Memorial University of Newfoundland

(Faculty of Engineering and Applied Science)

Design and Analysis of a Hybrid Renewable Power Systems for a Plant in Lahore Pakistan

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Introduction

Background

- According to the International Energy Agency (IEA) evaluation, 992 million people did not have electricity in 2018 and predicted that almost 674 million would remain without electricity by 2030 [1].
- Meanwhile, a 1000 W PV system produces 150 kWh per month, which impedes 75 kg of fossil being mined, ultimately stopping 150 kg of CO_2 from being injected into the environment [2].
- At this time, the world is going through the transition phase due to global warming and abrupt temperature change.
- Renewable resources are non-consumables and give zero emission during use.

Background

- But poor countries like Pakistan, have energy crises and still rely on fossil fuels for generating electricity.
- Pakistan is a South Asian country with the world's 6th most populous country with 220 million people and having an energy demand of 30,000 MW [3].
- The per unit cost of electricity from oil is 25 PKR which is unjustifiable for a country that is going through a development phase [4].
- Conventional power plants which are the main reason for high fuel adjustment prices (FAP) in Pakistan.

Electricity Prices

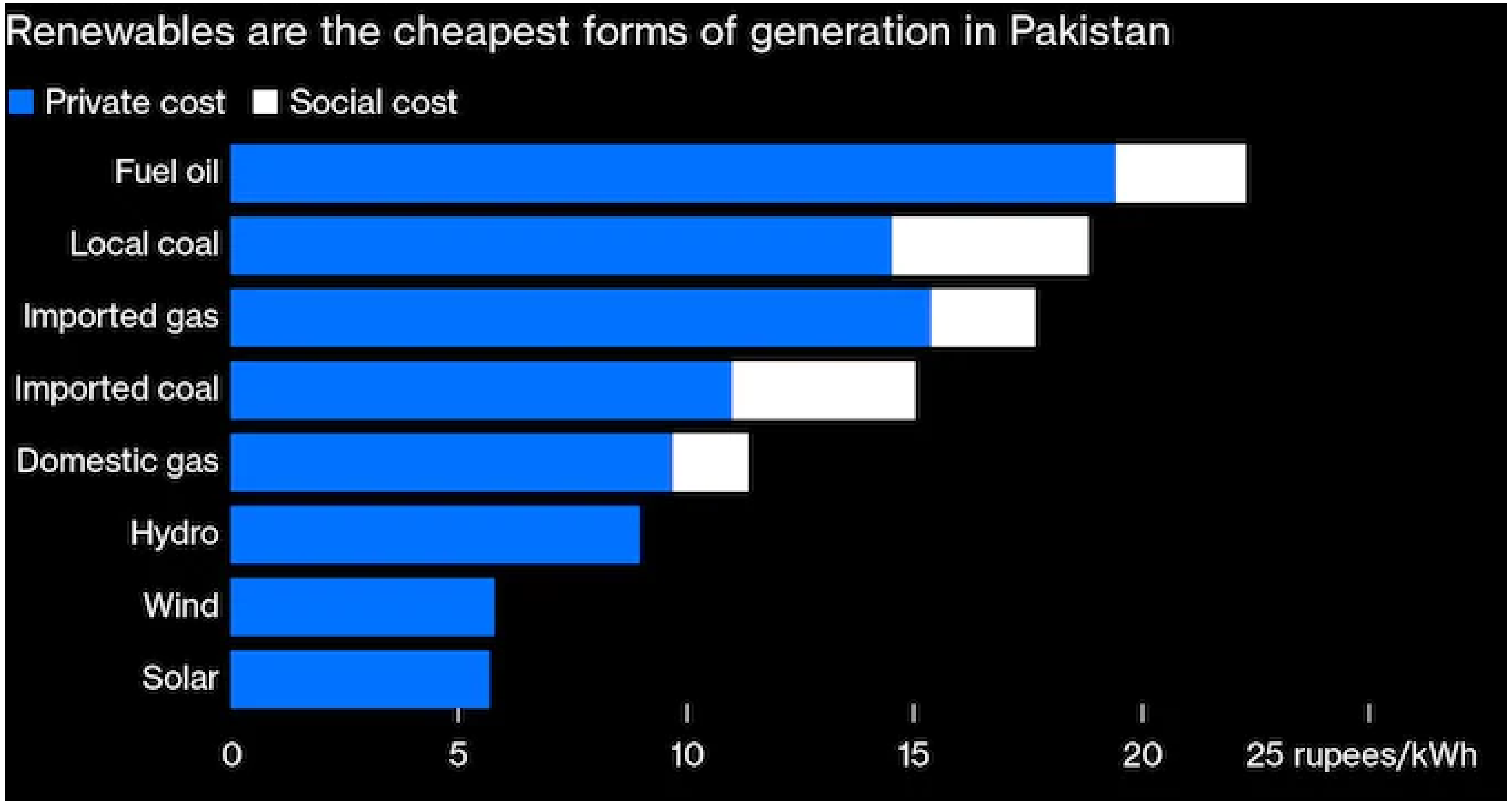


Figure 1: Monthly Irradiance of Selected Site [2]

Electricity Scenario of Pakistan

- The country's scenario is not ideal as a shortfall of 5,000MW is faced by the country.
- Tilt is towards fossil fuels for powering water pumping systems.

Figure 2: Electrical Shortfall in Pakistan

Hybrid Renewable Energy System

- There are two basic types of hybrid systems one is grid-connected, and the other one is a standalone system.
- Standalone systems are suitable for remote locations where it is difficult to supply power, and the system operates in islanding mode.
- Grid-connected system locations should be near the main grid where they can be synchronized with the national grid.
- The chosen site average load demand is 2185 kW and the peak load is 3100 kW which has LF of 76 %.

Feasibility

- Pakistan has massive potential for renewable energy.
- According to the world bank, using only 0.071 % of the total country area will be enough to meet the whole nation's demand and the overall renewable potential is 167.7 GW[5].
- For economic development, there should be a paradigm change in power source of industries from oil to PV systems which ultimately reduced the manufacturing cost of products along with reducing carbon emissions.

Feasibility

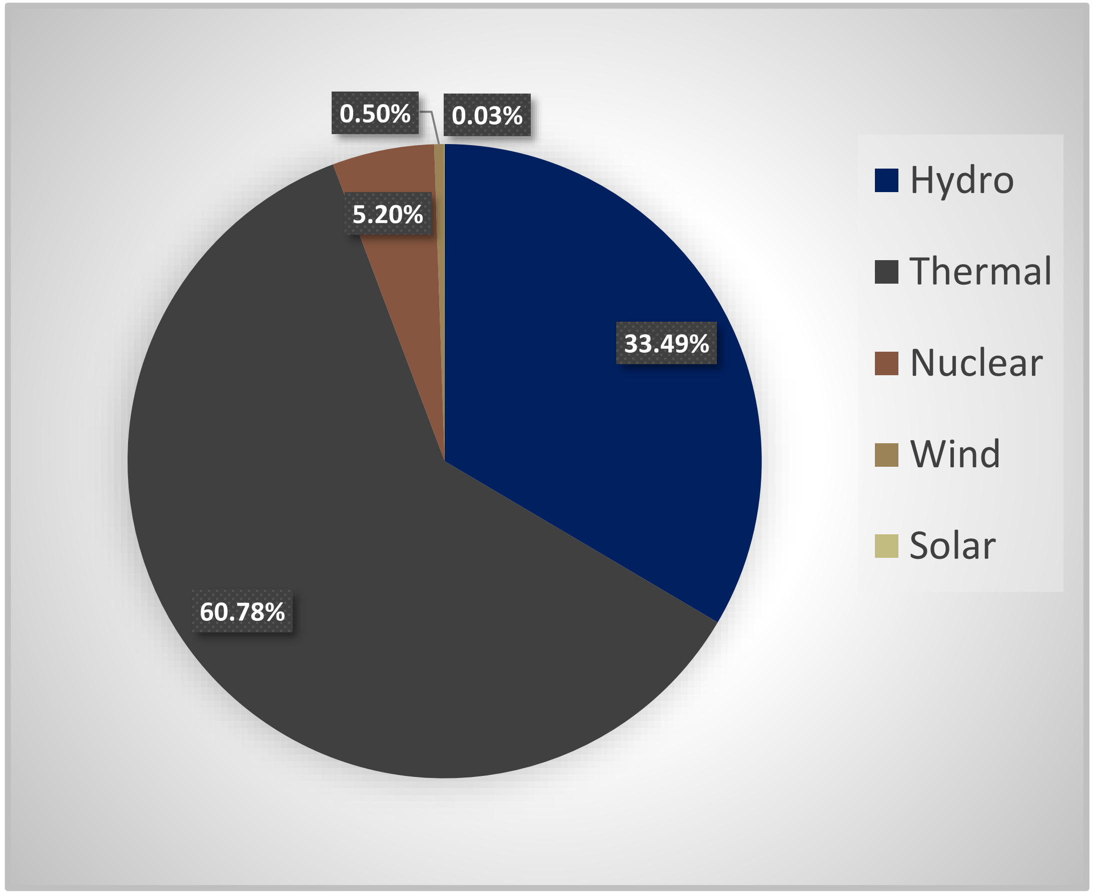


Figure 3: Electricity Generation Mix of Pakistan [6]

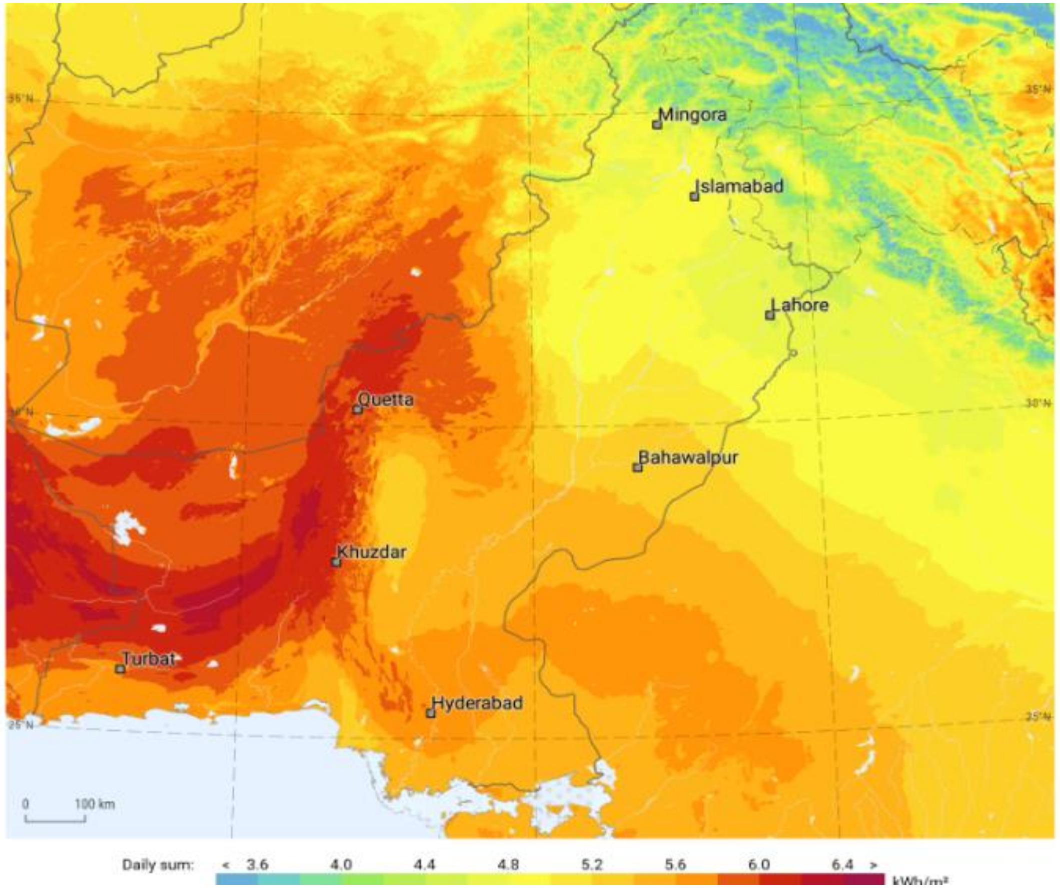


Figure 4: Solar Insolation levels in Pakistan [7]

Overview

- Mostly electricity generation is done using conventional resources which increase carbon emissions and cause global warming.
- In Pakistan, 60.78% generation is done with imported coal [8].
- Pakistan has massive potential for solar energy with average solar insolation of 5.5 $kWh/m^2/day$ and a potential of up to 100,000 MW using solar energy[9-10].
- Hybrid Energy System is designed for a plant having average load of 2415 kW.
- For this system, optimization analysis has been carried out using HOMER and PVWatt software.
- The dynamic modeling is done by MATLAB/Simulink and EMONCMS SCADA system is used for monitoring purpose.

