hundreds of megawatts of power), which refers to larger projects that connect to grid through transmission lines. Distributed solar PV power integration offers special advantages such less line losses, greater grid resilience (i.e., the ability to endure or recover fast from challenges), avoided generation expenses, and decreased operation costs. Grid operators have difficulties as a result of solar power's intermittent nature due to unpredictability, variability, and location-specificity as it becomes more widely used on the grid.

PV has a maximum generation limit; however, this limit is not precisely determined and changes over time (variability). As a result of high penetration, gird operators must be adaptable and quick to respond to changing circumstances and production patterns by taking additional supportive measures like frequency regulation and voltage support. If this isn't done, there could be power outages and shortages. When there is insufficient demand during periods of high production, grid operators must restrict output. This results in a financial loss for solar generators and drives up the levelized cost of electricity (LCOE) of PV generating. The list of difficulties is as follows:

2.7.1 Frequency Fluctuations

The frequency of a power system must be kept in close proximity to its nominal value (for example, 50 Hz or 60 Hz depending on the grid). Frequency fluctuation happen when the generation and load are out of sync. It is typically possible to lessen the effects of output fluctuations caused by weather changes by altering the output of conventional generators. As PV generation becomes increasingly common, the system's inertia continues to decline, which poses a serious threat to the frequency stability of the system.

2.7.2 Voltage Variations

Voltage variations in the low voltage grid may be generated by rapid transients in the power output of PV systems brought on by cloud transients. Any system with a high PV penetration is more significant. Standards for electricity quality might be broken as a result of this. The intensity of voltage fluctuations is influenced by the grid's location, installed PV capacity, and grid layout. Voltage fluctuations and flicker may cause damage to electrical equipment linked to the grid, and anyone exposed to them may feel discomfort and health problemsAs PV generation becomes increasingly common, the system's inertia continues to decline, which poses a serious threat to the frequency stability of the system.

2.7.3 Challenges in supplying Reactive power

Voltage and reactive power are directly related, hence managing reactive power is crucial for maintaining voltage stability in the power system. In order to maintain a continuous and dependable electricity supply, each new solar photovoltaic (PV) plant built within the grid system must meet the grid code requirements. The electrical system will have certain difficulties with reactive power control and voltage support as PV plant penetration increases.

2.7.4 Islanding

Unintentional islanding is the possibility that a portion of a distribution system will keep running even if a safety measure disconnects the main power supply. Equipment damage and safety risks could be brought on by an unforeseen island. Grid-connected PV inverters contain anti-islanding capabilities to prevent these issues. The two dangers associated with installing PV systems and conventional rotating-machine-based distributed generation are the potential for harm to utility workers using the circuit and the potential for equipment damage due to operation outside of regular utility-controlled conditions.

2.7.5 Increased Short Circuit level

Short circuit contributions to the electrical grid are increased when a PV system is added. Short circuit interference can result from faulty voltage channels that either directly or indirectly make contact with the circuit. In addition to endangering human safety, the short circuit harms machinery and the electrical system.

2.8 Mitigation Options for Integration Challenges

Due to declining costs, renewable energy policies, and net zero emission targets, solar energy is anticipated to experience significant growth in the upcoming years. The power system should be more adaptable in all areas, such as operations, demand, energy storage, generation, and transmission.

2.8.1 Operational Flexibility

Real-time forecasting, quicker scheduling, quicker power system operations, and integrating flexibility reserves into auxiliary services are the least expensive options for flexibility. In many energy systems, the problems of integrating renewable electricity at low to moderate penetration levels can typically be resolved solely by operational measures.

2.8.2 Generation Side Management

A few examples of a plant's flexibility include its capacity to start up and shut down fast, run at a low minimum load, quickly modify producing output, and offer ancillary services to ensure system reliability. Gas-fired or diesel power plants are frequently the most adaptable fossil fuel technology, but hydroelectric power plants are the most adaptable conventional technology. Comparing nuclear and coal-fired power plants, nuclear power plants offer the least flexibility. System flexibility can also come from varying renewable energy sources of electricity.

2.8.3 Demand Side Management

Demand response, which includes time-of-use pricing, real-time pricing, or "incentive-based" pricing for consumers' interruptible or curtailable load, improves flexibility by enabling or rewarding customers to change their demand in response to system events or financial conditions. Consumers who allow the system operator to immediately reduce the load may receive a financial award.

2.8.4 ESS

Energy storage can be used to adjust for variations in renewable generation over the course of a day or several days. When variable RE penetration is high, energy storage technologies like pumped hydro, compressed air, thermal storage, and batteries are beneficial. Storage can reduce curtailment throughout the day when energy output is at its highest and can absorb energy thanks to its short response times.

2.8.5 Transmission Network Interconnection

Access to a range of supply and demand side resources is made possible via transmission networks, increasing the energy system's adaptability. Diversifying the site of renewable electricity generation reduces the overall, system-wide unpredictability and uncertainty of solar generation since weather patterns are less correlated over large or diverse geographies. All generation assets are merged through such connectivity, increasing flexibility and reducing net variability across the whole power system. By extending the balancing zones, the load and variable RE's net variability and uncertainty are also decreased.

CHAPTER 3

METHODOLOGY

3.1 General

The grid-connected PV system is built for a single residential building using one-year load data. The designed PV system's technical and financial viability is assessed when net metering is implemented. Using output parameters, such as annual energy production, cumulative net metering (kWh), Net present value (NPV), Levelized cost of electricity (LCOE), payback period, and system capacity factor, the residential PV system is assessed. The System Advisory Model (SAM) from the National Renewable Energy Laboratory (NREL), USA, was used to simulate the examined PV system.

In the second stage, outputs for various tilt degrees and latitudes were calculated using the System Advisory Model (SAM). With the aid of simulation results and linear regression analysis, a mathematical model was produced. The production of AC energy from the system is considered a dependent variable in this model, while the tilt angle and azimuth are considered independent variables. The MATLAB "regress" function is then used to calculate the coefficient of the proposed linear model. The third stage of the study looked at the impact of the system in the gird after building a model of the system with a gird connection in SIMULINK. In Figure 3.1, the study's conceptual procedure is displayed.

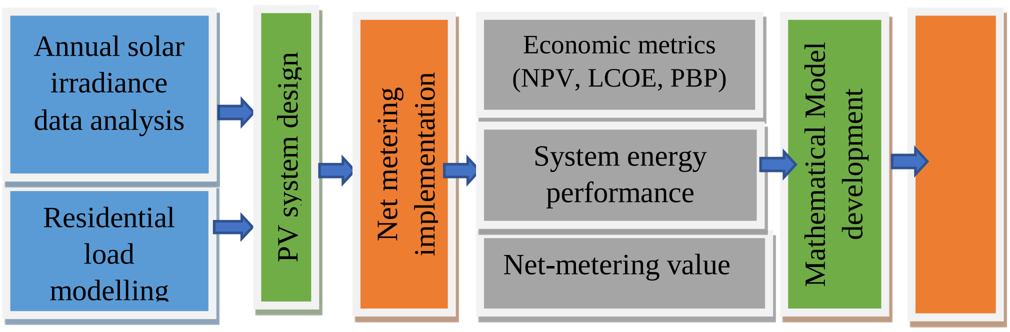


Figure 3.1: Methodology of the study

3.2 Selection of PV site location

The location is selected in a residential building at Mirpur DOHS in Dhaka District. The latitude and longitude of the location are 23.8365° N and 90.3695° E. Mirpur DOHS is the largest among all other DOHS covering 138.81 Acres of land having 1,290 allotted plots for the defense officers. The average rooftop area available per building is 220 m^2. The weather data used for this simulation is from Himawari satellite data available at the National solar irradiation database (NSRDB) [29]. Figure 3.2 shows the yearly average irradiance at the site location. The maximum average irradiance is found 655 w/m^2 at 12.00 am [30].

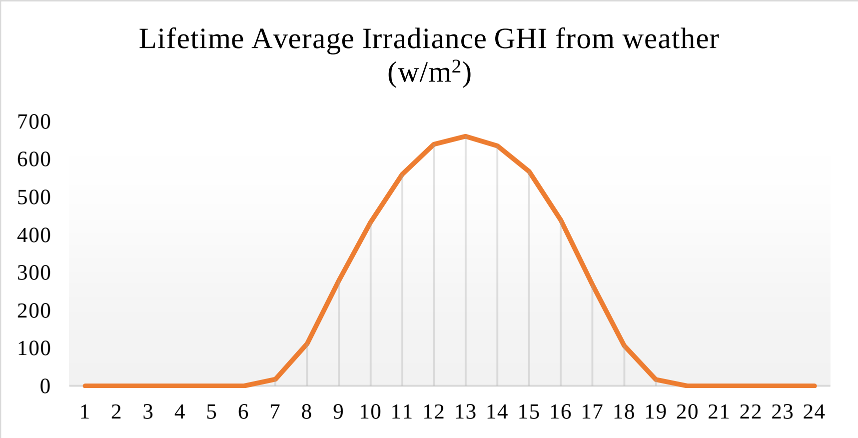


Figure 3.2: Yearly average irradiance at the site location

3.3 Load profile for the Individual Building

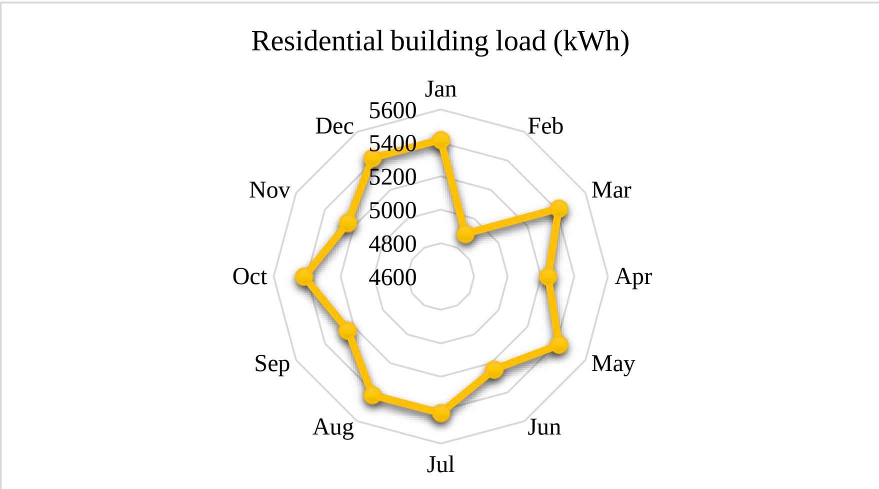


Figure 3.3: Load profile for individual building

The load is calculated for the 4-storied building which is composed of two types of 1100 square feet and 2300 square feet flat size. The building has a total of 8 flats and a common utility load. Then, one-year hourly load data is calculated and 7:00 PM - 11:00 PM is considered as peak hour, 6:00 AM - 9.00 AM is a semi-peak hour, and the rest of the time is off-peak. The calculated load data is multiplied with random factors for summer and

Figure 3.3 presents the load profile for a building where an average monthly load is calculated as 5315 kWh.

3.4 PV Components

In this study, the design of the solar system is based on the net-metering guideline of SREDA. The PV modules and inverters used in this design comply with standards set by SREDA. In the design, JASolar JAM72D30 – 540/MB 540 Wp 11BB Half - Cell monocrystalline solar panels have been considered. These double glass modules provide higher output power, less shading loss, and enhanced tolerance for mechanical loading. The key electrical parameters of this panel are shown in Table 3.1[31].