Site Detail

- The site selection plays a vital role in the feasibility of a PV power plant.
- Therefore, a site is selected in capital city Lahore industrial area.
- The selected insdustrial unit name “ Shafi Texcel Limited” is a textile company

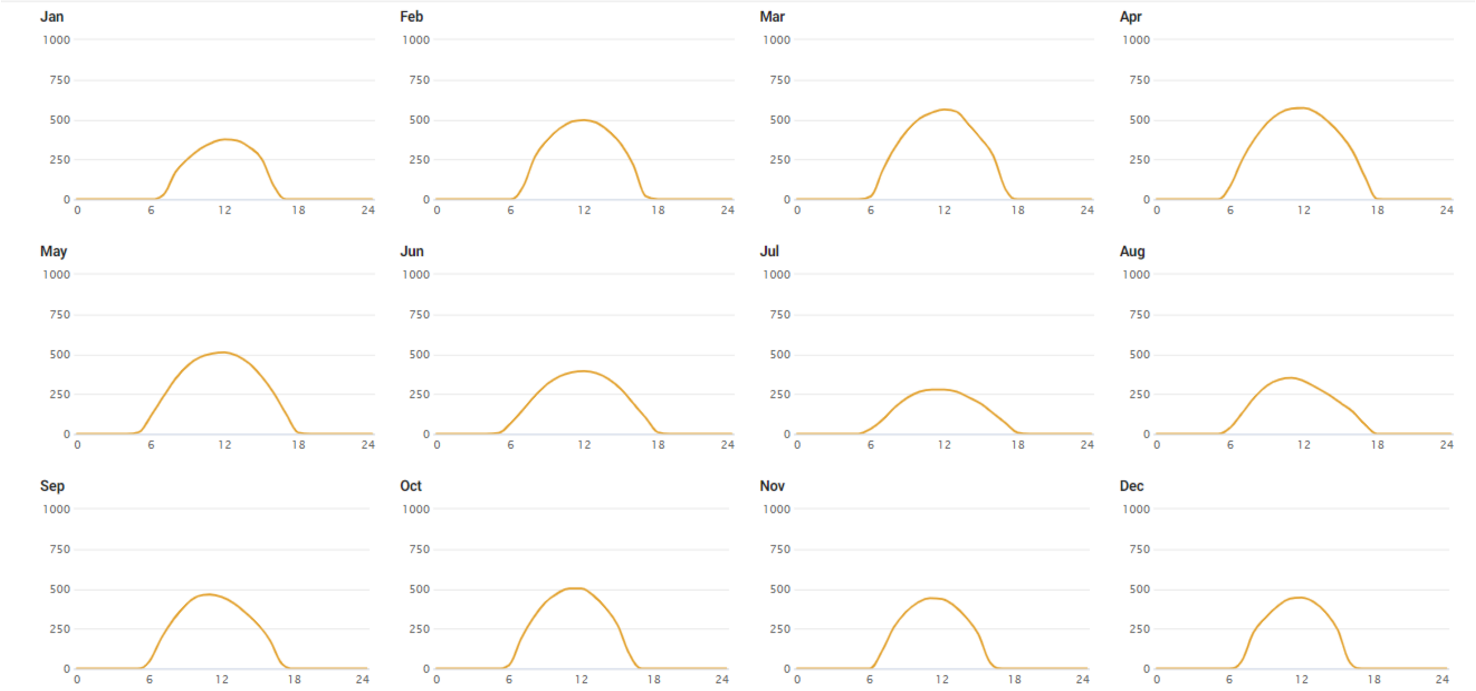


Figure 5: Monthly Irradiance of Selected Site [3]

Site Details

- First, the selected site is Shafi Texcel Limited, situated on 4.5 km Raiwind Manga Road, Lahore, Punjab 55150 Pakistan (31.2616, 74.1674)
- From Fig. 7, it can be observed that solar radiation is available throughout the year, and its values vary between 3.05 to 6.90 kWh/m^2/day

Figure 6: Location of the Site on Google Map

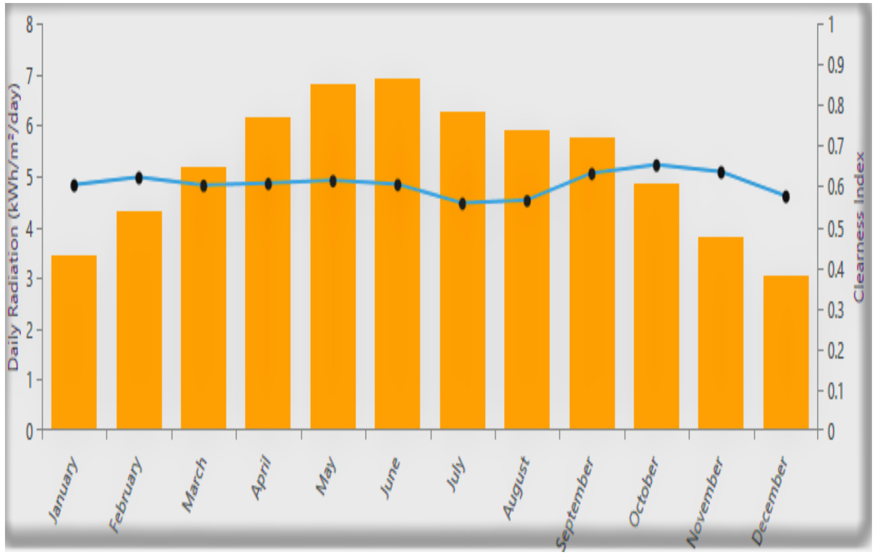


Figure 7: Irradiance and Clearance Index of the Site

Site Electrical Load

- The hourly data of load has been collected for the year 2020.
- The average consumed units per day are 59655, and average & peak load over the year is 2485.6 kW & 3257.7 kW.
- Load factor is the efficient utilization of electrical power network, and it is 76%.

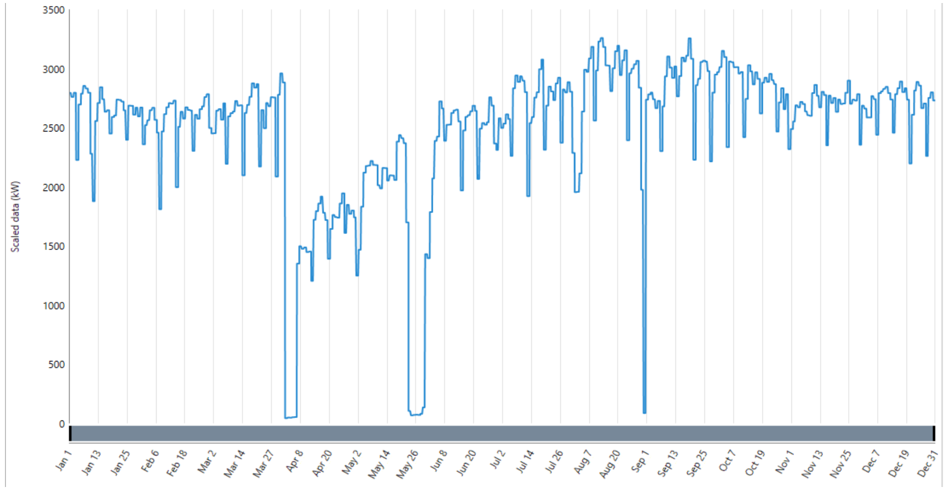


Figure 8: The Site Electrical Demand

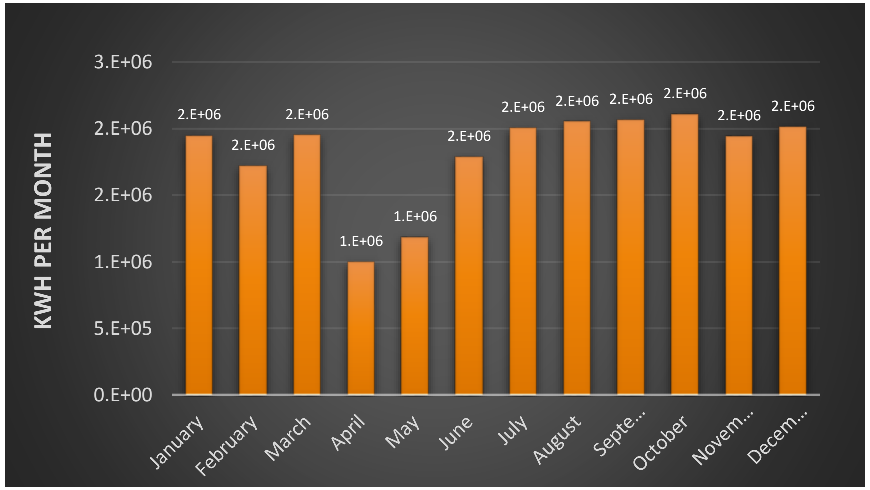


Figure 9: Monthly Electrical Consumption

Literature Review

- The following papers are reviewed before site selection and sizing of PV system.

Paper Reviewd	Deductions
C. E. Lin, B. C. Phan and Y. Lai	Wind and solar energy-based hybrid systems have been used for power generation in Basco island
N. Tahir and H. Jatala	3kW solar PV system is modeled using HOMER. It is deduced that a grid-tied system is more efficient as compared to a standalone
M. Nurunnabi and N. K. Roy	This paper presents an economical expediency of grid connected hybrid system for rural area in the southern city of Bangladesh. HOMER is used for analyzing the site data.
M. A. Khattak, S. M. Syahir, A. Aziz Aiza, S. Mansor S. Al	Diesel Power Plant working has been discussed in this paper. A detail operation & maintenance cost analysis is done.
Y. Abid, M. A. Khan and T. Muhammad	This paper presents a design of microgrid with hybrid power generation system. Two different systems are designed. One system has only renewable resources, while other has a backup diesel generator

Literature Review

- The following papers are reviewed before site selection and sizing of PV system.

Paper Reviewd	Deductions
V. Raviprasad and R. K. Singh	Manual Formulation Methods has been for sizing of PV system which only include tilt angle, irradiance, storage.
Asrari, A.; Ghasemi, A.; Javidi	The authors did the economic feasibility of hybrid renewable energy systems (HRES) for rural electrification in Iran. The selected site is a remote rural village named Sheikh Abolhassan.
N. Tahir and H. Jatala	Designed a grid-tied hybrid power system in which a diesel generator is used along with PV system. A 03-kW solar power system is modeled, and optimization analysis is carried out using the HOMER PRO.
M. Nurunnabi and N. K. Roy	Designed a PV system for a rural area in Bangladesh. The maximum load demand of that area is very low i.e. 60 kW, and there is very small load fluctuation in the residential load

Literature Review

- The following papers are reviewed before site selection and sizing of PV system.

Paper Reviewd	Deductions
D. Li, N. Gebraeel and K. Paynabar	Real-time information has become imperative for managing renewable energy assets with the rapid growth of renewable energy generation worldwide.
Qays, MO, Ahmed, MM, Parvez Mahmud, MA, et al.	SCADA system is used to remotely control and monitor inverters with grid connectivity. To maintain stable energy prices and maintaining network stability require utility providers proper monitoring and control of grid connected inverters.
Lawrence O. Aghenta, M. Tariq Iqbal	Low-cost and open-source SCADA system by using the internet of things (IoT) and advanced SCADA system design. The proposed system applies, ESP32 micro controller, Voltage sensors, current sensors, ThingsBoard IoT server and HMIs.
C. N. Oton and M. T. Iqbal	Used ESP32 and Arduino IoT Cloud are used to implement 95 an open source, low-cost, IoT-based SCADA system for a rural Base Transceiver Station 96 (BTS).

Research Objectives

- Explore the potential of renewable energy in poor countries to reduce the impact of climate change all over the world.
- Design a hybrid power plant for an industrial unit that gives lowest possible per unit cost of energy along with the reliability and security of a system.
- Create awareness among public and industrialists about the distributed power generation to earn revenue by selling the electricity to utility companies through net metering.
- Study the dynamics of hybrid power plants during the load variations and abrupt irradiance change due to clouds.
- Design a low-cost, open-source SCADA system for distributed PV generation to record the system behavior for future planning purposes.

Plant Electrical Layout

- Plants are designed for flexibility in operation and maintenance without affecting the end-user.
- Therefore, the captive power plants are designed efficiently with backup resources to supply 24/7 without any interruption.
- Overall, Solar & Grid will be utilized maximum, and Gas & Diesel generators will act as backup sources.
- Grid (Lesco) contracted load is 3500 kW with tariff B3 (14)T in which 20.39 PKR/kWh is charged for peak load, and 12.61 PKR/kWh charges for off Peak [4].
- CAT 3516B Genset has fuel consumption of 9776 Btu/kWh [5] and 3512 Diesel Genset has 0.28L/kWh fuel consumption [6].