Table 3.1. Electrical Parameters of Solar Panel

Parameters	**Value**
Rated Maximum Power [w]	540
Open Circuit Voltage (Voc) [V]	49.60
Maximum Power Voltage [V]	41.64
Short Circuit Current [A]	13.86
Maximum Power Current [A]	12.97
Module Efficiency [%]	20.8
Bi-faciality	70%
Annual DC degradation rate [%]	5

As per the net metering policy of SREDA, the AC output of a renewable energy converter cannot be more than 70 % of the sanctioned load. Therefore, in this design SUN2000-40KTL-US three-phase inverter from Huawei technologies is used which has an AC output capacity of 40 kW (66.67 % of sanction load). This inverter is compliant with technical standards set by SREDA. The key electrical parameters of this panel are shown in Table 3.2

Table 3.2: Electrical Parameters of the Inverter

Parameters	**Value**
Max. Efficiency [%]	98.9
CEC. Efficiency [%]	98.5
Max. Input Voltage [V]	1000
Max. Current per MPPT [A]	22
Max. Short Circuit Current per MPPT [A]	30
MPPT Operating Voltage Range [V]	200 - 1000
Number of MPP Tracker	4
Rated AC Active Power [kW]	40
Max. Total Harmonic Distortion	< 3%

3.5 System Design

Assuming a DC to AC ratio of 1.2, the total module capacity that can be used is 48 kWp. However, the area requirements of such a system are higher than the available rooftop area of each building. In this study 60 panels are used for each building. The approximate area requirement of this PV system is 201 m^2. The nameplate DC capacity of this PV system would be 43.16 kWp. Since there are 4 MPPT inputs available in the inverter, 80 panels are arranged in 4 strings with 20 panels in each string. One MPPT input is connected to each string. Thus, the maximum current through each MPPT would be 12.97 A which is less than the maximum current per MPPT (22 A). The output of the inverter is connected to MDB. A bidirectional meter is installed at the 11 kV side of the distribution transformer. PV modules are installed with a fixed orientation. Key design assumptions are summarized in Table 3.3

Table 3.3: Design Parameters and Assumptions

Design Parameters	**Value**
PV system size	43.16 kWp
Number of Strings	4
Panels Per string	20
Max Current Per String (A)	12.97
String Vmp at Reference Condition (V)	832
Tracking	MPPT
Tilt	23
Azimuth	180
DC power loss	3.45%
AC wiring loss	1%
Transformer no-load loss	1%
Transformer load loss	1%
Module aspect ratio	2

The tariff structure is based on the energy price set by BREC. As per this price policy, the prosumer needs to pay approximately $39 as demand and other fixed charges. Prosumers buy energy from the grid at a flat rate of $.093/unit [15-16]. As per the net metering policy, at the end of each billing period, if import and export energy is equal, then the prosumer needs to pay only demand charges. After adjusting with any carryover credit from the previous billing period (if any), if the prosumer remains a net importer, the prosumer needs to pay energy charges along with demand charges. After adjusting with any carryover credit from the previous billing period (if any), if the prosumer remains a net exporter, then the excess units are carried over to the next billing period. In case the prosumer remains a net exporter at the end of the settlement period, the utility pays at a bulk tariff rate for 33kV lines for all accumulated units [32]. At present, the bulk tariff rate for 33kV lines for DESCO is $.068/unit [33]. The forex rate used in this analysis is the forex rate of Sonali bank as of 25/7/2022. Module cost and Inverter cost are assumed after in-depth market studies. The net capital cost of the system is $29,170. The total installed cost is consistent with other relevant studies [34]-[35].This study assumes 100% equity investment. Tariff, cost, and other financial assumptions of this study are summarized in Table 3.4 [33].

Table 3.4: Tariff, Cost and Financial Assumptions

Parameters	**Value**
Module cost [$/Wp]	0.35
Inverter cost [$/Wp]	0.2
Total Installed cost [$/Wp]	0.68
Operating cost [$/per year]	1000
Inflation rate [%]	5.7
Real Discount rate [%]	6
Net Salvage value [%]	10
Electricity Buy rate[$/unit]	0.093
Electricity Sell rate[$/unit]	0.068
Demand and other fixed charges [$/month]	39

3.6 Mathematical Model Development

To find out a mathematical model of PV yield of the solar panel at different roof orientation and tilt angle, a Multiple linear regression technique is used. In the linear model

$$[\mathbf{Y}] = [\mathbf{X}]*[\mathbf{B}]$$

Here, the MATLAB function "B = regress (Y, X)" gives the vector B of regression coefficients. Observations are represented in the row of the n-by-p design matrix **X**, and predictor variables are represented in the columns. Y is an n-by-1 vector of observations of the response. Three columns make up the **X** matrix used in this investigation. The constant term in the regression equation is represented by Column 1. Angle "Tilt" corresponds to Column 2. Azimuth is represented by column 3. To generate necessary observations for regression analysis, the tilt angle was varied from 0-23 with a step size of 5 and SAM was used for generating output matrix for Azimuth 180, 170 and 160. Finally generated data was passed to 'regress' function to calculate parameters a, b and c of equation 3.1

$$AC\ Energy\ Output\ = a + b * tilt + c * Azimuth \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

Table 3.1: **X** matrix (column 1-3) and **Y** matrix(column 4)

Index	Tilt	Azimuth	Output(KWH)
1	23	180	64498
1	22	180	64420
1	20	180	64228
1	15	180	63408
1	10	180	62198
1	5	180	60610
1	0	180	58654
1	0	160	58672
1	5	160	60500
1	10	160	61962
1	15	160	63049
1	20	160	63758
1	23	160	64019
1	23	170	64395
1	20	170	64078
1	15	170	63294
1	10	170	62124
1	5	170	60576
1	0	170	58659

3.7 Grid Impact analysis

The model used for gird impact analysis is shown in Figure 3.4 The system consists of a solar PV module of approximately 8 MW at average irradiance level of 655 W/m^2 at 25^0 C. The total load supplied by DESCO in Mirpur DOHS area under two substations are 3.47 MW and 2.91 MW respectively [36]. Hence, the cumulative load at PCC of the designed system has been chosen to be 6.38 MW. The solar PV is equipped with MPPT based on perturb and observe algorithm.

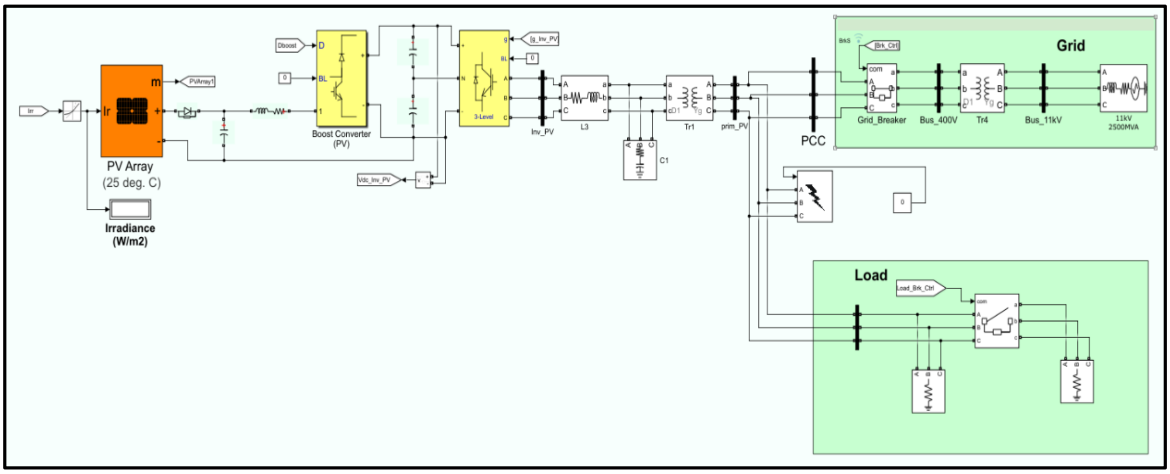
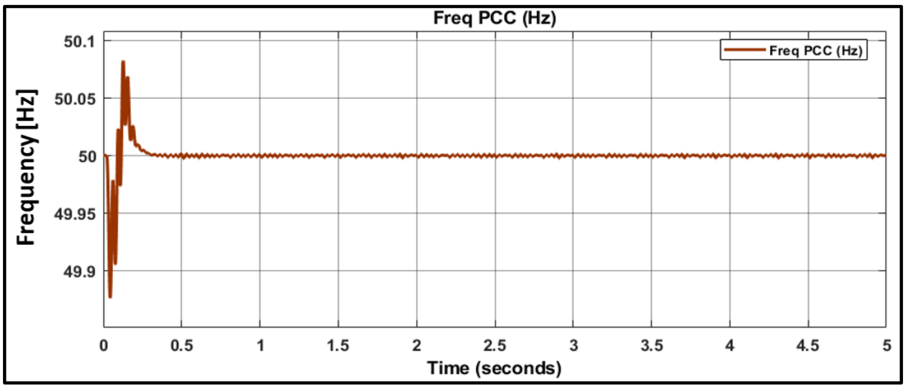
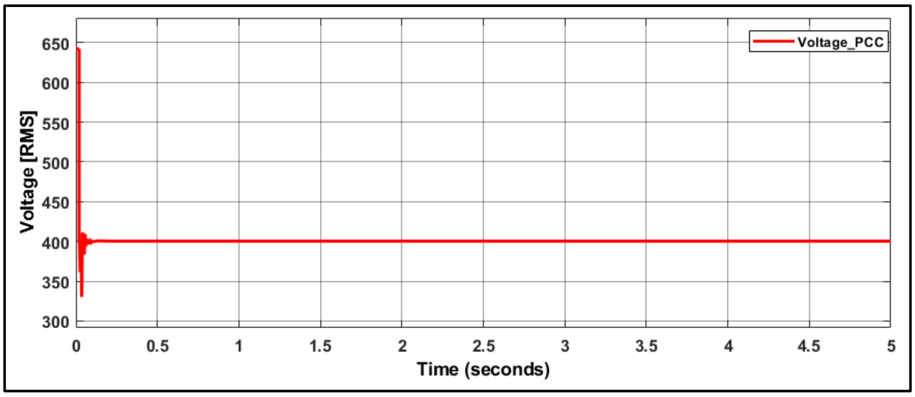


Figure 3.4: Software implementation of the studied system.

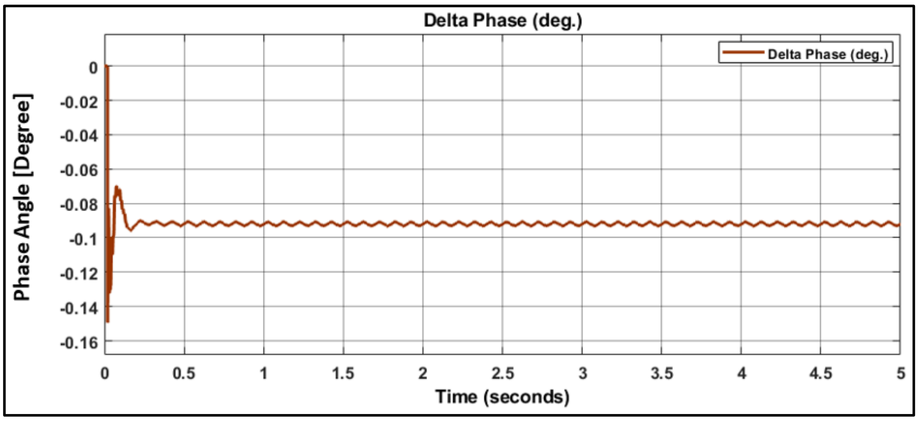
Under normal condition, the system parameters are shown in Figure 3.5 As seen from the graph, the system voltage is 50 Hz and the rms line voltage at point of common coupling (PCC) is 400 V. From Figure 3.5 (e), it is seen that the PV generation is approximately 8 MW which fulfils the demand of connected load at PCC which has been 6.38 MW. Hence, remaining power from PV goes to the grid.



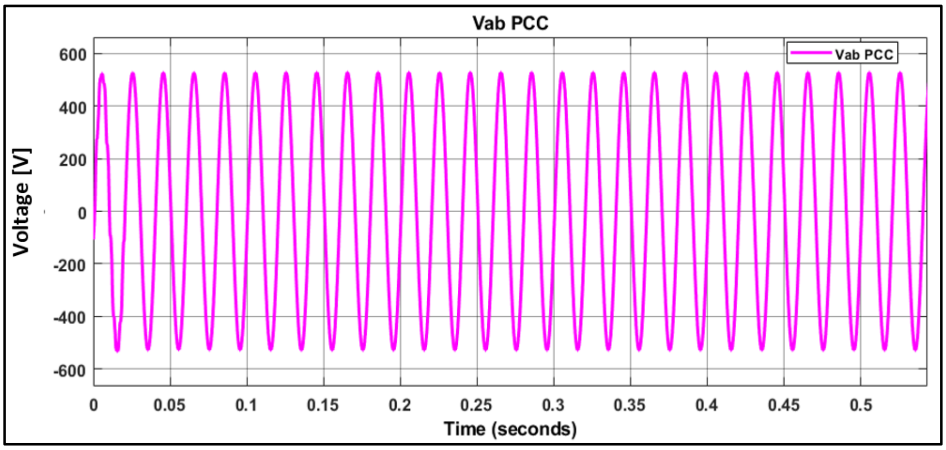
(a)


Voltage_PCC
Voltage [RMS]
650
600
550
500
450
400
350
300
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (seconds)

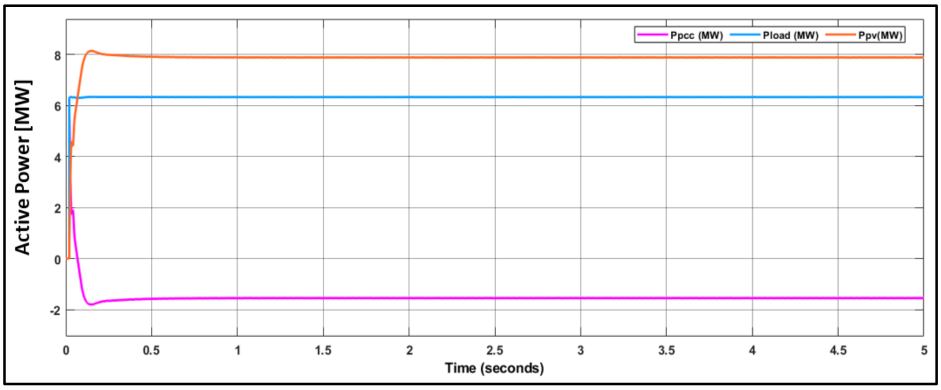
(b)


Delta Phase (deg.)
Delta Phase (deg.)
Phase Angle [Degree]
0
-0.02
-0.04
-0.06
-0.08
-0.1
-0.12
-0.14
-0.16
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (seconds)

(c)


Vab PCC
Vab PCC
Voltage [V]
600
400
200
0
-200
-400
-600
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Time (seconds)

(d)



(e)

Figure 3.5: (a) Frequency at PCC (b) Phase angle at PCC (c) System rms voltage at PCC (d) Line voltage (e) Power sharing between PV, Grid and Load in normal condition

3.8 Chapter Conclusion

This chapter discussed the development of PV net metering system in the residential area and mathematical model to observe the energy output variation. The system for grid impact analysis has been presented in this chapter. The system consists of cumulative PV generation, lumped load and grid. Under normal operating condition, the system seems to be stable as observed from the voltage and frequency at PCC.

CHAPTER 4

RESULT AND ANALYSIS

4.1 General

The results from the designed net-metering-based PV system for a single building are presented based on the system performance of energy production, valuation of energy trading using net-metering, and annual bill saving. In addition, net metering is applied in the DOHS community, and the capacity of annual energy production is determined. The SAM software was used to generate output matrix for various tilt and azimuth angles. The results of these simulations have been used to find the parameters of the proposed linear mathematical model. Finally, the impact of the proposed system on gird is simulated using SIMULINK.

4.2 System performance analysis

The total AC energy output in the first year is 62,831 kWh and the yield is 1456 kWh/kW. The DC capacity factor is 16.6% in the first year which shows the PV potential in the area. Table V presents the assessed output metrics to evaluate system performance. For example, the LCOE is the ratio of lifetime cost to total energy production which shows the economic competitiveness of the system. In this case, the nominal LCOE value is USD 0.0745. The economic evaluation of the PV systems is assessed using NPV which denotes the investment potential. Here, the system NPV is USD 32963 which is positive means that the PV investment is profitable. The payback periods are 4.2 years means the requisite time to recover the initial investment. In this analysis, all performance metrics are found to be positive for the PV investment for residential load under this policy.

Table 4.1: System performance metrics

Assessed Metrics	**Value**
Annual AC energy in Year 1	62,831 kWh
DC capacity factor in Year 1	16.60%
Energy yield in Year 1	1,456 kWh/kW
Performance ratio in Year 1	0.79
LCOE Levelized cost of energy (nominal)	7.45 ¢/kWh
LCOE Levelized cost of energy (real)	4.61 ¢/kWh
Net present value	$32,963
Simple payback period	4.2 years
Discounted payback period	6.1 years
Net capital cost	$ 29,170
Equity	$ 29,170

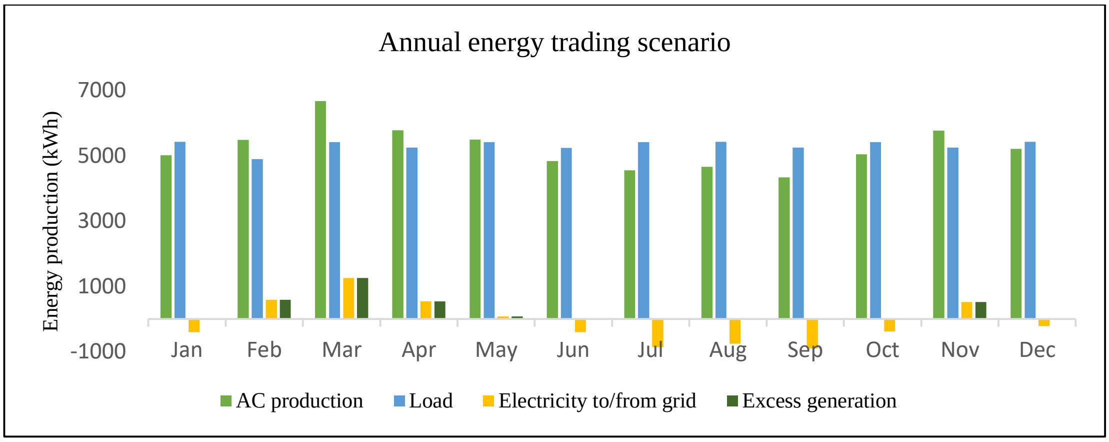


Figure 4.1 Energy trading under net metering scheme

Figure. 4.1 presents the monthly AC Energy output for the first year and energy-trading scenario after implementing net metering in the residential load. A total of 2979 kWh excess energy is produced and exported to the grid. In opposite, only 6% means 3935 kWh of energy is imported from the grid. During the months of February, March, April, May, and November electricity is exported to the grid and implies the potential of net-metering in the residential loads. In the negative months in Fig. 4.1 represents that, electricity is imported for these seven months.

4.3 System Net Metering Bill Analysis

The bill analysis of the customer having proposed PV system is done as per the present net metering policy of SREDA. The one-year settlement period is used. Figure 4.2 shows the comparison of the electricity bill with system and without system and net-saving for twelve months. For year 1 Electricity bill without a system is USD 6,400. With a net metering-based PV system, this bill reduces to USD 637, and net-savings are USD 5763. The maximum bill is saved in the month of December and average savings per month are USD 486.

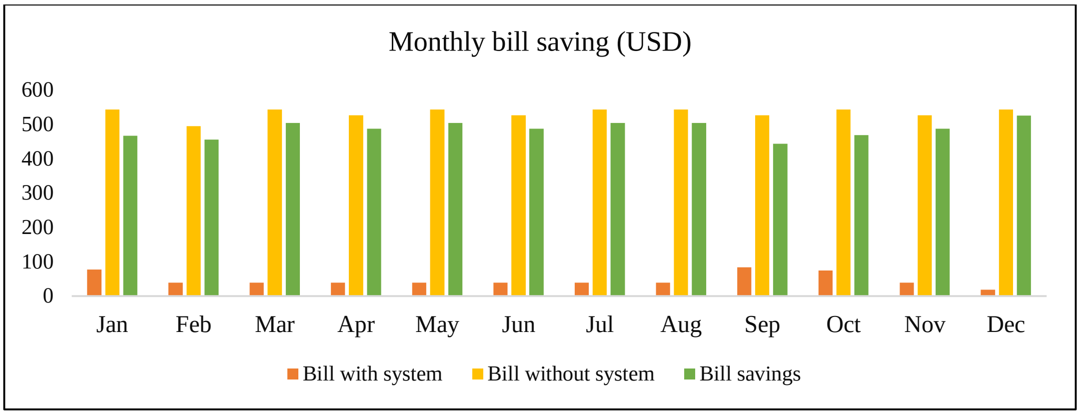


Figure 4.2: Bill without system Vs bill with system

Figure 4.3 presents the net-metering cumulative credit for the first year shows that during the month February to May the system has generated excess energy and net-metering cumulative credit exists for the next three months up to August. Again, excess generation is found in November and then credit exists in November. In the months of September, October, and January no net-metering credit is accounted

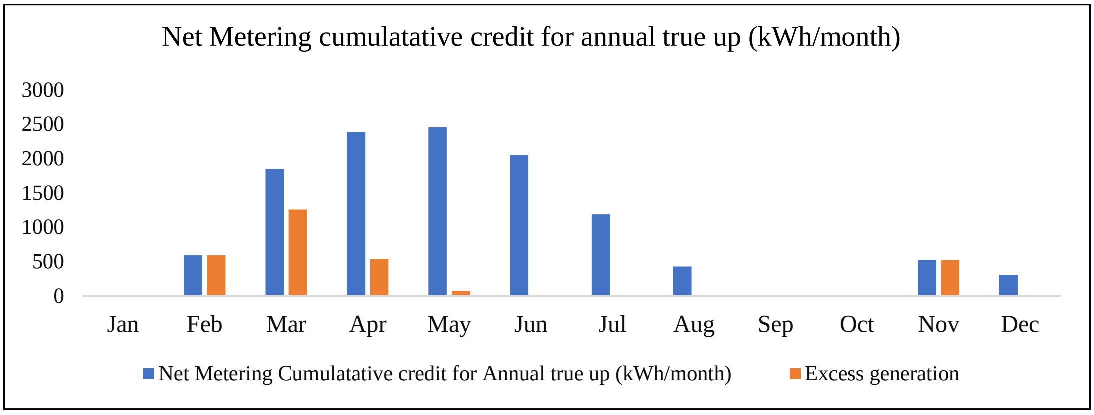


Figure 4.3: Net metering cumulative credit for annual true up

4.4 Annual Energy Production for Community

The total rooftop area available in Mirpur DOHS is approximately 283,800 m^2. This study assumes 233,520 m^2 areas can be used for PV system installation. If JASolar JAM72D30 – 540/MB 540Wp module is used as a PV module, this area can host 50 MWp solar. The simulation result shows that the proposed system would produce 74,911,272 kWh AC energy in year 1 with an energy yield of 1,498 kWh/kW and a DC capacity factor of 17.1%. AC energy out per month for year 1 is shown in Figure 4.4.

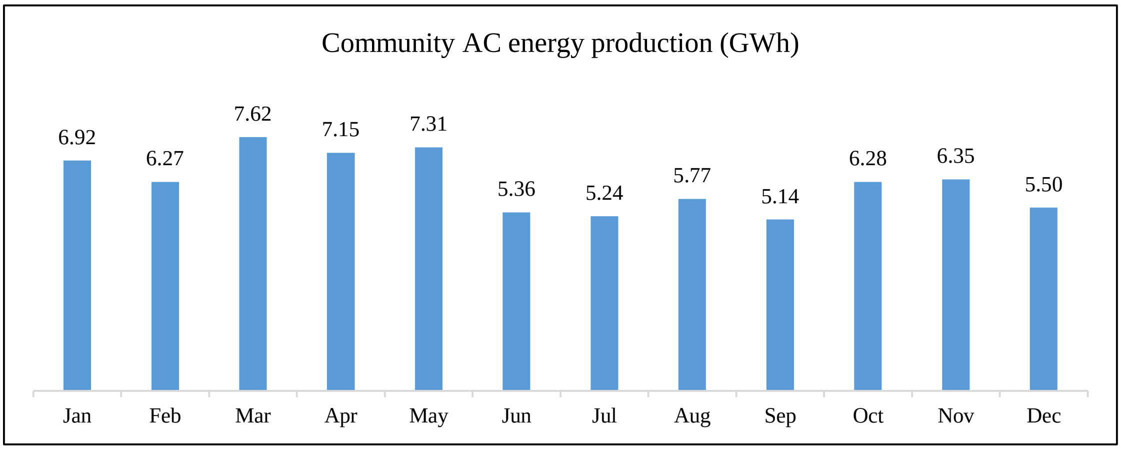


Figure 4.4: Monthly energy production for DOHS community

4.5 Energy Output with the Variation of Tilt and Azimuth

The proposed mathematical model of PV yield of the solar panel at different roof orientations and tilt for this study is

$$AC\ Energy\ Output\ (\ Eout) = a + b * tilt + c * Azimuth \ldots \ldots \ldots \ldots \ldots \ldots (i)$$

Linear regression model finds the parameters a, b, and c. Observations required to find the model parameters are generated using SAM software. Results of simulations are presented in Table 4.2

Table 4.2: Output Variation with variation of tilt angel and azimuth.