Plant Electrical Layout (Cont'd)

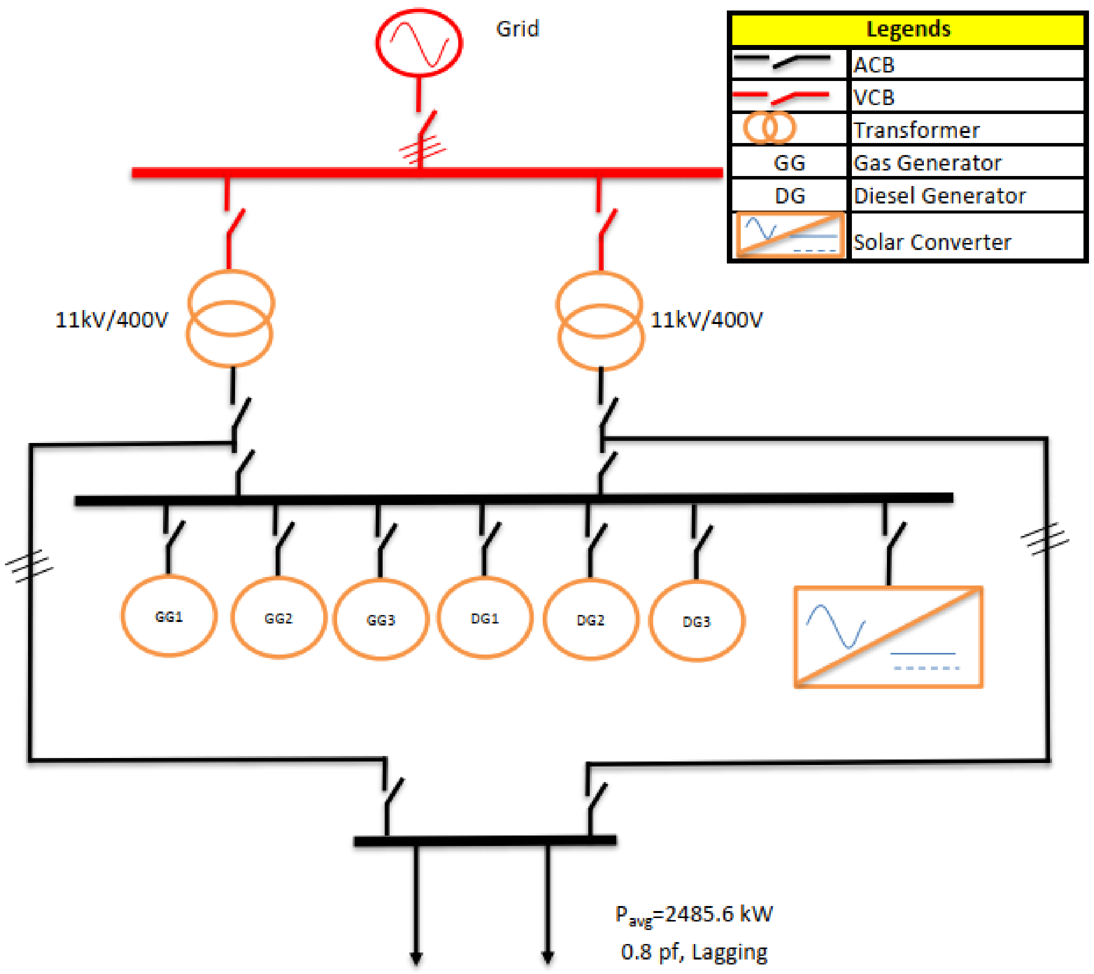


Figure 10.:Single Line Electrical Diagram of the Site

Optimization Of PV Plant (Case 01-Without Storage And Zero Constraint)

- For optimization of solar plant, HOMER is used which was originally developed at NREL.
- The system has DC bus voltage is 806 V_{dc} & AC bus voltage is $400V_{ac}$ and DC bus is connected with 480 W flat plate solar module of ENN Solar Energy480EST-480
- Two buses are connected with the help of a solar converter. Eaton Power Xpert 2250kW is used to convert the DC voltage into the AC voltage.
- Sizing results depict that system takes 50.9 % of electricity from solar for which 8382 kW solar modules along with 3119 kW Eaton inverter are required.
- The analysis of land requirement has also been done in PVWatts.

Optimization Of PV Plant (Case 01-Without Storage and Zero Constraint) (Cont'd)

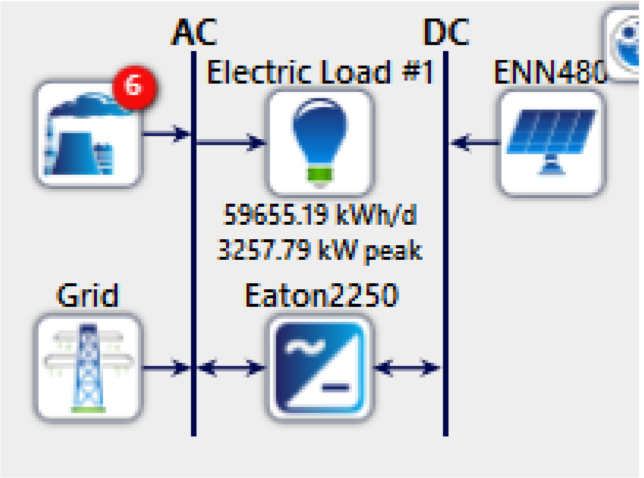
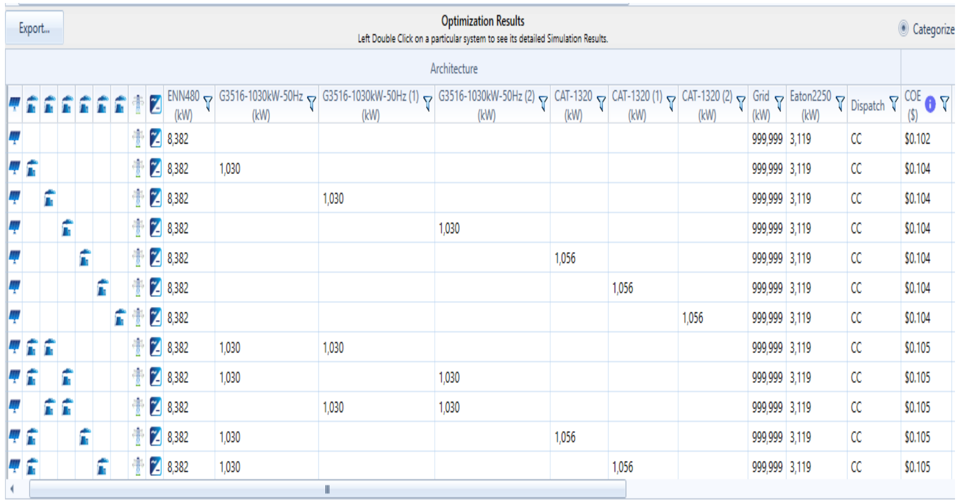


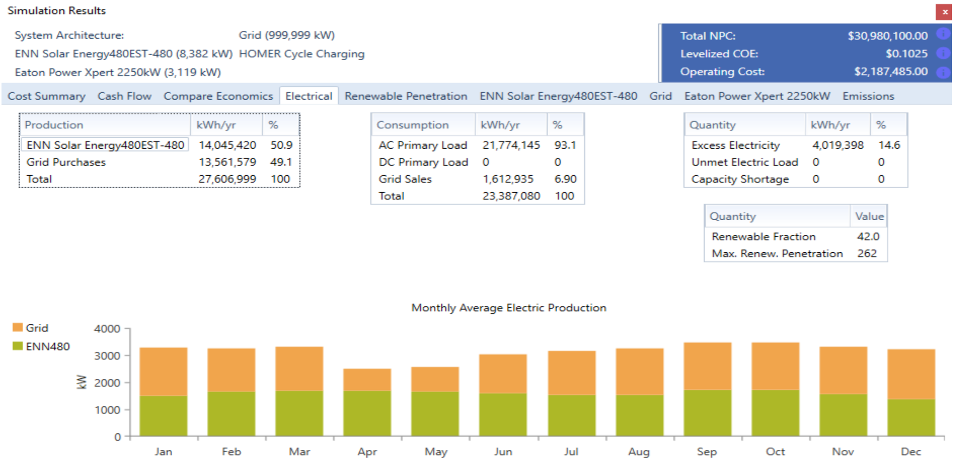
Figure 11: Schematic of System without Storage

Figure 13: Required Land Marking for 8382 kWdc Solar System



ENN480 (kW)	G3516-1030kW-50Hz (kW)	G3516-1030kW-50Hz (1) (kW)	G3516-1030kW-50Hz (2) (kW)	CAT-1320 (kW)	CAT-1320 (1) (kW)	CAT-1320 (2) (kW)	Grid (kW)	Eaton2250 (kW)	Dispatch	COE ($)
8,382							999,999	3,119	CC	$0.102
8,382	1,030						999,999	3,119	CC	$0.104
8,382		1,030					999,999	3,119	CC	$0.104
8,382			1,030				999,999	3,119	CC	$0.104
8,382				1,056			999,999	3,119	CC	$0.104
8,382					1,056		999,999	3,119	CC	$0.104
8,382						1,056	999,999	3,119	CC	$0.104
8,382	1,030	1,030					999,999	3,119	CC	$0.105
8,382	1,030		1,030				999,999	3,119	CC	$0.105
8,382		1,030	1,030				999,999	3,119	CC	$0.105
8,382	1,030			1,056			999,999	3,119	CC	$0.105
8,382	1,030				1,056		999,999	3,119	CC	$0.105

Figure 12: Optimization Results without Storage



Production	kWh/yr	%
ENN Solar Energy480EST-480	14,045,420	50.9
Grid Purchases	13,561,579	49.1
Total	27,606,999	100

Consumption	kWh/yr	%
AC Primary Load	21,774,145	93.1
DC Primary Load	0	0
Grid Sales	1,612,935	6.90
Total	23,387,080	100

Quantity	kWh/yr	%
Excess Electricity	4,019,398	14.6
Unmet Electric Load	0	0
Capacity Shortage	0	0

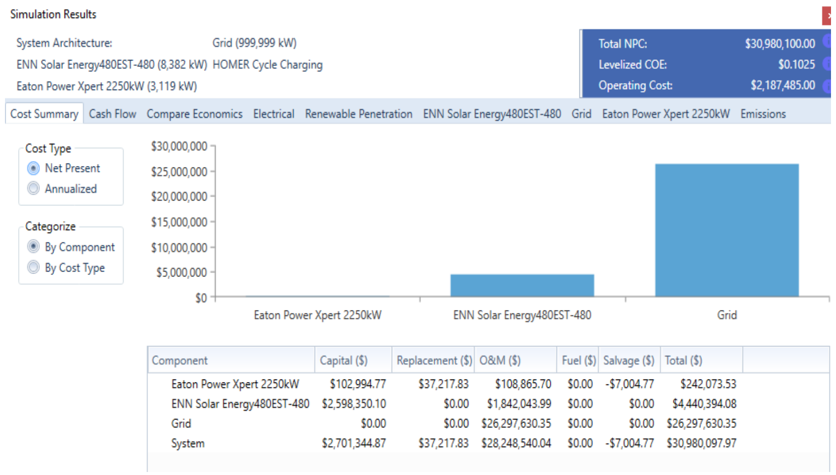
Quantity	Value
Renewable Fraction	42.0
Max. Renew. Penetration	262

Figure 14: Simulation Results in HOMER (0% Constraint)

Optimization Of PV Plant (Case 01-Without Storage and Zero Constraint) (Cont’d)

✓ **Cash Summary**

- Total cost of equipment installation and operation over its whole life span named net capital cost is $ 30,980,100.
- Levelized cost is the net present cost of electricity generation over the entire life of plant, it is $ 0.1025.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Eaton Power Xpert 2250kW	$102,994.77	$37,217.83	$108,865.70	$0.00	-$7,004.77	$242,073.53
ENN Solar Energy480EST-480	$2,598,350.10	$0.00	$1,842,043.99	$0.00	$0.00	$4,440,394.08
Grid	$0.00	$0.00	$26,297,630.35	$0.00	$0.00	$26,297,630.35
System	$2,701,344.87	$37,217.83	$28,248,540.04	$0.00	-$7,004.77	$30,980,097.97