Index	Tilt	Azimuth	Output(KWH)
1	23	180	64498
1	22	180	64420
1	20	180	64228
1	15	180	63408
1	10	180	62198
1	5	180	60610
1	0	180	58654
1	0	160	58672
1	5	160	60500
1	10	160	61962
1	15	160	63049
1	20	160	63758
1	23	160	64019
1	23	170	64395
1	20	170	64078
1	15	170	63294
1	10	170	62124
1	5	170	60576
1	0	170	58659

The MATLAB function 'B = regress (Y, X)' returns the vector B of regression coefficients in t linear model **[Y]** = **[X]** * **[B]** . X is an n-by-p design matrix, with row corresponding to observations and columns to predictor variables. Y is an n-by-1 vector of response observations. X matrix is formed using column 1-3 of Table 4.2 and Y matrix is formed using Column -4. The code for the regression analysis is as follows

$$a = 5.7180 * 10^4, \qquad b = 241\,, \qquad c\ = 12$$

Figure 4.5 compares the actual output and output prediction from proposed model. Proposed model has very good accuracy.

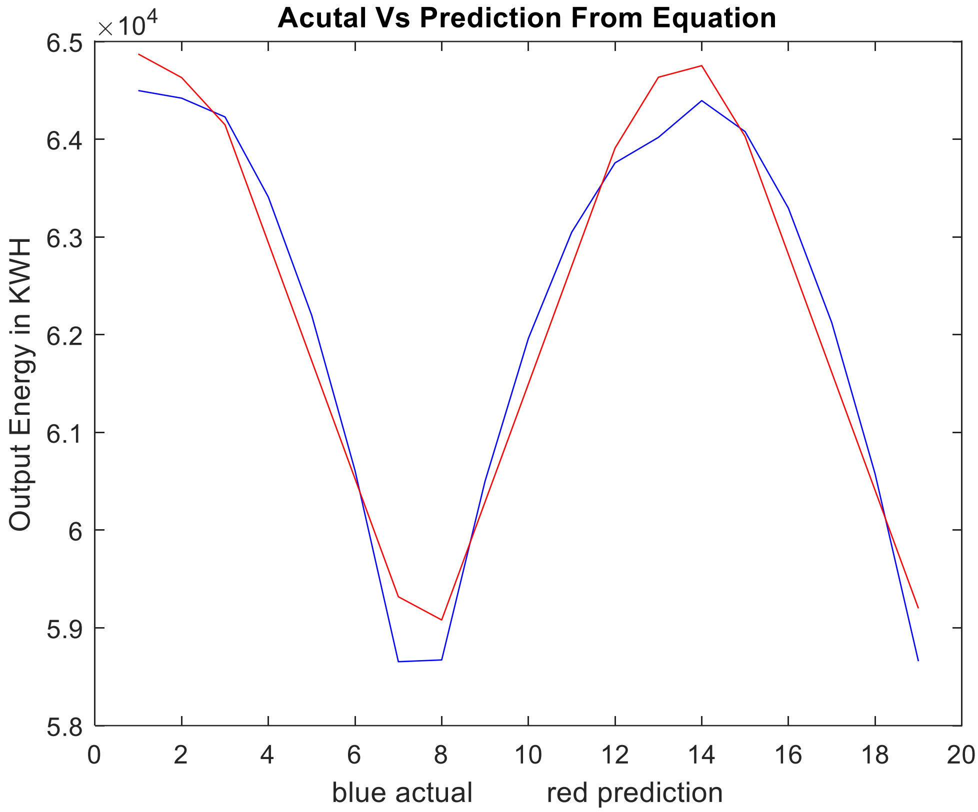


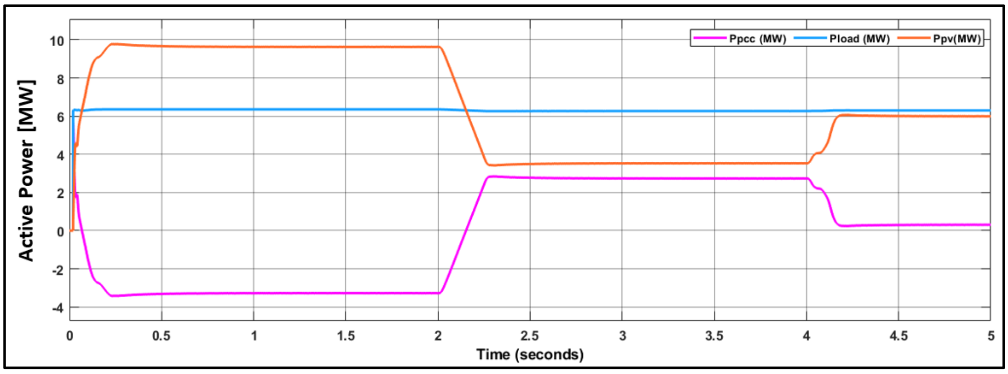
Figure 4.5 Comparison of the actual output and output prediction from proposed model.

4.6 Grid Impact Analysis

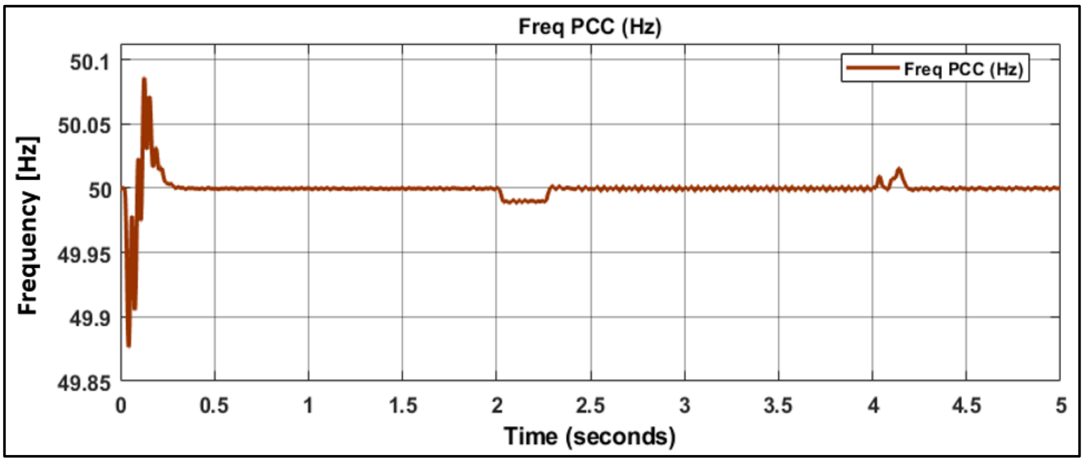
In this part of analysis, the impact of dynamic weather situation and load variation for the above-discussed system will be tested. After that, the stability of the system will be analyzed by applying three different types of faults at PCC.

4.6.1 Solar Irradiance Variation

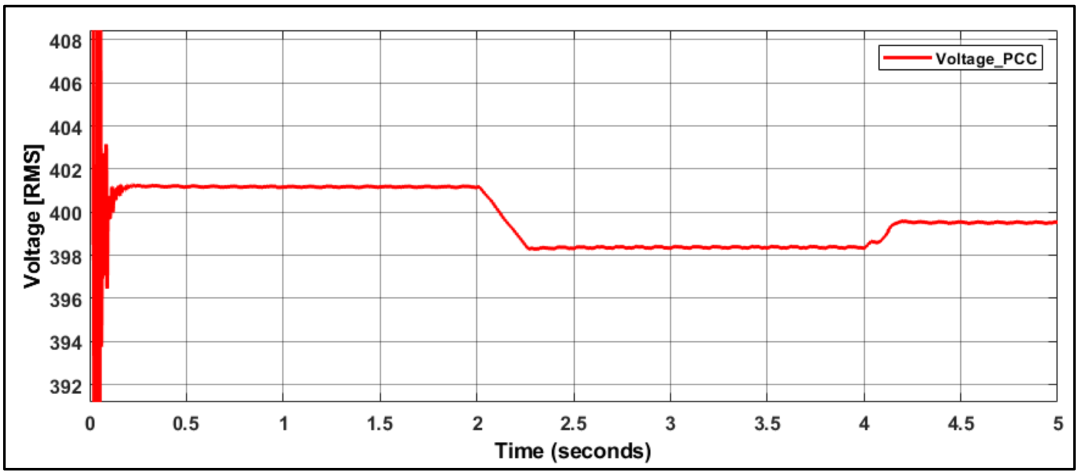
The impacts of dynamic weather condition on grid due to PV have been simulated in this part of analysis. The solar irradiance has been varied from 800 W/m^2 to 300 W/m^2 at $t = 2\ s$ and again 300 W/m^2 to 500 W/m^2 at $t = 4\ s$ respectively.



(a)



(b)



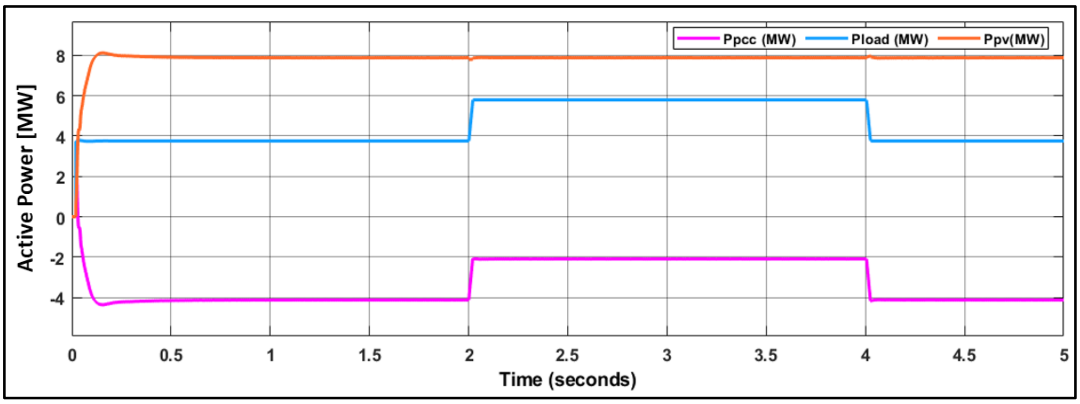
(c)

Figure. 4.6: (a) Power sharing between PV, Grid and Load (b) Frequency at PCC (c) System rms voltage at PCC in solar irradiance variation

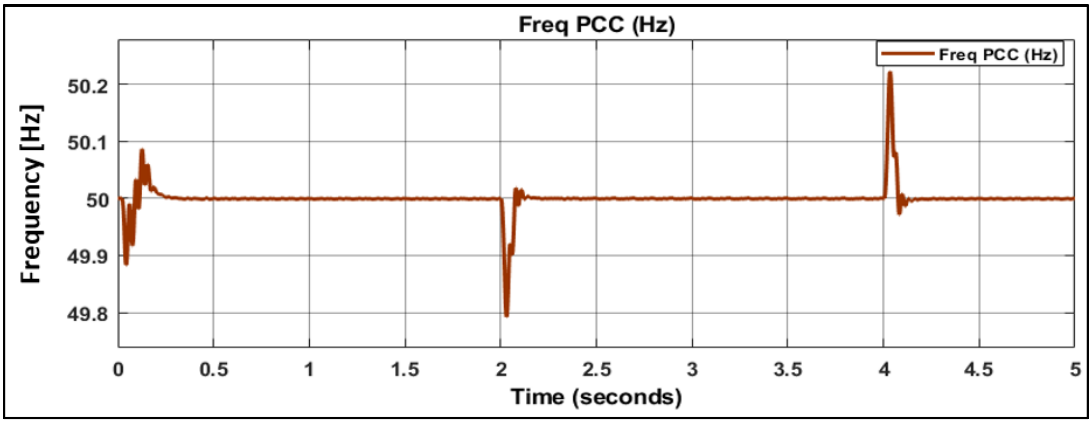
Figure 4.6 shows the impacts of solar irradiance variation on grid parameters. As seen from Fig. 3 (a), the power generated by PV varies with respect to the irradiance and hence accordingly, the power shared by the grid changes. The main impact can be seen in the grid frequency at PCC. As the irradiance changes from 800 W/m^2 to 300 W/m^2, the PV power generation drops from 9.8 MW to 2.6 MW and hence the grid frequency falls from 50 Hz to 49.98 Hz since the bus at PCC experiences short time overload due to the reduction in PV generation. The rms voltage at PCC has been seen to be reduced slightly. Similarly, when the irradiance changes from 300 W/m^2 to 500 W/m^2, the PV power generation increases from 2.6 MW to 6 MW and hence the grid frequency rises from 50 Hz to 50.02 Hz since the bus at PCC experiences short time underload due to the increase in PV generation. The rms voltage at PCC has been seen to be increased slightly.

4.6.2 Load Variation

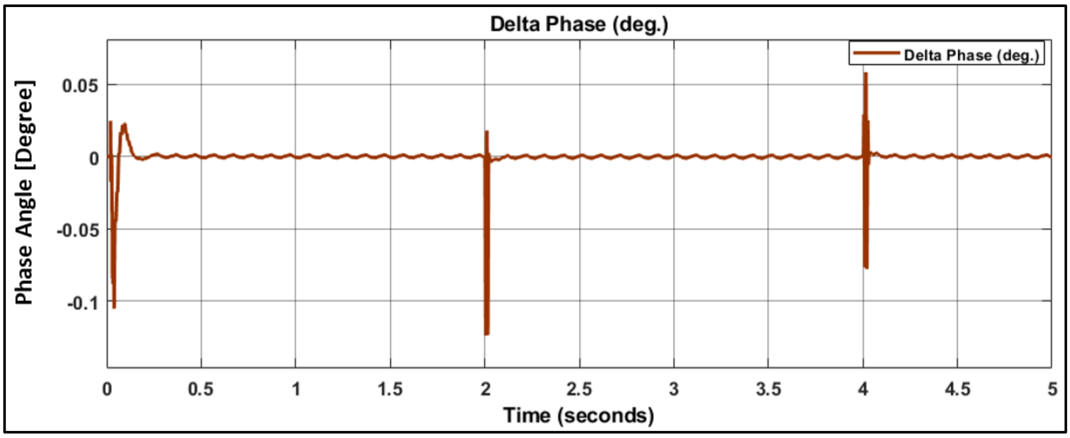
The impacts of load variation on grid have been tested in this part of analysis. The load has been varied from 3.9 MW to 5.95 MW at $t = 2\ s$ and again 5.95 MW to 3.9 MW at $t = 4\ s$ respectively. Figure 4.7 shows the impacts of load variation on grid parameters. As seen from Figure 4.7 (a), the power generated by PV has been kept fixed and hence, the power shared by the grid changes with load. Significant impact can be seen in the grid frequency at PCC due to this sudden load change. As the load varied from 3.9 MW to 5.95 MW, the grid frequency drops from 50 Hz to 49.79 Hz since the bus at PCC experiences short time overload. The rms voltage at PCC has been seen to be reduced slightly. Similarly, when the load changes from 5.95 MW to 3.9 MW, the grid frequency rises from 50 Hz to 50.23 Hz since the bus at PCC experiences short time underload. The rms voltage at PCC has been seen to be increased slightly.



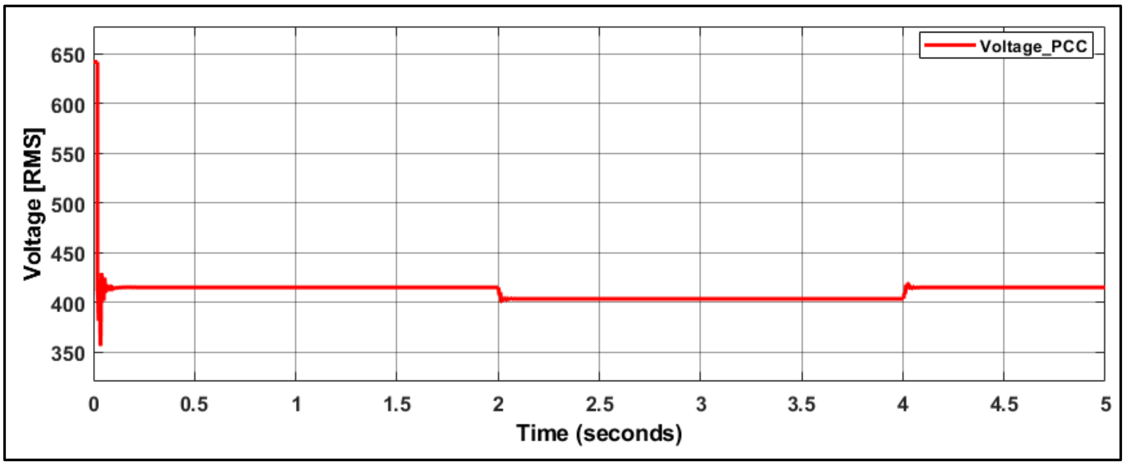
(a)


Freq PCC (Hz)
Freq PCC (Hz)
Frequency [Hz]
50.2
50.1
50
49.9
49.8
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (seconds)

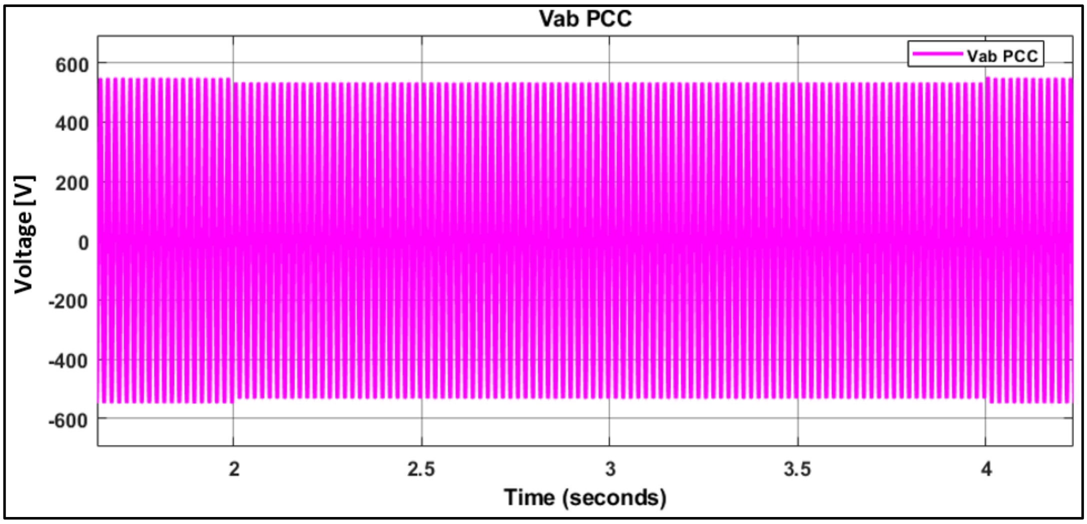
(b)


Delta Phase (deg.)
Delta Phase (deg.)
Phase Angle [Degree]
0.05
0
-0.05
-0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (seconds)

(c)


Voltage_PCC
Voltage [RMS]
650
600
550
500
450
400
350
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (seconds)

(d)

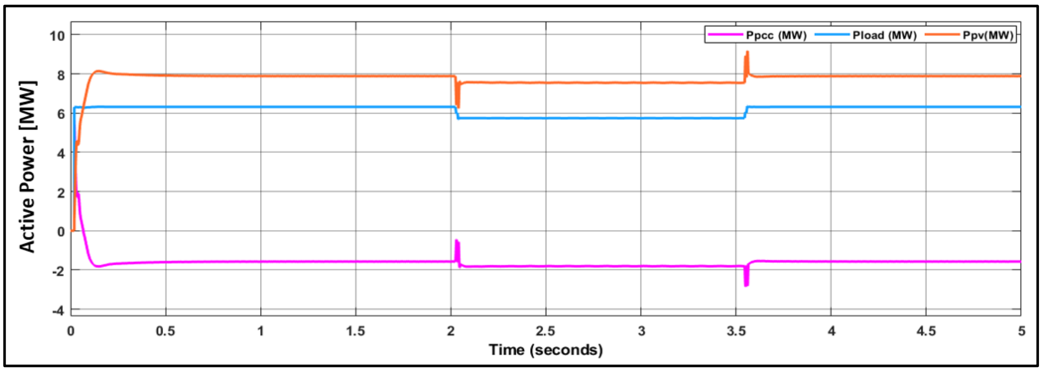


(e)

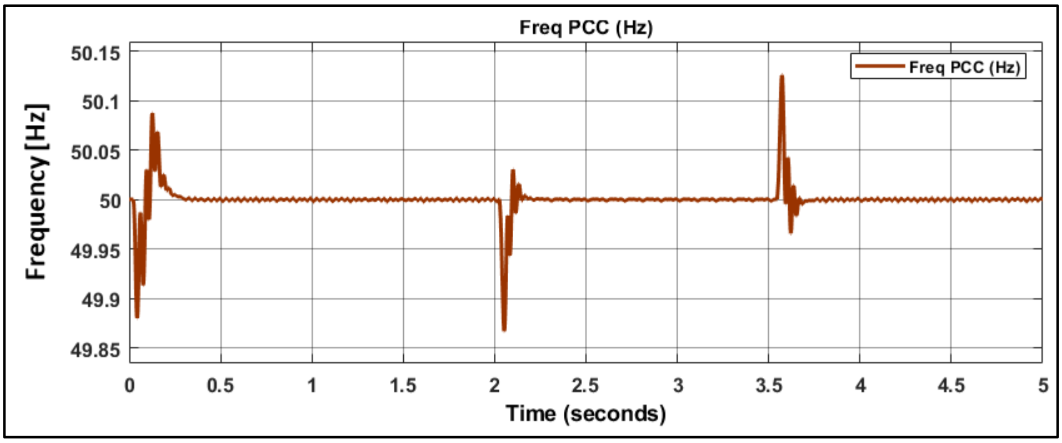
Figure 4.7: (a) Power sharing between PV, Grid and Load (b) Frequency at PCC (c) Phase angle at PCC (d) System rms voltage at PCC and (e) Line voltage during load variation

4.6.3 Short Circuit Fault (L-G)

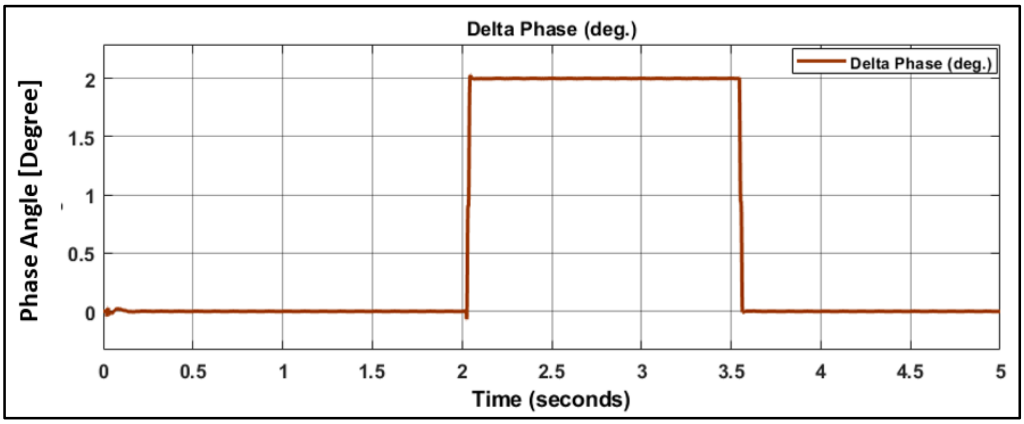
In this part of analysis, the system stability has been assessed by applying a line to ground (L-G) short circuit fault in phase-a. The fault has been applied at $t = 2\ s$ and it has been removed from the system at $t = 3.6\ s$. Fig. 5 shows the impacts of L-G fault on grid parameters. As seen from Figure. 4.8 (a), the power contribution from PV, grid and also the load power changes slightly during fault. Significant impact can be seen in the grid frequency at PCC due to this fault. During injection of fault, the grid frequency drops from 50 Hz to 49.87 Hz since huge number of current flows from the system to the point of fault. Similarly, when the fault was removed from the system, the grid frequency rises from 50 Hz to 50.12 Hz since the fault current is zero. The phase angle incurs a drastic change during this fault.