Figure 15: Cost Summary of 8382 kW PV System

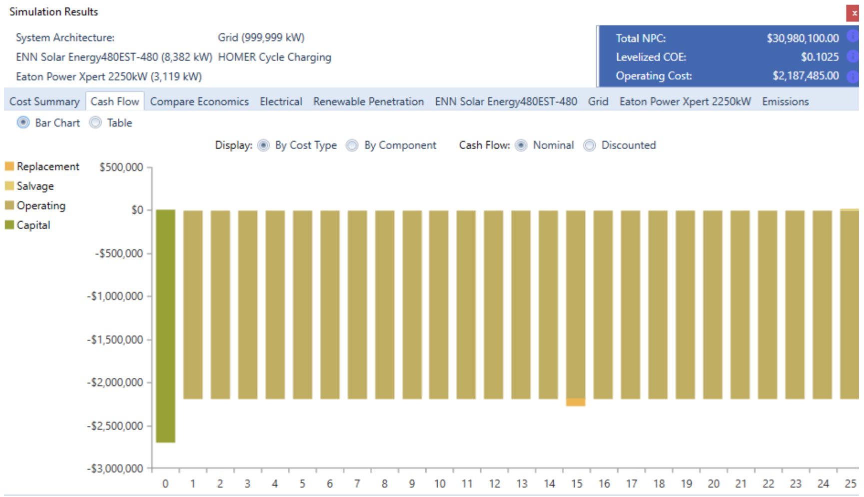
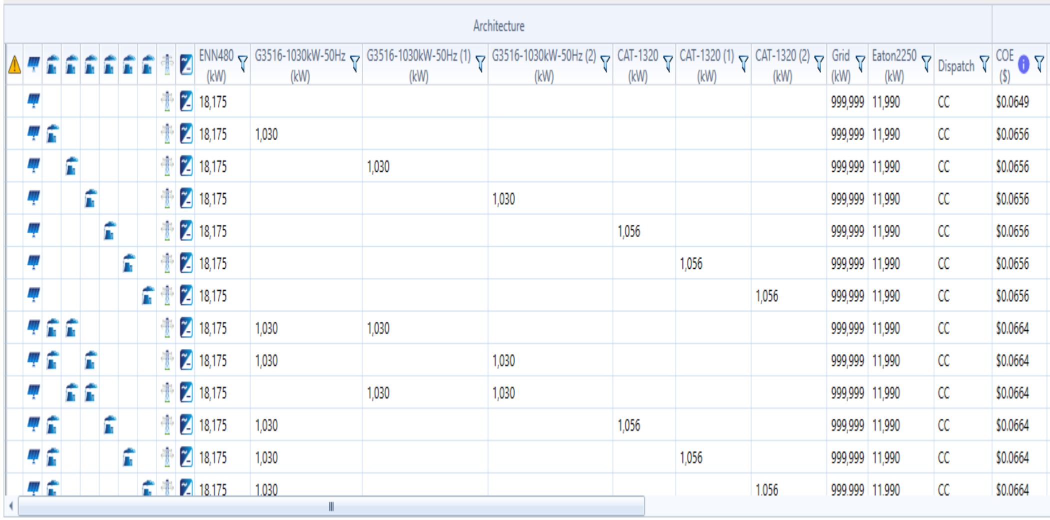


Figure 16: Cash Flow of 8382 kW PV System

Optimization Of PV Plant (Case 02-No Storage and 70% RE Constraint)

- The electrical load demand is increasing consistently due to which plants should be in that area where enough land is available for future extension.
- A constraint is putted to generate the 70 % electricity from the PV power plant to extend solar power.



ENN480 (kW)	G3516-1030kW-50Hz (kW)	G3516-1030kW-50Hz (1) (kW)	G3516-1030kW-50Hz (2) (kW)	CAT-1320 (kW)	CAT-1320 (1) (kW)	CAT-1320 (2) (kW)	Grid (kW)	Eaton2250 (kW)	Dispatch	COE ($)
18,175							999,999	11,990	CC	$0.0649
18,175	1,030						999,999	11,990	CC	$0.0656
18,175		1,030					999,999	11,990	CC	$0.0656
18,175			1,030				999,999	11,990	CC	$0.0656
18,175				1,056			999,999	11,990	CC	$0.0656
18,175					1,056		999,999	11,990	CC	$0.0656
18,175						1,056	999,999	11,990	CC	$0.0656
18,175	1,030	1,030					999,999	11,990	CC	$0.0664
18,175	1,030		1,030				999,999	11,990	CC	$0.0664
18,175		1,030	1,030				999,999	11,990	CC	$0.0664
18,175	1,030			1,056			999,999	11,990	CC	$0.0664
18,175	1,030				1,056		999,999	11,990	CC	$0.0664
18,175	1,030					1,056	999,999	11,990	CC	$0.0664

Figure 17: Optimization Results without Storage (70% RE Constraint)

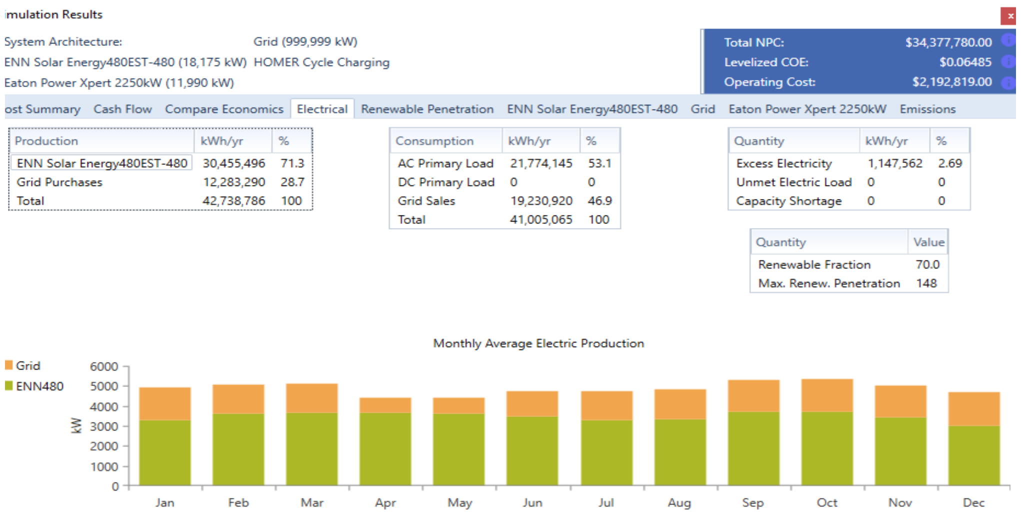


Figure 18: Simulation Results in HOMER (70% RE Constraint)

Optimization Of PV Plant (Case 02-No Storage and 70% RE Constraint) (cont'd)

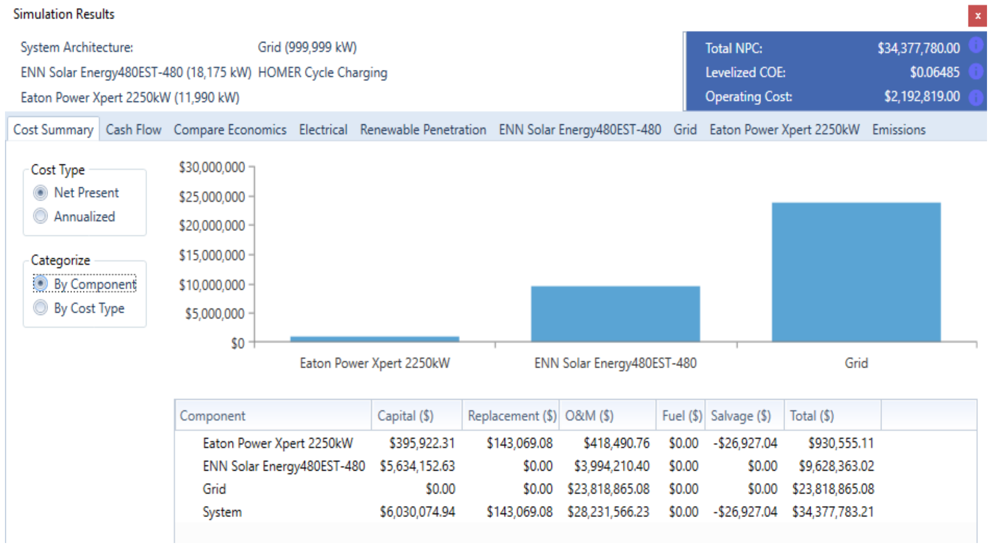


Figure 19: Cost Summary of 18175 kW PV System

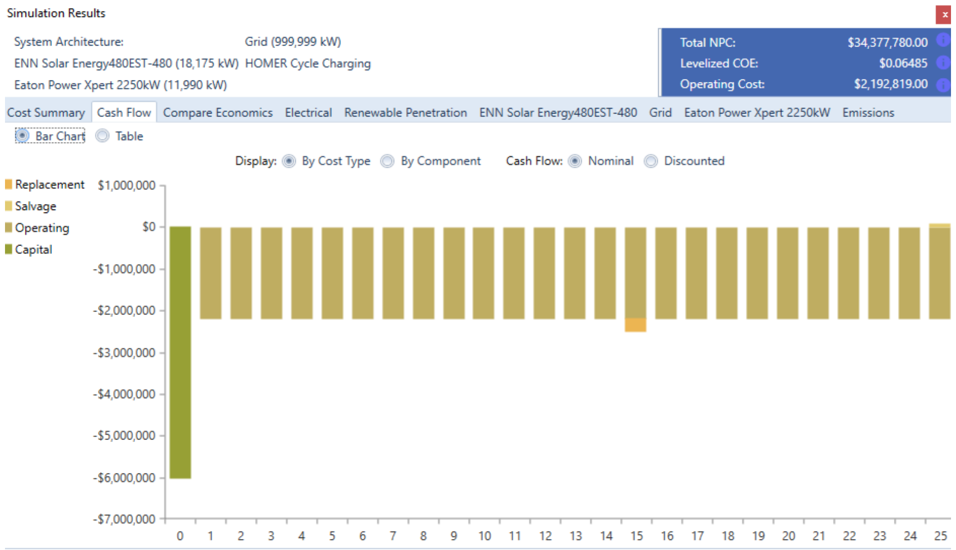


Figure 20: Cost Flow of 18175 kW PV System

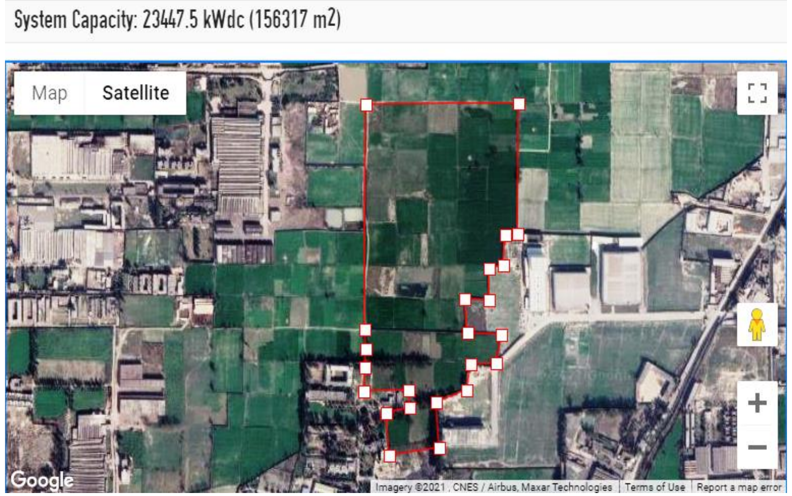


Figure 21: Land Marking for 18175 kW_{dc} PV System

Optimization Of PV Plant (Case 03-With Storage and 0% RE Constraint)

- A battery is used to store the electrical energy in DC form. It also provides energy during the nighttime and zero irradiance situation.
- For small systems battery play a vital role in the stabilization of output voltage and frequency by absorbing/delivering additional power.

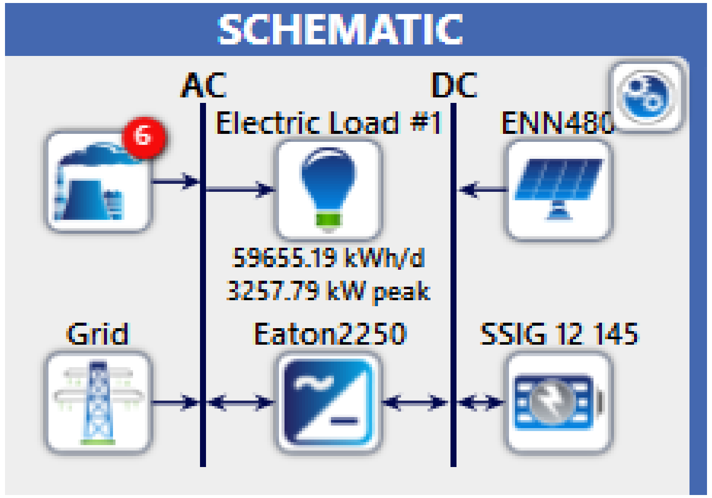


Figure 22: Schematic of System with Storage

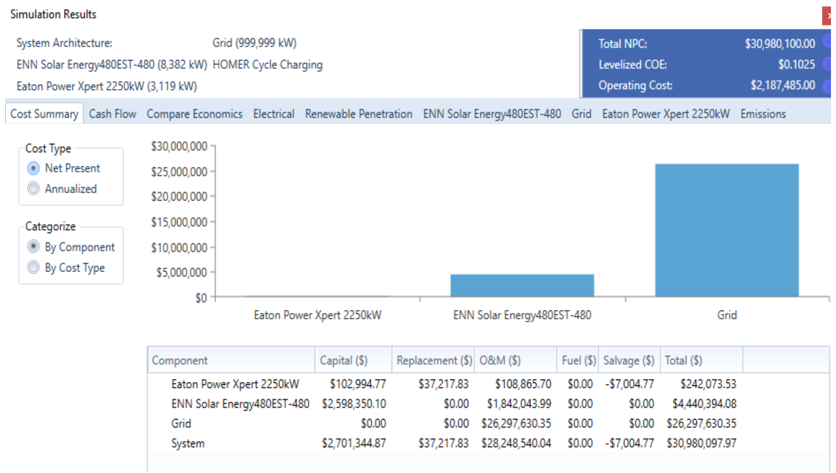
ENN480 (kW)	G3516-1030kW-50Hz (kW)	G3516-1030kW-50Hz (1) (kW)	G3516-1030kW-50Hz (2) (kW)	CAT-1320 (kW)	CAT-1320 (1) (kW)	CAT-1320 (2) (kW)	SSIG 12 145	Grid (kW)	Eaton2250 (kW)
8,382								999,999	3,119
8,470							2,412	999,999	3,207
8,382	1,030							999,999	3,119
8,382		1,030						999,999	3,119
8,382			1,030					999,999	3,119
8,382				1,056				999,999	3,119
8,382					1,056			999,999	3,119
8,382						1,056		999,999	3,119
8,470	1,030						2,412	999,999	3,207
8,470		1,030					2,412	999,999	3,207
8,470			1,030				2,412	999,999	3,207
8,470				1,056			2,412	999,999	3,207
8,470					1,056		2,412	999,999	3,207