(a)



(b)

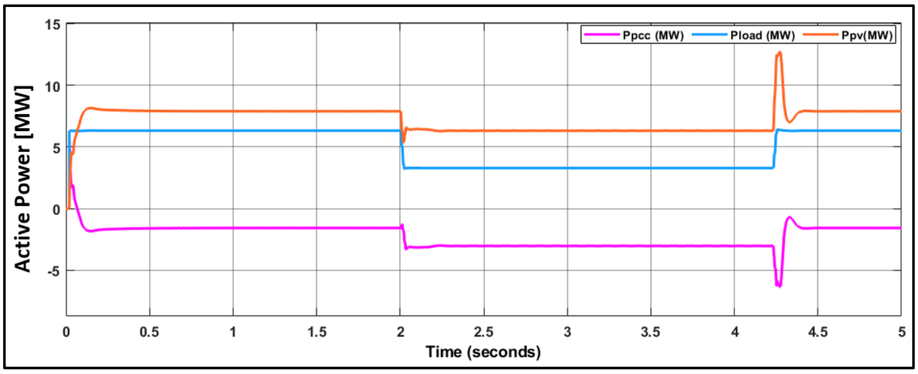


(c)

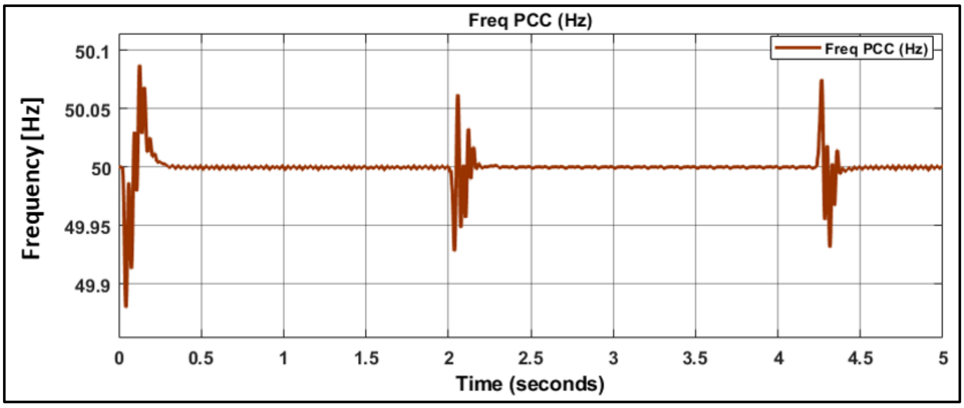
Fig.4.8 : (a) Power sharing between PV, Grid and Load (b) Frequency at PCC (c) Phase angle at PCC in L-G short circuit fault

4.6.4 Short Circuit Fault (L-L-G)

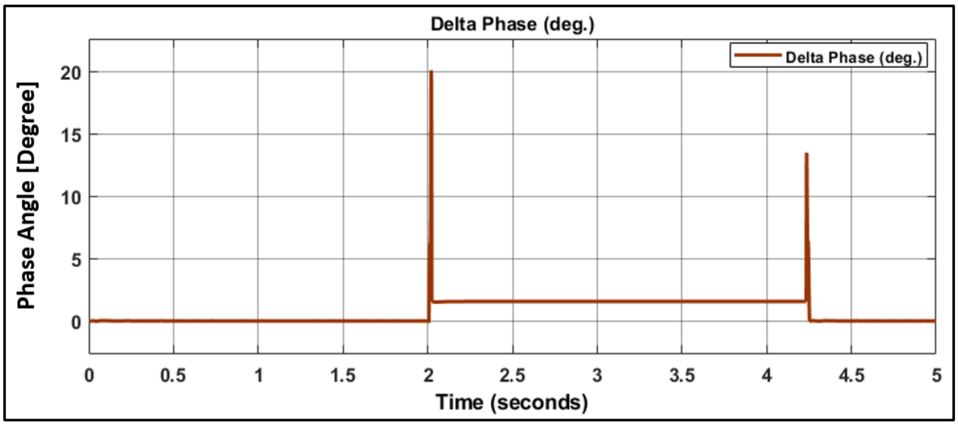
In this part of analysis, the system stability has been assessed by applying a L-L-G short circuit fault between phase-a and phase-b. The fault has been applied at $t = 2\ s$ and it has been removed from the system at $t = 4.25\ s$. Figure 4.9 shows the impacts of L-L-G fault on grid parameters. As seen from Fig. 4.9 (a), the power contribution from PV, grid and the load power change slightly during fault. Significant impact can be seen in the grid frequency at PCC due to this fault. During injection of fault, the grid frequency drops from 50 Hz to 49.92 Hz since huge number of current flows from the system to the point of fault. Similarly, when the fault was removed from the system, the grid frequency rises from 50 Hz to 50.07 Hz since the fault current is zero. The phase angle incurs a drastic change during this fault.


Ppcc (MW)
Pload (MW)
Ppv(MW)
Active Power [MW]
Time (seconds)

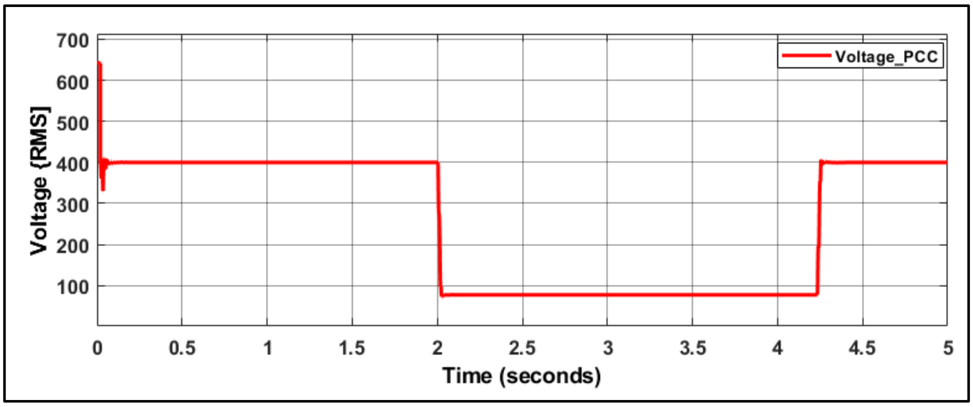
(a)


Freq PCC (Hz)
Freq PCC (Hz)
Frequency [Hz]
Time (seconds)

(b)


Delta Phase (deg.)
Delta Phase (deg.)
Phase Angle [Degree]
Time (seconds)

(c)

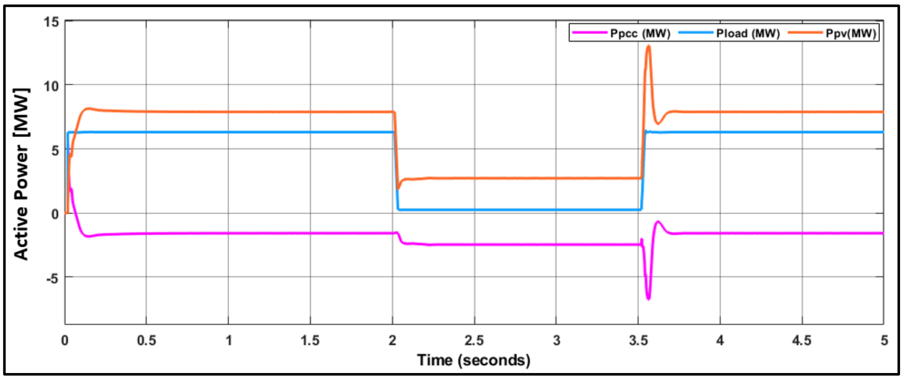


(d)

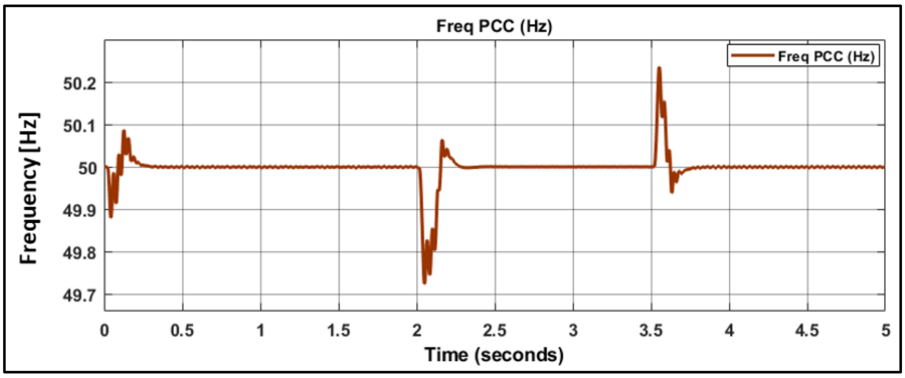
Figure. 4.9: (a) Power sharing between PV, Grid and Load (b) Frequency at PCC (c) Phase angle at PCC (d) System rms voltage at PCC L-L-G short circuit fault.

4.6.5 Three Phase Short Circuit Fault (L-L-L-G)

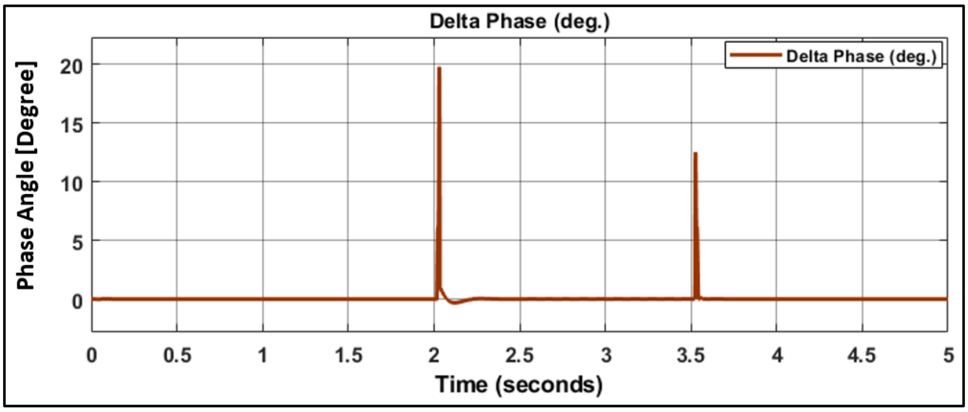
In this part of analysis, the system stability has been assessed by applying a three phase (L-L-L-G) short circuit fault. The fault has been applied at $t = 2\ s$ and it has been removed from the system at $t = 3.5\ s$. Fig. 7 shows the impacts of L-L-L-G fault on grid parameters. As seen from Figure 4.10 (a), the power contribution from PV, grid and the load power change drastically during fault. Load power becomes zero i.e. no power flows to the load. Significant impact can be seen in the grid frequency at PCC due to this fault. During injection of fault, the grid frequency drops from 50 Hz to 49.72 Hz since huge amount of current flows from the system to the point of fault. Similarly, when the fault was removed from the system, the grid frequency rises from 50 Hz to 50.24 Hz since the fault current is zero. The phase angle incurs a drastic change during this fault.



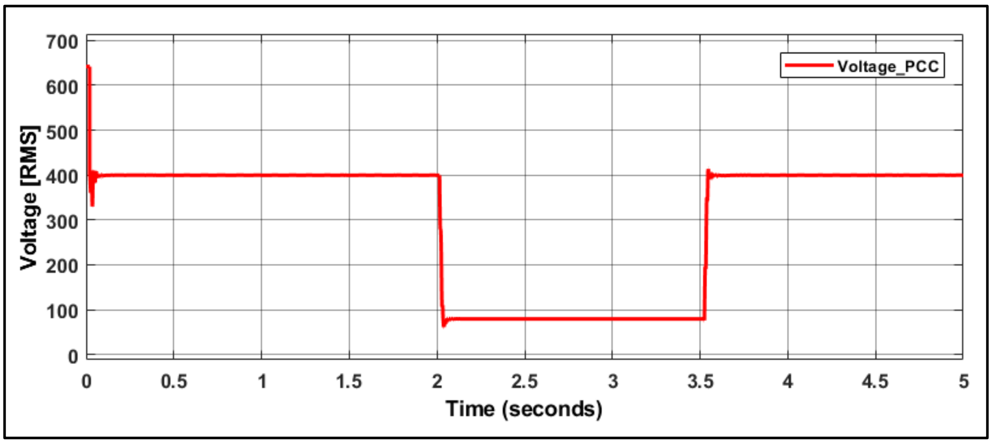
(a)



(b)



(c)



(d)

Fig. 4.10: (a) Power sharing between PV, Grid and Load (b) Frequency at PCC (c) Phase angle at PCC (d) System rms voltage at PCC L-L-L-G short circuit fault

4.7 Concluding Remarks

The PV net metering value and annual energy production for the building and community is presented. The impact of different abnormalities i.e., solar irradiance variation, load variation and fault has been analyzed in this chapter. The simulation results show significant impact on the system voltage, frequency and phase angle but the variation in frequency and voltage is within the grid stability limit. The system has been found to be enough stable under these abnormalities.

CHAPTER 5

CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Conclusion

It is apparent from performance analysis that the proposed PV system with net metering offers a high return on investment (ROI). The studied system has a very quick payback period too. The yearly output is 62831 kWh for a single house and 74,911,272 kWh for the community. The energy yield is 1456 kWh/kW which is quite high. This is mainly due to the proper selection of tilt, and azimuth. The bi-faciality feature of the selected PV panel has also contributed to making this design superior. The proposed Technical and financial model for a net metering-based PV system for residential takes all the policy, regulatory and physical constraints into account. From this study, it is observed that under the current net metering policy any building owner can benefit from installing a net metering-based PV system on the rooftop. This reduces electricity bills significantly. The proposed system promises a $5,920 bill reduction in the inception year. Investment in the proposed system has a significantly higher NPV and Payback period than government bonds. Due to the present high price of fossil fuel, the retail price and bulk price of electricity are likely to increase very soon. This will make the net metering-based rooftop solar PV system more financially rewarding. Besides, electricity generated from the solar PV system is clean as there is no emission. So, such a system helps in reducing emissions and improving the air quality of Dhaka city. If the net meter system is adopted throughout the country for residential load net emission and LCOE will decrease significantly. The country will also benefit from increased energy security. The study can be conducted with accurate load data rather than modelled data with the physical set of PV systems to understand the practical implementations features of residential PV systems under net-metering schemes.

5.2 Limitations of the Work

(i) This study is simulated with synthetic load data where few assumptions are used in the load distribution. If one-year hourly consumption data was considered that would produce more accurate result.

(ii) Small scale physical PV system set up will help to assess the simulation results more effectively.

5.3 Future Recommendations

(i) The economic and technical assessment of the residential community area can be investigated to identify the net-energy metering value for the community area.

(ii) The grid impact analysis can be assessed with real time grid for the particular 11-KV distribution feeder and others power quality parameters can be evaluated.

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LIST OF PUBLICATIONS

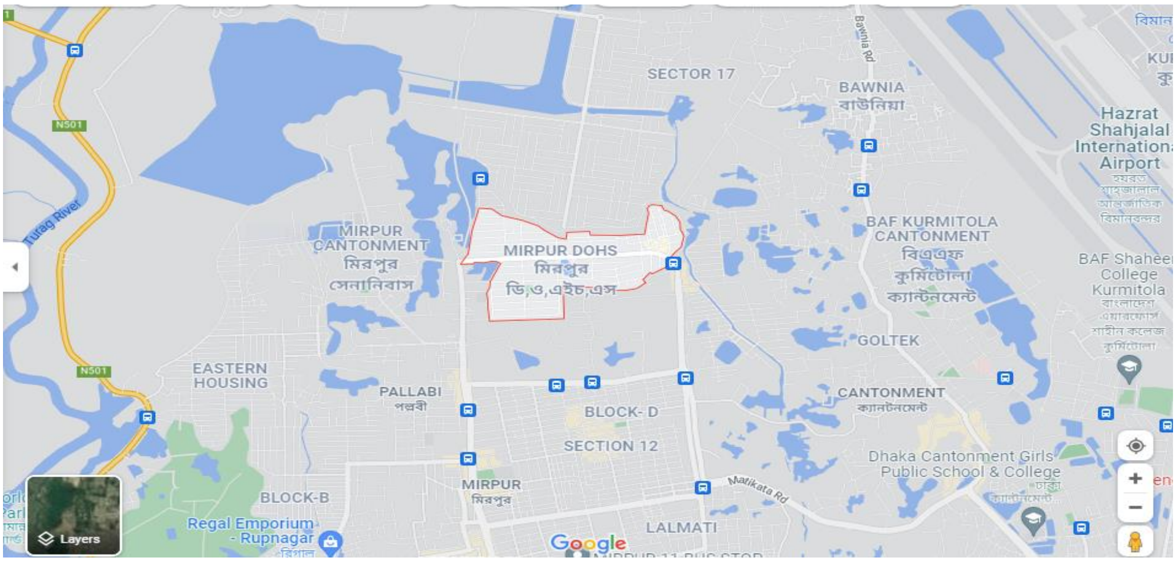
Conference Papers:

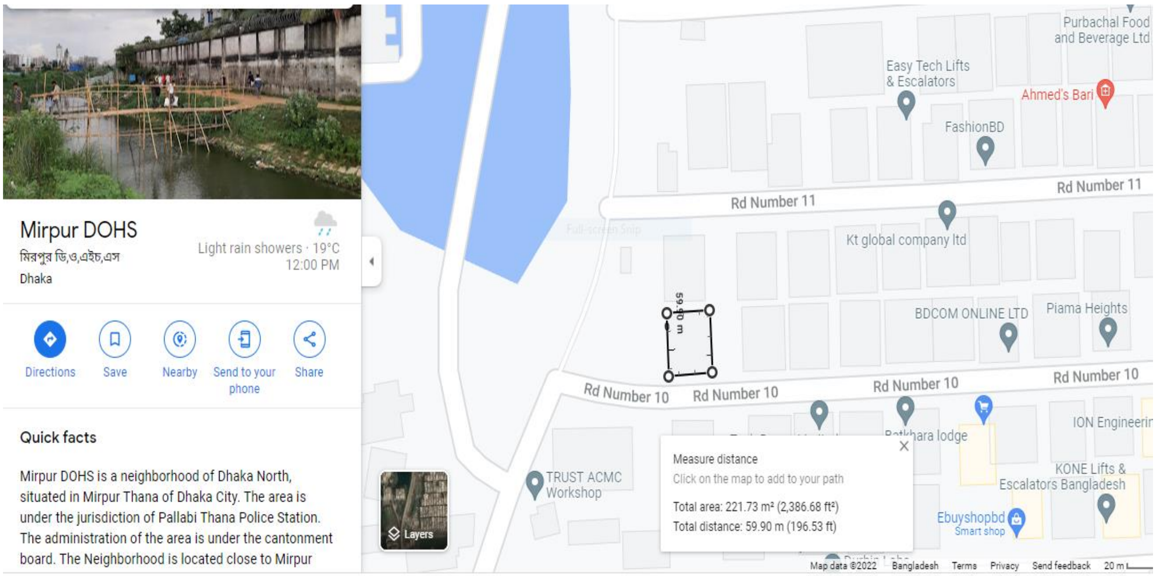
- M S A A F Shiblee, Md. Ziaur Rahman, Hasan Monir, Md. Ahsan Kabir, “Exploratory Perspective of PV Net-Energy Metering for Residential Prosumers: A Case Study in Dhaka, Bangladesh”, *2023 International Conference on Electrical, Computer and Communication Engineering (ECCE*), CUET, Feb 2023

- F. R. Saquib, A. Chakma, and M. S. A. A. F. Shiblee, “Analyzing the technical constraints of single-phase residential grid connected PV under net-metering scheme”, *Khulna Univ. Stud*., pp. 93–103, Oct. 2022

APPENDIX

Mirpur DOHS Area





Feeder Data from DESCO

DESCO

11 KV Feeder Maximum Demand (Amps)				
Date	**DOHS(East) Max (Amp)**	**Power (MW)**	**DOHS(West) Max (Amp)**	**Power (MW)**
13/08/20	302.00	5.18		-
		-	220.00	3.77
05.09.20	260.00	4.46		-
		-	328.00	5.62
15.10.2020	240.00	4.12		-
		-	235.00	4.03
1/11/2019	180.00	3.09		-
		-	150.00	2.57
10.12.2020	140.00	2.40		-
		-	135.00	2.31
20.01.2021	155.00	2.66		-
		-	150.00	2.57
22.02.2021	180.00	3.09		-
		-	150.00	2.57
29.03.2021	265.00	4.54		-
		-	240.00	4.12
27.04.2021	320.00	5.49		-
		-	245.00	4.20
01.05.2021	230.00	3.94		-
		-	110.00	1.89
04.06.2021	125.00	2.14		-
		-	80.00	1.37
11.07.2021	130.00	2.23		-
		-	90.00	1.54
01.08.2021	105.00	1.80		-
			70.00	1.20
Total	**2,632.00**	**45.13**	**2,203.00**	37.77
Average	202.46	3.47	169.46	2.91

MATLAB CODE for Load Modeling

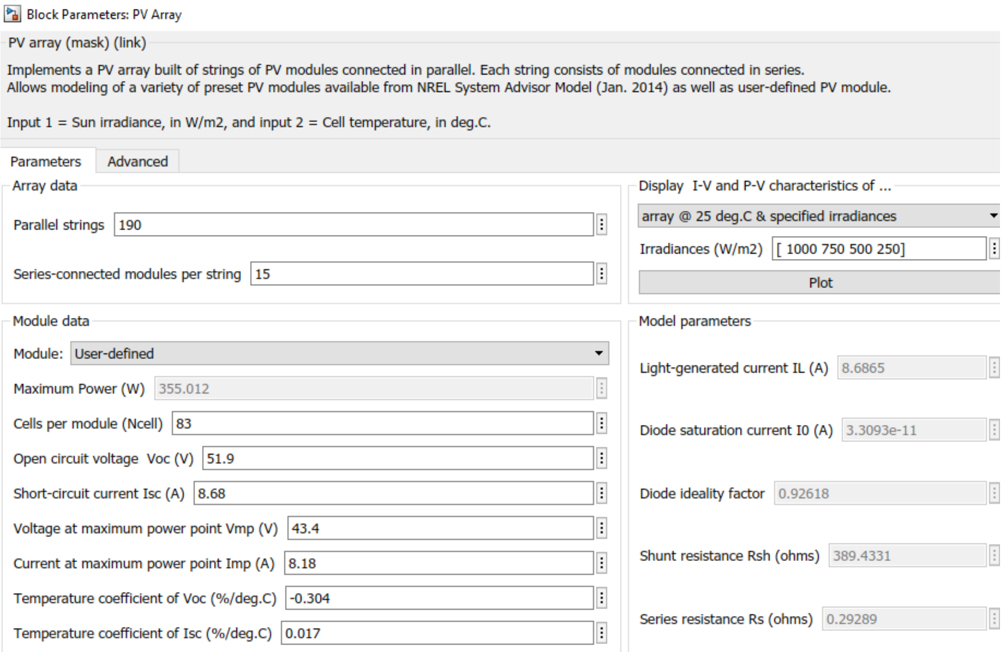
```
clc;
clear all;
close all;
M = 17000;
k= 1;
Peak1 = ((84/100)*M)+(((85/100)*M)-((84/100)*M))*rand(3,1);
Off_Peak_1 = ((19/100)*M)+(((20/100)*M)-((19/100)*M))*rand(7,1);
Semi_Peak_1 = ((69/100)*M)+(((70/100)*M)-((69/100)*M))*rand(2,1);
Off_Peak_2 = ((19/100)*M)+(((20/100)*M)-((19/100)*M))*rand(6,1);
Semi_Peak_2 = ((59/100)*M)+(((60/100)*M)-((59/100)*M))*rand(5,1);
Peak_2 = ((84/100)*M)+(((85/100)*M)-((84/100)*M))*rand(1,1);
Result = vertcat(Peak1,Off_Peak_1,Semi_Peak_1,Off_Peak_2,Semi_Peak_2,Peak_2);
for k=1:364
Peak1 = ((84/100)*M)+(((85/100)*M)-((84/100)*M))*rand(3,1);
Off_Peak_1 = ((19/100)*M)+(((20/100)*M)-((19/100)*M))*rand(7,1);
Semi_Peak_1 = ((69/100)*M)+(((70/100)*M)-((69/100)*M))*rand(2,1);
Off_Peak_2 = ((19/100)*M)+(((20/100)*M)-((19/100)*M))*rand(6,1);
Semi_Peak_2 = ((59/100)*M)+(((60/100)*M)-((59/100)*M))*rand(5,1);
Peak_2 = ((84/100)*M)+(((85/100)*M)-((84/100)*M))*rand(1,1);
Result =
vertcat(Result,vertcat(Peak1,Off_Peak_1,Semi_Peak_1,Off_Peak_2,Semi_Peak_2,Peak_
2));
end
x = 1:length(Result);
figure(1)
plot(x, Result)
grid

%For exporting to excel (CSV format) for SAM, initially, extra digit required(8761 in
total) (Uncomment)
Initial_Value=0000;
Total= vertcat(Initial_Value,Result);
%" csvwrite('Load Modelling-Residential Building.csv',Total) "  to command window
```