Figure 23: Optimization Results with Storage

Optimization Of PV Plant (Case 03-With Storage and 0% RE Constraint) (Cont'd)

✓ **Cash Summary**

- Total cost of equipment installation and operation over its whole life span named net capital cost is also $ 30,980,100.
- Levelized cost is the net present cost of electricity generation over the entire life of plant, it is $ 0.1025.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Eaton Power Xpert 2250kW	$102,994.77	$37,217.83	$108,865.70	$0.00	-$7,004.77	$242,073.53
ENN Solar Energy480EST-480	$2,598,350.10	$0.00	$1,842,043.99	$0.00	$0.00	$4,440,394.08
Grid	$0.00	$0.00	$26,297,630.35	$0.00	$0.00	$26,297,630.35
System	$2,701,344.87	$37,217.83	$28,248,540.04	$0.00	-$7,004.77	$30,980,097.97

Figure 24: Cost Summary of System with Storage

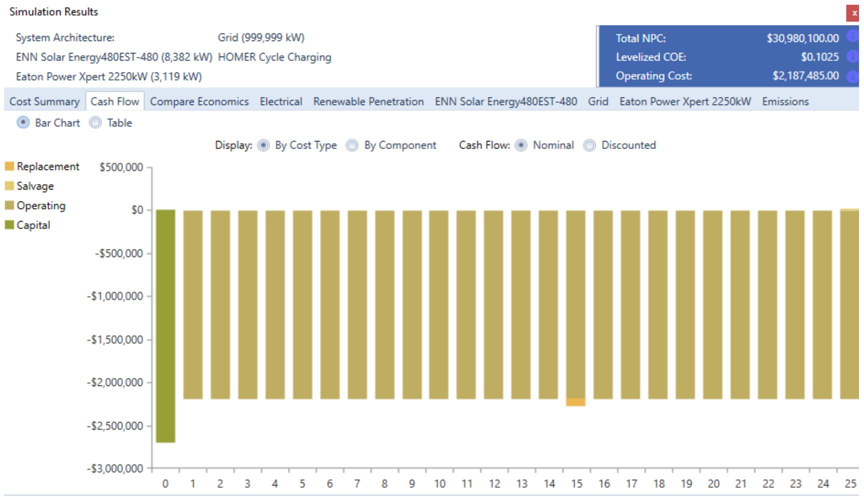


Figure 25: Cash flow of System with Storage

PV System Layout

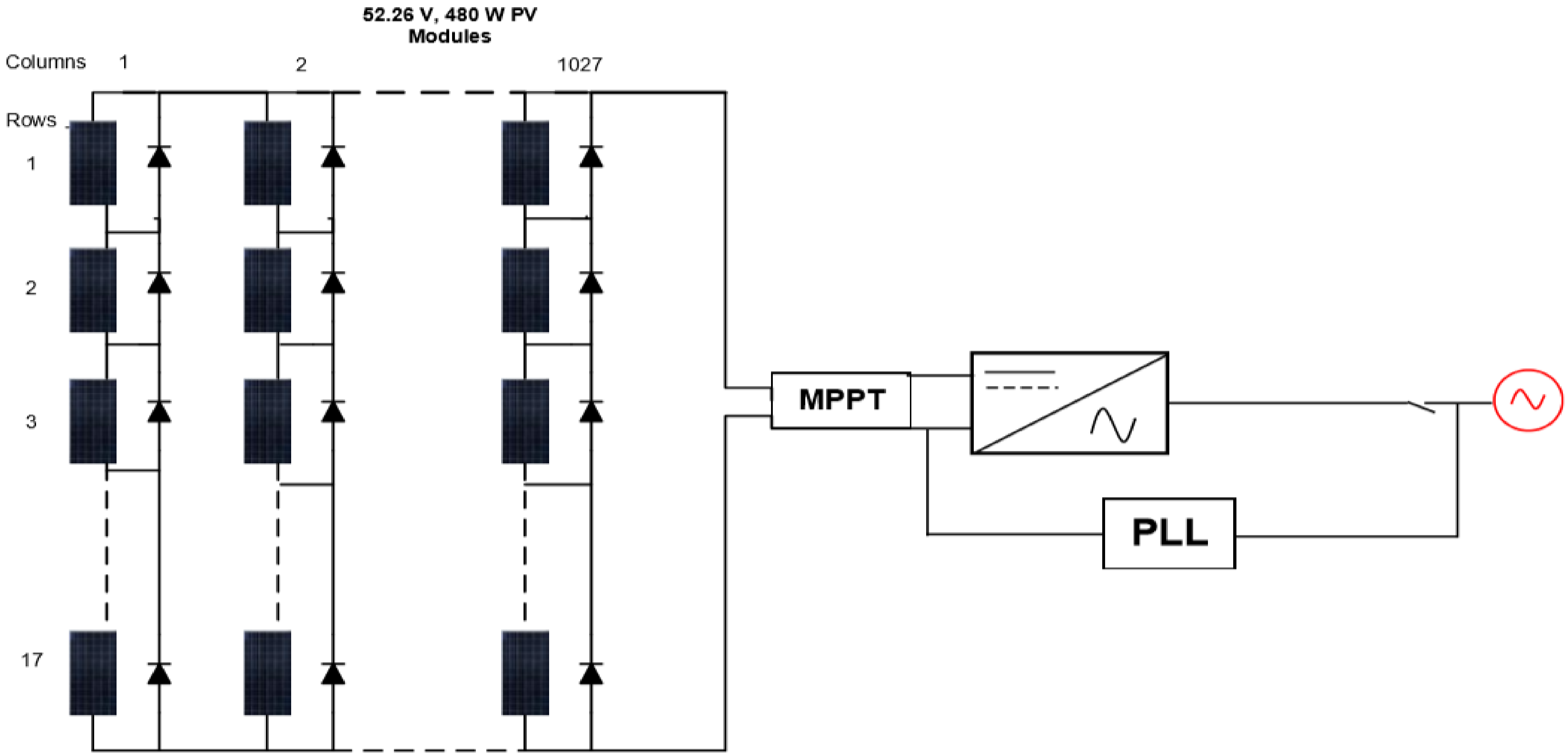


Figure 26: PV Configuration of System

Dynamic Modeling of an Optimal Hybrid Power System for a Captive Power Plant in Pakistan

MATHEMATICAL MODELING OF HRES

➢ PV System Sizing

- A 480 W panel specifications are given in the table 1. Fig. 29 shows that the maximum power point voltage of one string is 679 V at 25 °C and maximum power point current is 6190.8 A

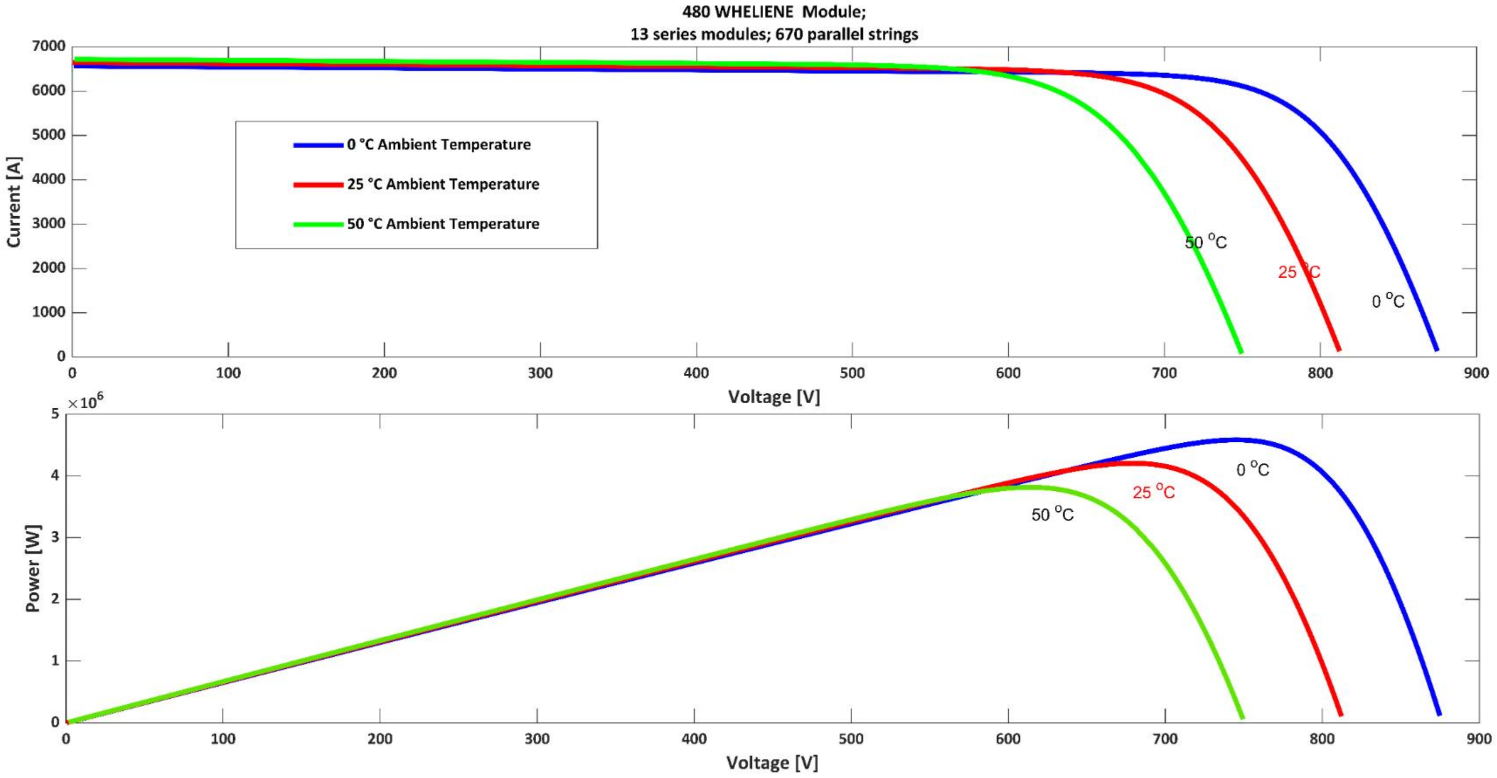


Fig. 29. PV module P-V & I-V characteristics.

MATHEMATICAL MODELING OF HRES

➢ Maximum Power Point Tracking

- The solar energy is dependent on irradiance, the shape of I-V characteristics curve changes and it can also be observed from fig. 30 that the I-V curve is non-linear.
- The power taken from PV module depends upon the operating point on the curve.

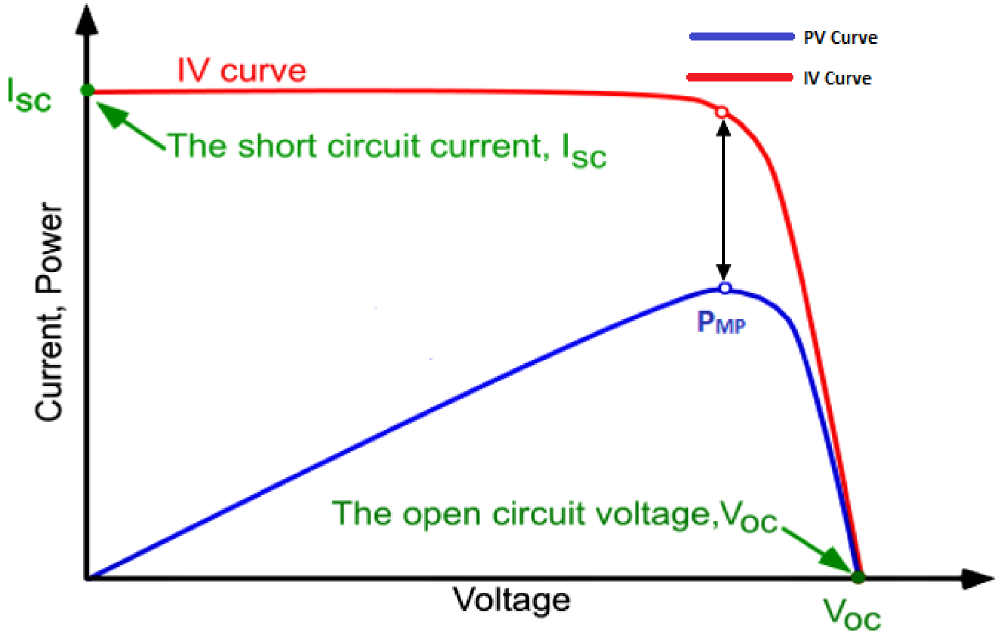


Fig. 30. P-V curve maximum power point.