MATLAB CODE for Linear regression

```
clc;
close all;
clear all;
num=xlsread('a.xlsx');
b(:,1)=num(:,1);
b(:,2)=num(:,2);
b(:,3)=num(:,3);
c=num(:,4);
cof=regress(c,b);
predict=b*cof;
plot(c,'b')
hold on
plot(predict,'r')
title('Acutal Vs Prediction From Equation')
ylabel('Output Energy in KWH')
xlabel('blue actual        red prediction')
```

Software implementation of PV System by SIMULINK

Solar PV Specifications


Block Parameters: PV Array

PV array (mask) (link)

Implements a PV array built of strings of PV modules connected in parallel. Each string consists of modules connected in series.
Allows modeling of a variety of preset PV modules available from NREL System Advisor Model (Jan. 2014) as well as user-defined PV module.

Input 1 = Sun irradiance, in W/m2, and input 2 = Cell temperature, in deg.C.

Parameters | Advanced

Array data

Parallel strings	190
Series-connected modules per string	15

Display I-V and P-V characteristics of ...

	array @ 25 deg.C & specified irradiances
Irradiances (W/m2)	[1000 750 500 250]
	Plot

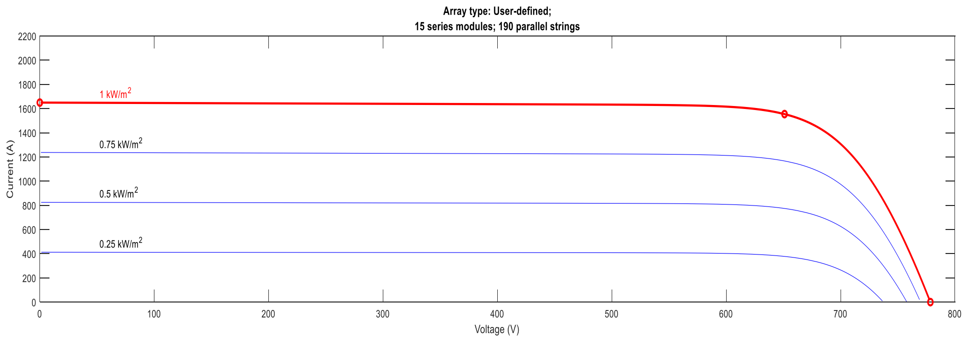
Module data

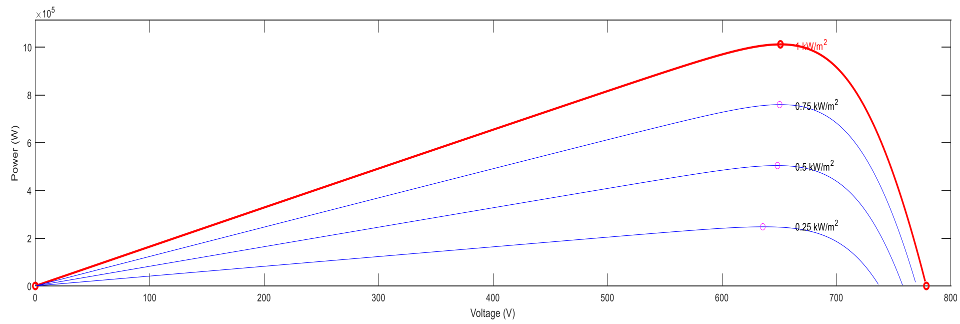
Module:	User-defined
Maximum Power (W)	355.012
Cells per module (Ncell)	83
Open circuit voltage Voc (V)	51.9
Short-circuit current Isc (A)	8.68
Voltage at maximum power point Vmp (V)	43.4
Current at maximum power point Imp (A)	8.18
Temperature coefficient of Voc (%/deg.C)	-0.304
Temperature coefficient of Isc (%/deg.C)	0.017

Model parameters

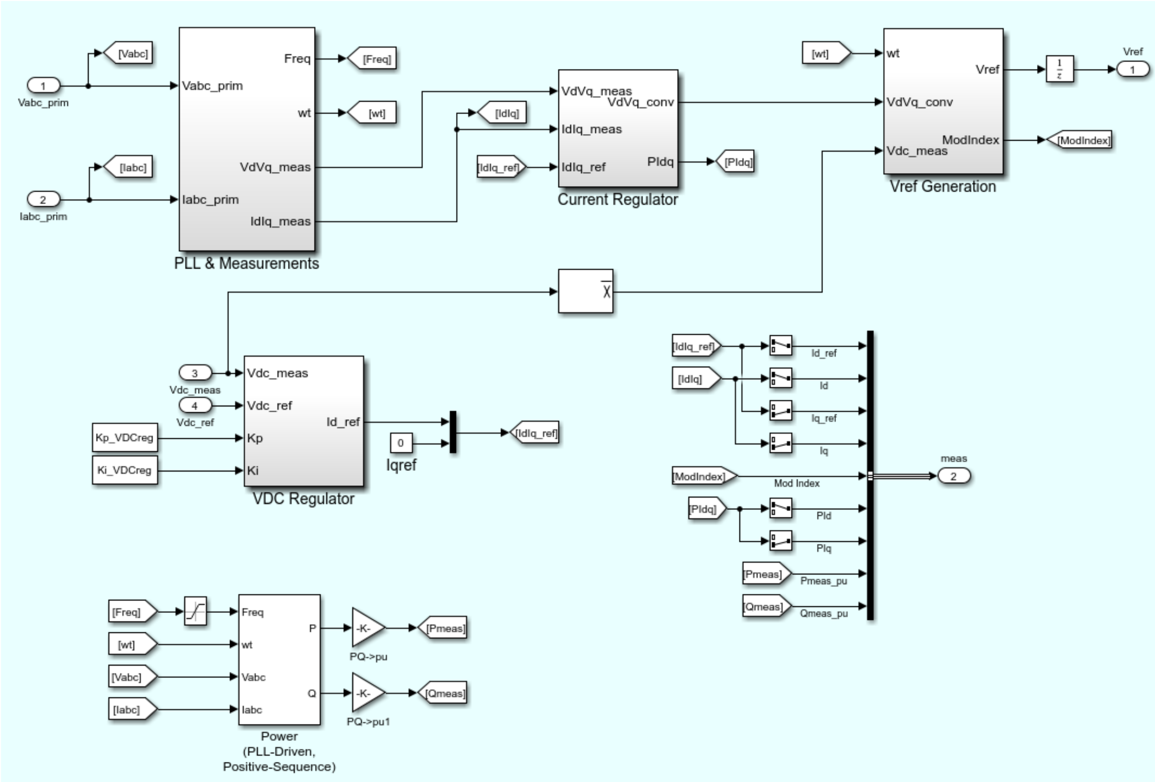
Light-generated current IL (A)	8.6865
Diode saturation current I0 (A)	3.3093e-11
Diode ideality factor	0.92618
Shunt resistance Rsh (ohms)	389.4331
Series resistance Rs (ohms)	0.29289

Solar PV Characteristics

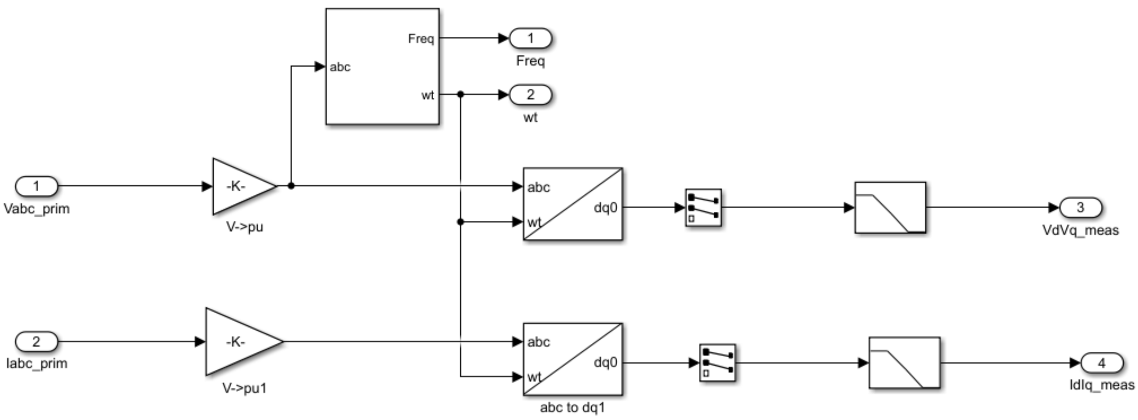




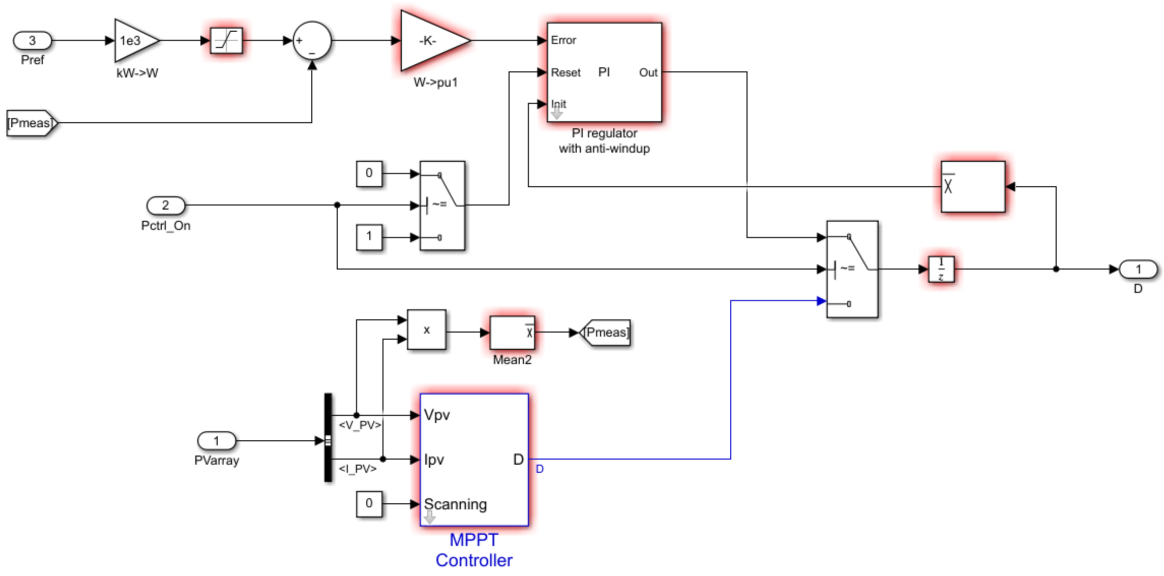
Reference Signal Generation for PWM Based Inverter



PLL & Measurements



MPPT Control and Duty Cycle Generation for DC-DC Converter



D-axis and Q-axis Voltage Generation