MATHEMATICAL MODELING OF HRES

- Maximum Power Point Tracking

- Fig. 31 shows the IC algorithm, in which firstly ∆I & ∆V is determined then depending upon the values if else conditions are used for the final duty cycle.

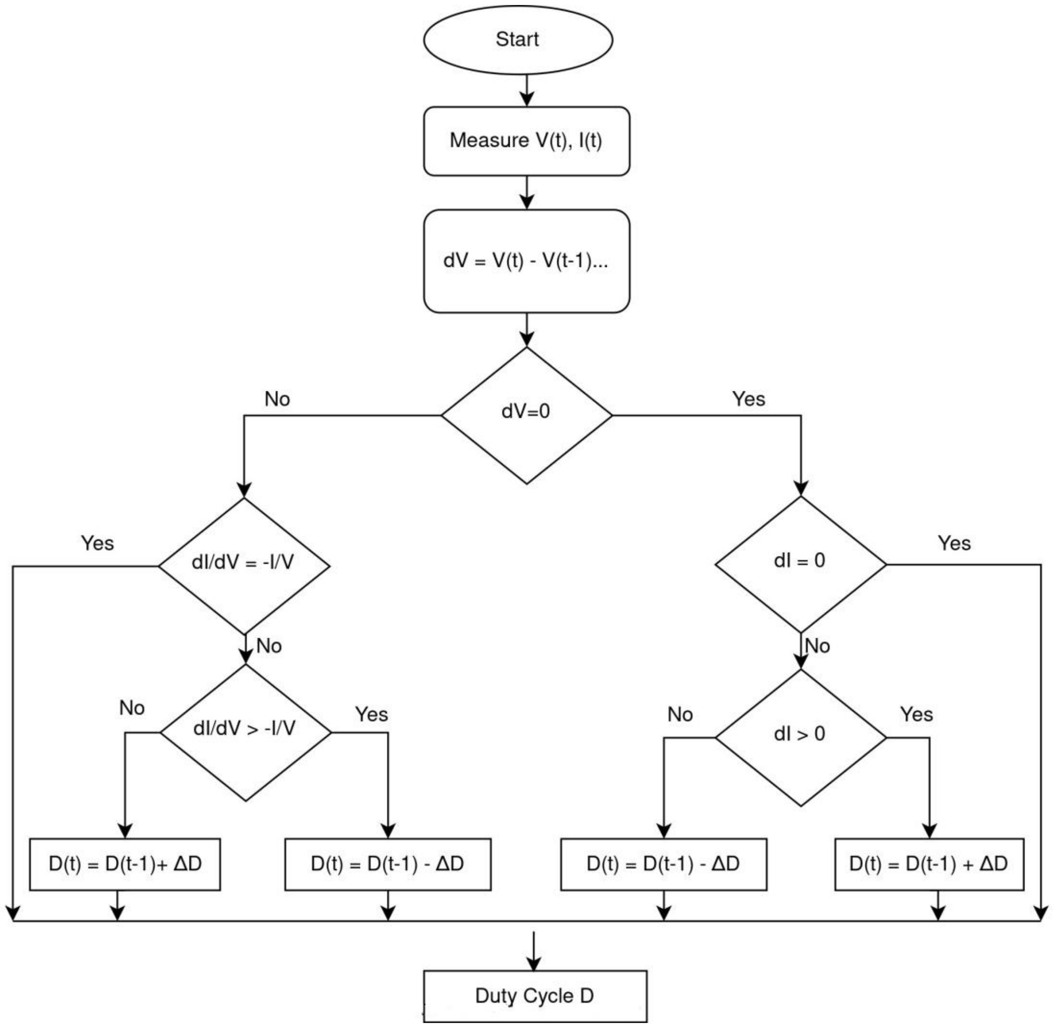


Figure. 31. Flow chart of incremental conductance.

MATHEMATICAL MODELING OF HRES

➢ Design of Boost Converter

- A boost converter is a dc step-up transformer with high output voltage and low current compared to input voltage & current respectively. Ideally, the total power on both sides of the converter remains constant.
- The output voltage is controlled with the help of switch S shown in fig. 32

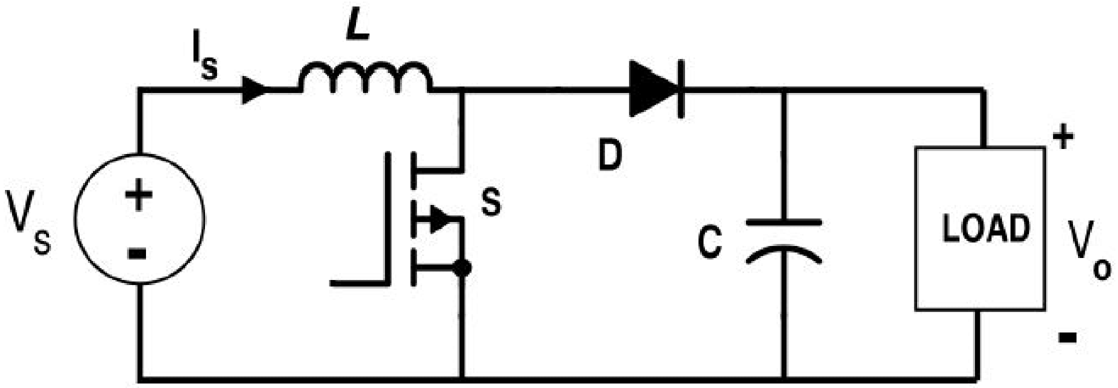


Fig. 32. Boost converter circuit.

$$V_O = \frac{-1}{1-D} \times V_i$$

$$I_L = (1-D) \times I_S$$

MATHEMATICAL MODELING OF HRES

➢ Design of Boost Converter

- Therefore, the conventional equations for design of input inductor and capacitor remain no more valid
- Input inductor and output capacitor should always operate in continuous conduction mode; both should not discharge completely during the off cycle. Therefore, the ripple in input current (ΔIL) is usually taken as 13% of total input maximum current.

$$L_{boost} = \frac{V_S \times (V_O - V_S)}{\Delta I_L \times f_S \times V_O}$$

$$\Delta I_L = 0.13 \times I_o \times \frac{V_o}{V_s}$$

$$L_{boost} = 5.0811\ \mu H$$

MATHEMATICAL MODELING OF HRES

➢ Design of Boost Converter

- Therefore, the conventional equations for design of input inductor and capacitor remain no more valid
- Input inductor and output capacitor should always operate in continuous conduction mode; both should not discharge completely during the off cycle. Therefore, the ripple in input current (∆IL) is usually taken as 13% of total input maximum current in Eq

$$L_{boost} = \frac{V_S \times (V_O - V_S)}{\Delta I_L \times f_S \times V_O}$$

$$\Delta I_L = 0.13 \times I_o \times \frac{V_o}{V_s}$$

$$L_{boost} = 5.0811\ \mu H$$

MATHEMATICAL MODELING OF HRES

➢ Design of Boost Converter

- The capacitor on the output side regulates the voltage and delivers the power during the half cycle of pulse. It can be calculated using Eq

$$C_{boost} = \frac{P}{2 \times \omega \times u \times U_c}$$

- Here, U_c is the mean voltage across the capacitor, and u & "ω" are the amplitude and angular frequency of output ripple voltage respectively.

$$C_{boost} = 0.84215 \text{ mF}$$

MATHEMATICAL MODELING OF HRES

- ➢ DC-AC Inverter

- The boost converter's output is fed to the input of inverter for converting the DC power into AC power.
- Neutral Point Clamping (NPC) topology is selected with 3 level bridge.

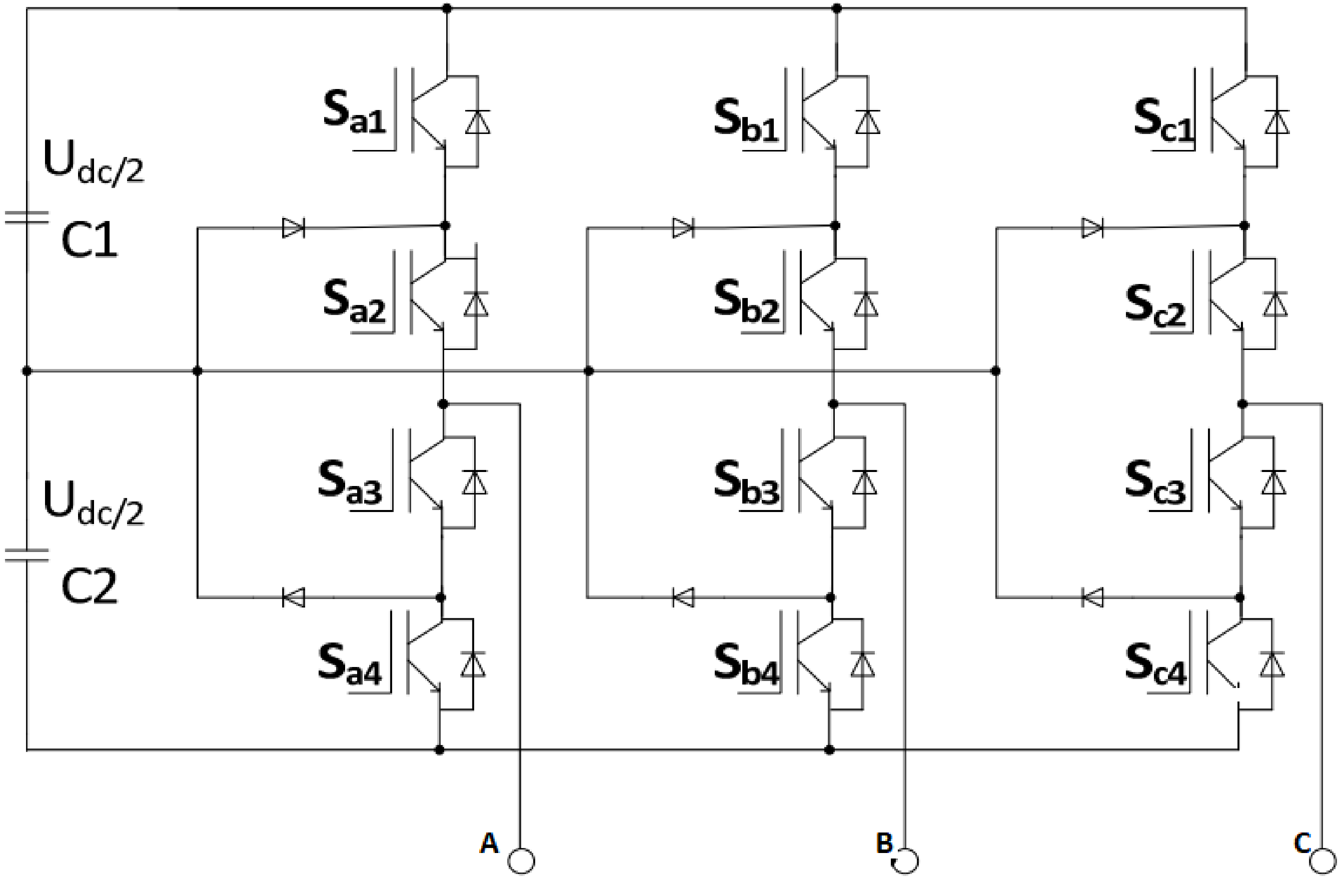


Fig. 33. Inverter NPC topology.

MATHEMATICAL MODELING OF HRES

➢ DC-AC Inverter

- To control the switching frequency of the inverter, the Sinusoidal pulse width modulation (SPWM) technique is used.
- A sine reference signal is compared with two triangular carrier signals for generating the desired pulses as shown in fig. 34.
- In NPC topology, switches S1 & S3 operate in complementary mode, and S2 & S4 also operate in complementary mode; otherwise, it may short circuit the source through any leg of inverter switches

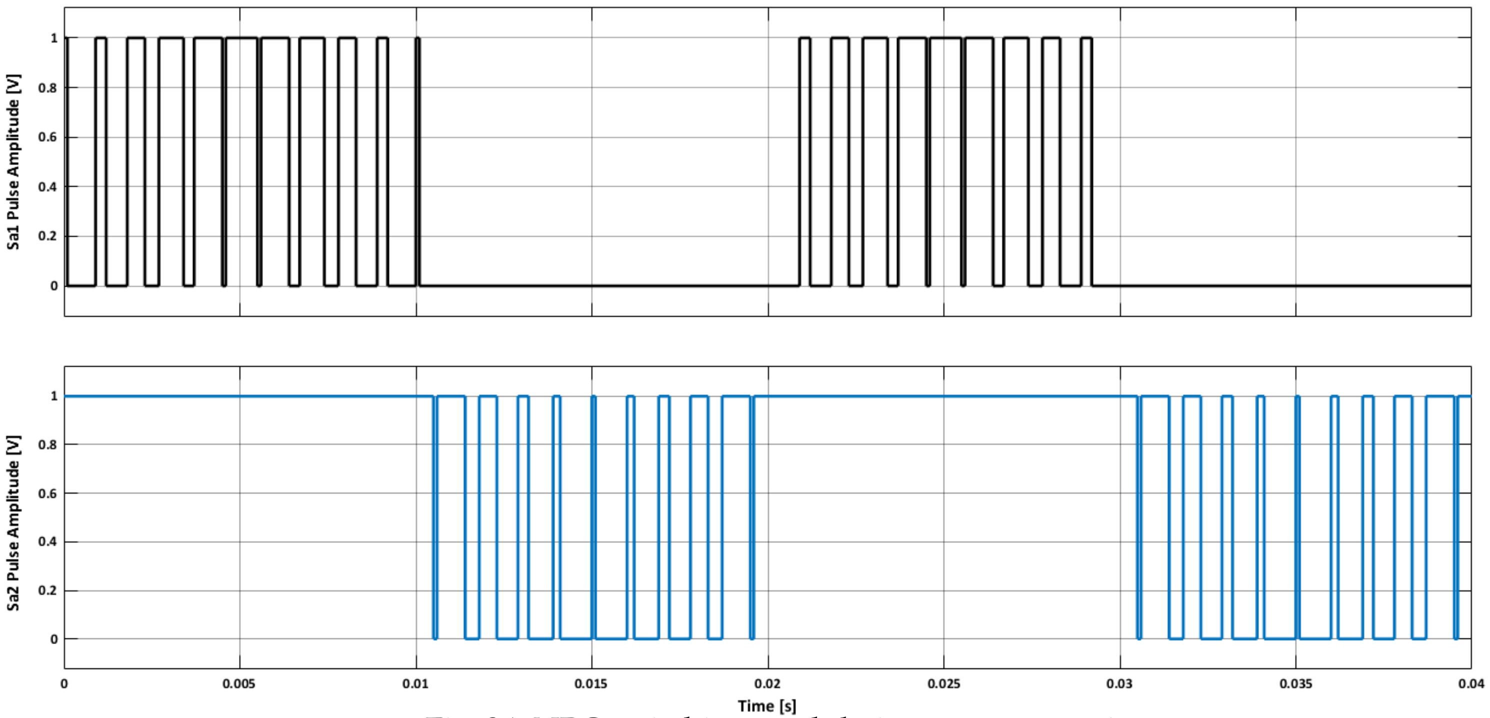


Fig. 34. NPC switching modulating wave vs carrier wave

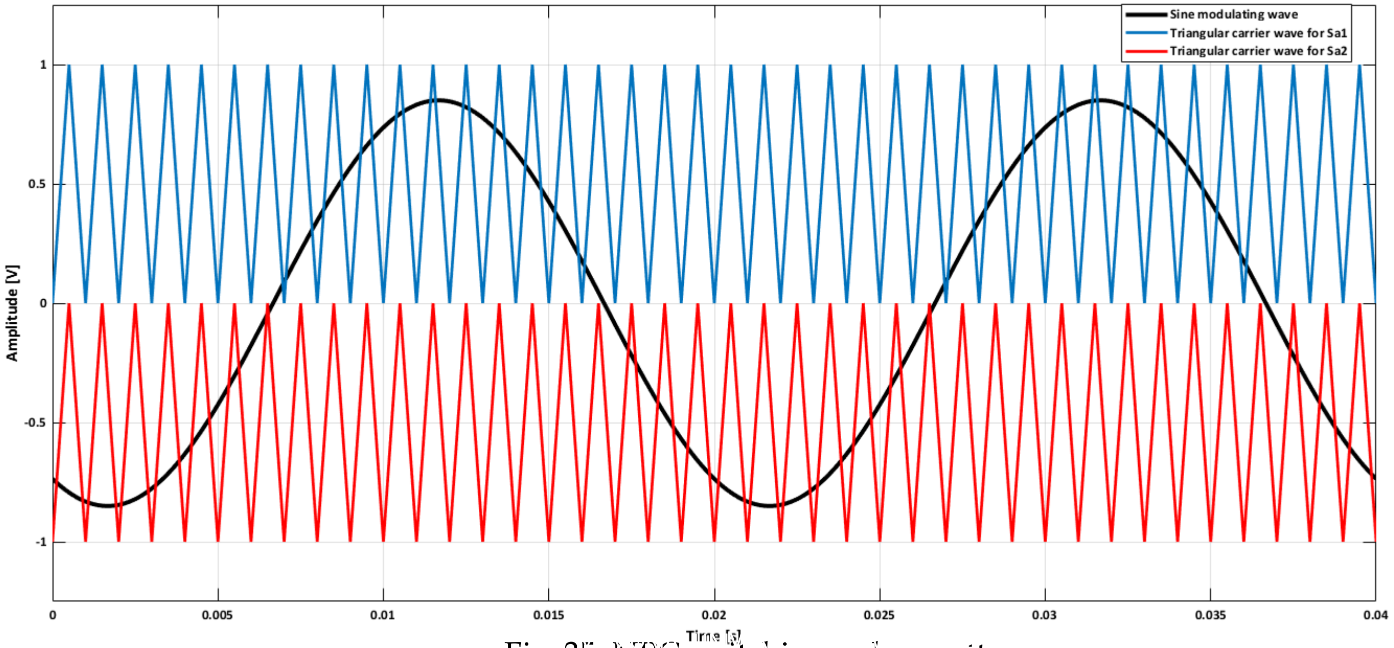


Fig. 35. NPC switching pulses pattern

MATHEMATICAL MODELING OF HRES

➢ Grid Synchronization & Inverter Power Control

- Grid is a source of power and can deliver or absorbed any amount of power.
- For a grid-tied PV system, the grid also acts like a battery.
- To control the voltage parameters of the inverter, it is compulsory to have an idea about the grid voltage magnitude, phase, and frequency.
- As grid quantities are AC and inverter input is dc; therefore, it is necessary to transform the grid quantities into d-q frame of reference, a 2-D synchronous frame rotating at a constant speed so that quantities in that frame appear as constant quantities

MATHEMATICAL MODELING OF HRES

➢ Grid Synchronization & Inverter Power Control

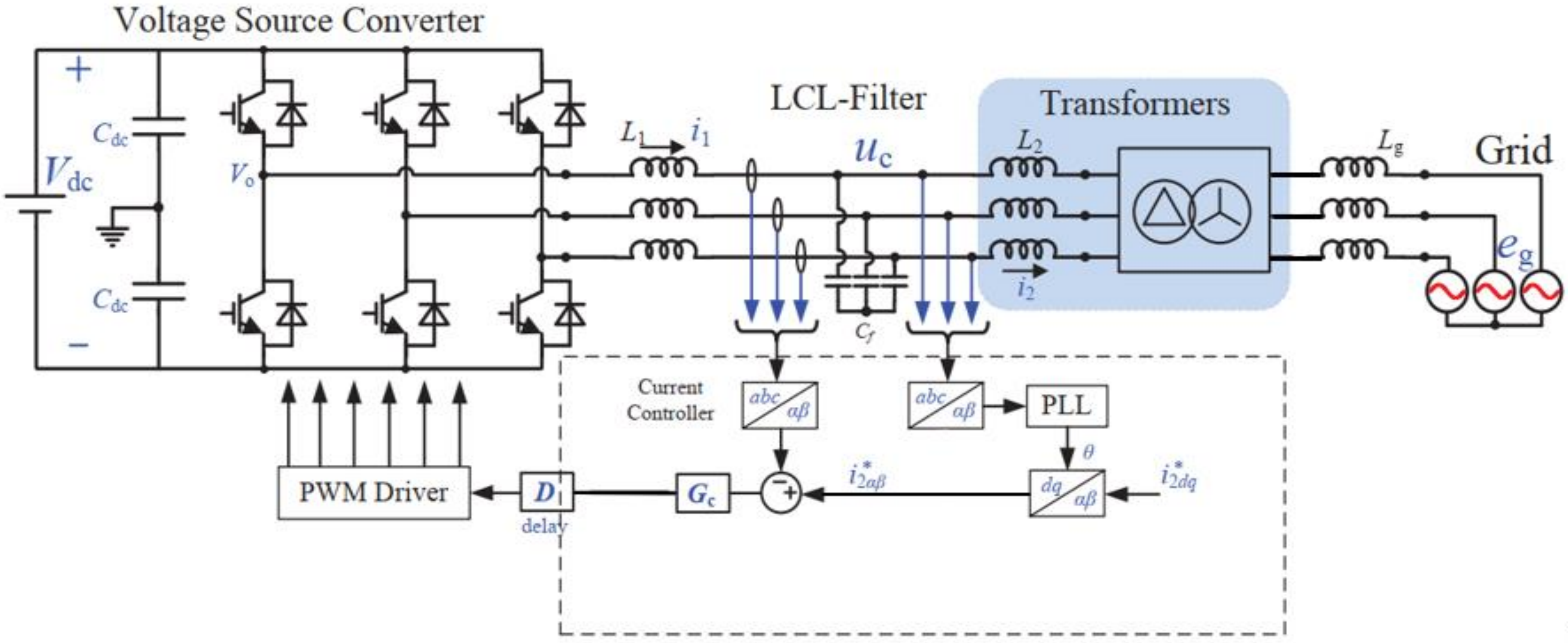


Fig. 36. Schematic configuration of PV grid synchronization.

MATHEMATICAL MODELING OF HRES

➢ LCL Filter Design

- Grid is a source of power and can deliver or absorbed any amount of power.
- It is compulsory to reduce the harmonic content in that waveform for which different filters can be used.

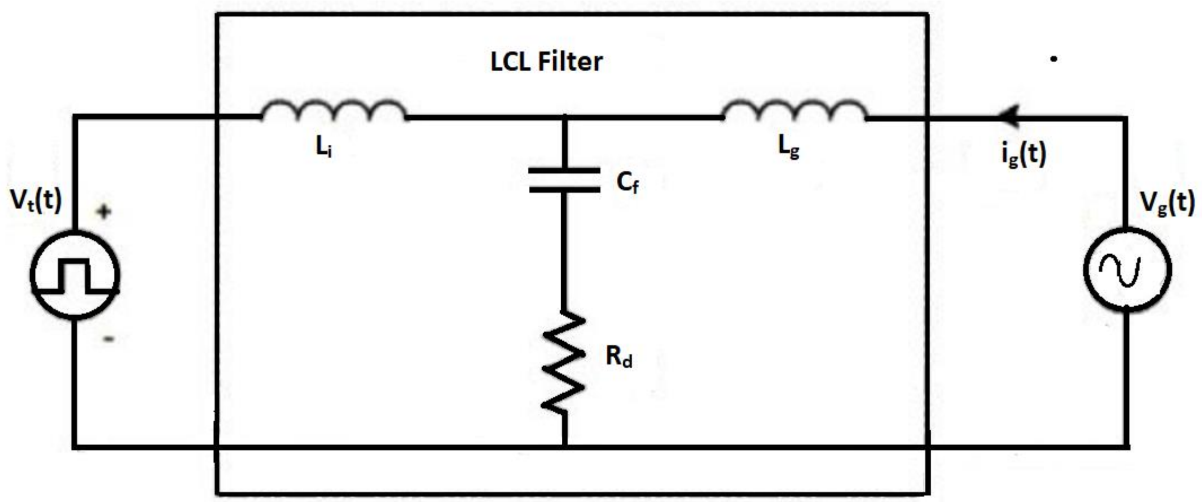


Figure 37. LCL filter configuration.

MATHEMATICAL MODELING OF HRES

LCL Filter Design

- The first step in designing LCL is to calculate the inverter side inductor (L_i), which can be calculated using the below Eq

$$Li = \frac{U_{dc}}{16 \times f_s \times \Delta I_L}$$

$$Li = 20.94\ \mu H$$

- The grid side inductor Lg can be calculated using the below Eq.

$$Lg = 0.6 \times Li$$

$$Lg = 16.766\ \mu H$$

MATHEMATICAL MODELING OF HRES

LCL Filter Design

- Finally, the filter capacitor (C_f) design is such that there should be a maximum 5% oscillation in the inverter output voltage for the stable operation of grid-tied PV system.

$$C_f = \frac{P_{nominal}}{\omega_{grid} \times V_{ph-grid}}$$

$$C_f = 4.01146 \text{ mF}$$

$$R_d = \frac{1}{3 \times \omega_{res} \times C_f}$$

$$R_d = 0.01763\ \Omega$$

MODELING OF THE DESIGNED HRES IN SIMULINK

- MATLAB provides a numeric computation environment developed by MathWorks and Simulink is a MATLAB blocks-based programming interface that provides the modeling, analysis, and simulation of dynamical systems.
- For modeling of hybrid power system, Simscape blocksets are used.
- All modeling has been done using the calculated parameters and the effect of real time conditions is also included in the block's parameters like transformer saturation, excitation current, inductor resistance, etc.

MODELING OF THE DESIGNED HRES IN SIMULINK

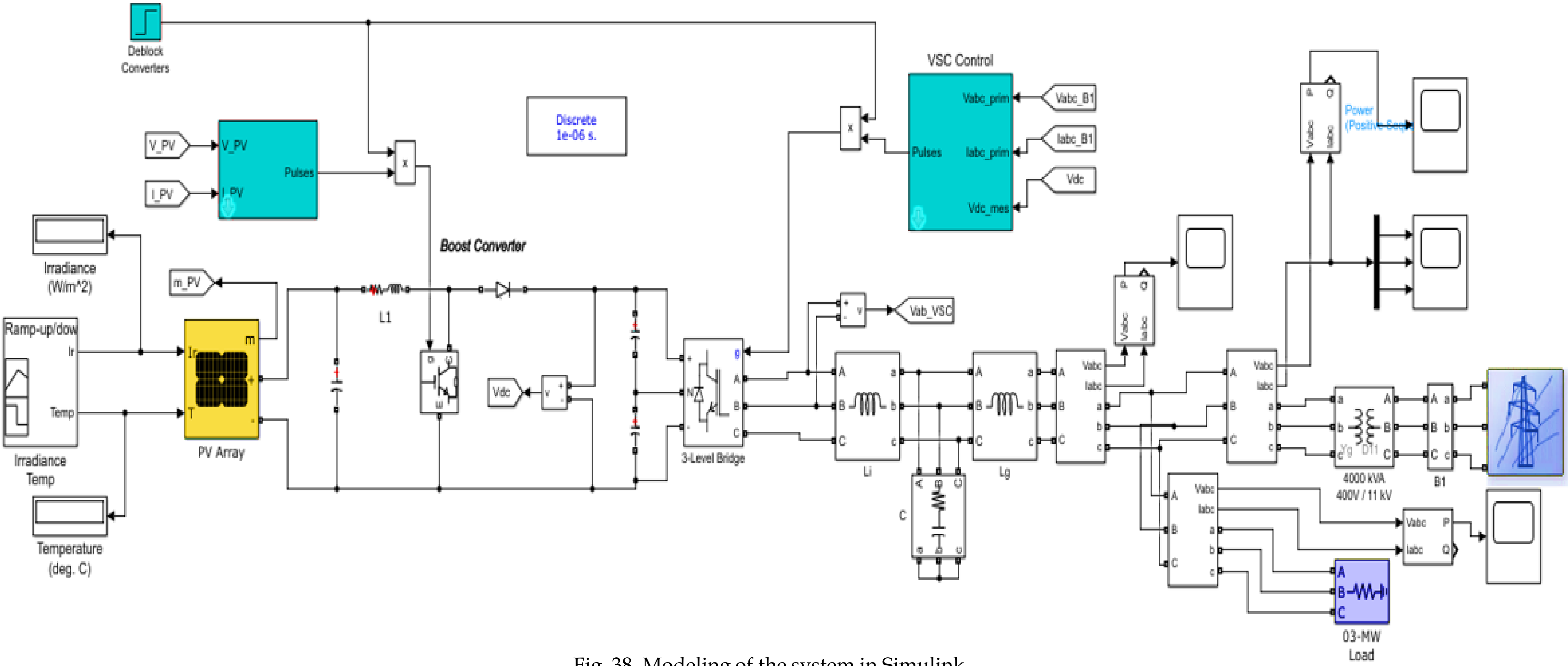


Fig. 38. Modeling of the system in Simulink.

MODELING OF THE DESIGNED HRES IN SIMULINK

➢ Power Generation

- The three-phase peak voltage at PCC during the grid-tied operation is shown below in fig. 39

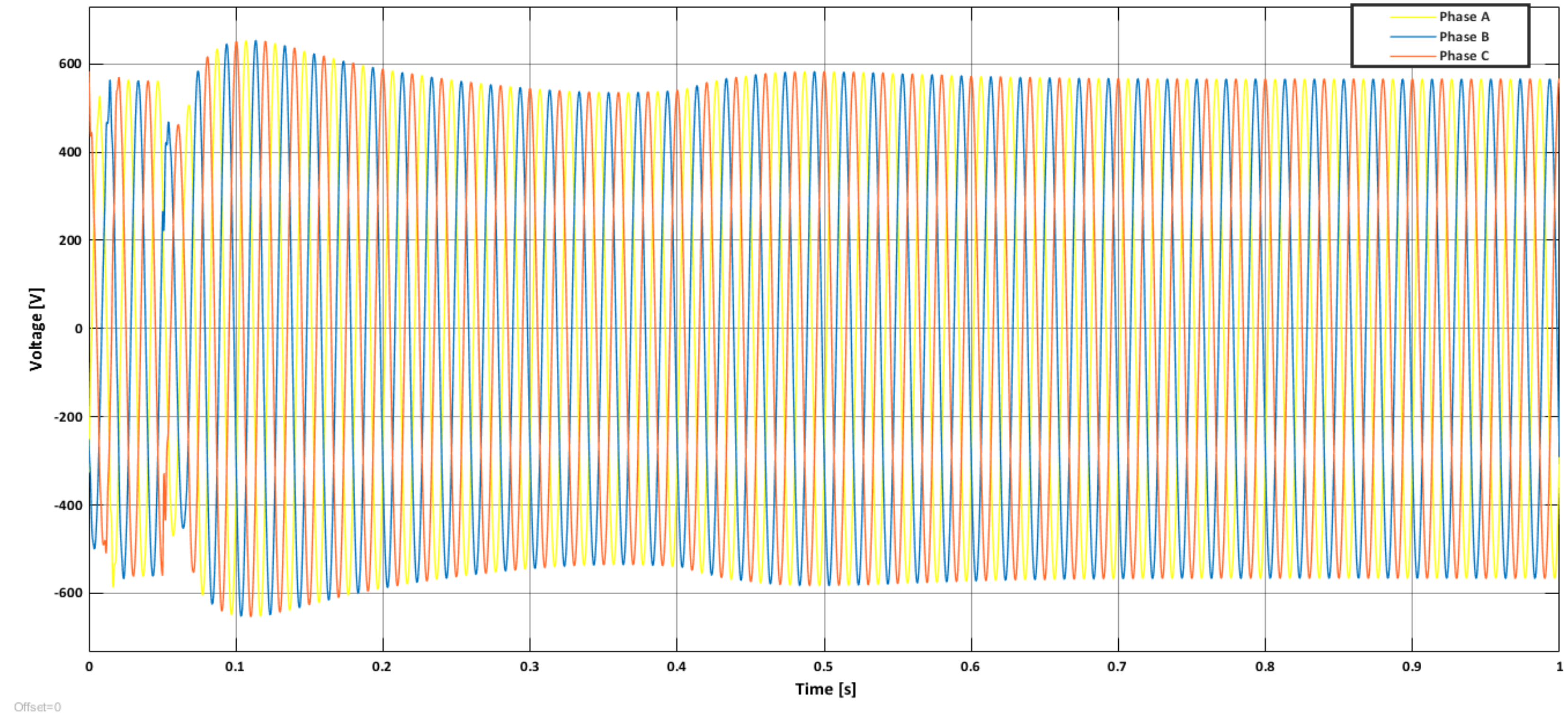


Fig. 39. Peak Voltage at 400 V bus.

MODELING OF THE DESIGNED HRES IN SIMULINK

- Power distribution on 400 V Bus

- The power at the common bus varies with irradiance, and during the low irradiance and night time, the power will also be delivered by the grid as per load demand but during the high irradiance PV system will transfer surplus power to grid.

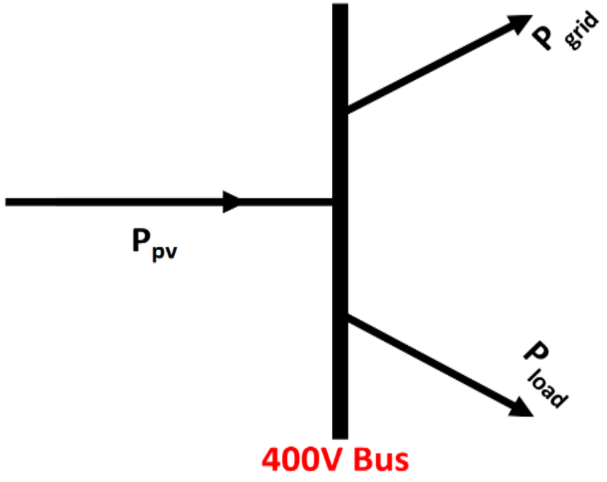


Fig. 40. Power distribution at 400 V bus.

MODELING OF THE DESIGNED HRES IN SIMULINK

- Power distribution on 400 V Bus

- The power delivered by the PV system is equal to the sum of power absorbed by the grid and load.

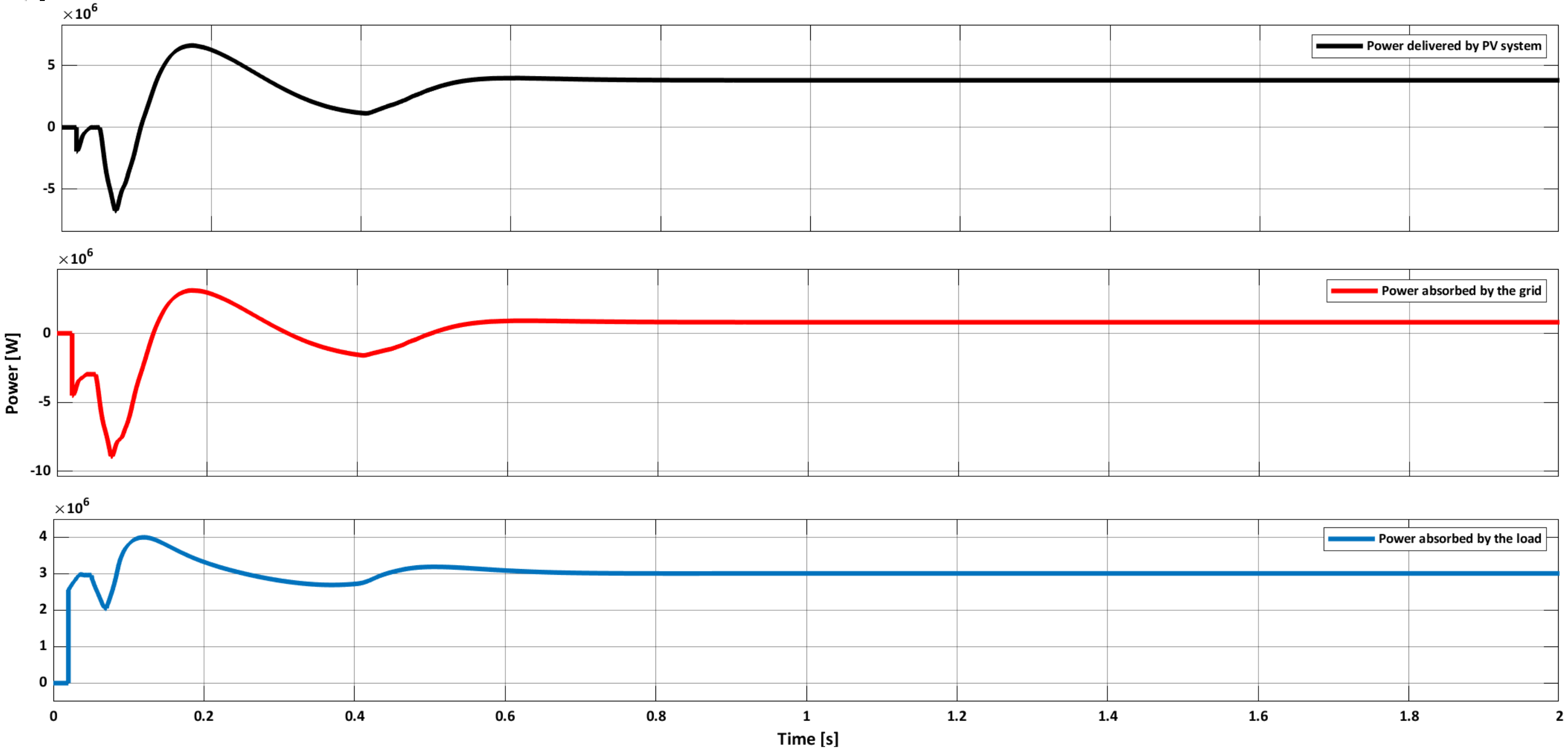


Fig. 41. Power distribution of PV system in Simulink.

MODELING OF THE DESIGNED HRES IN SIMULINK

- Effect of abrupt change in irradiance

- The simulation results for step change are shown in the fig

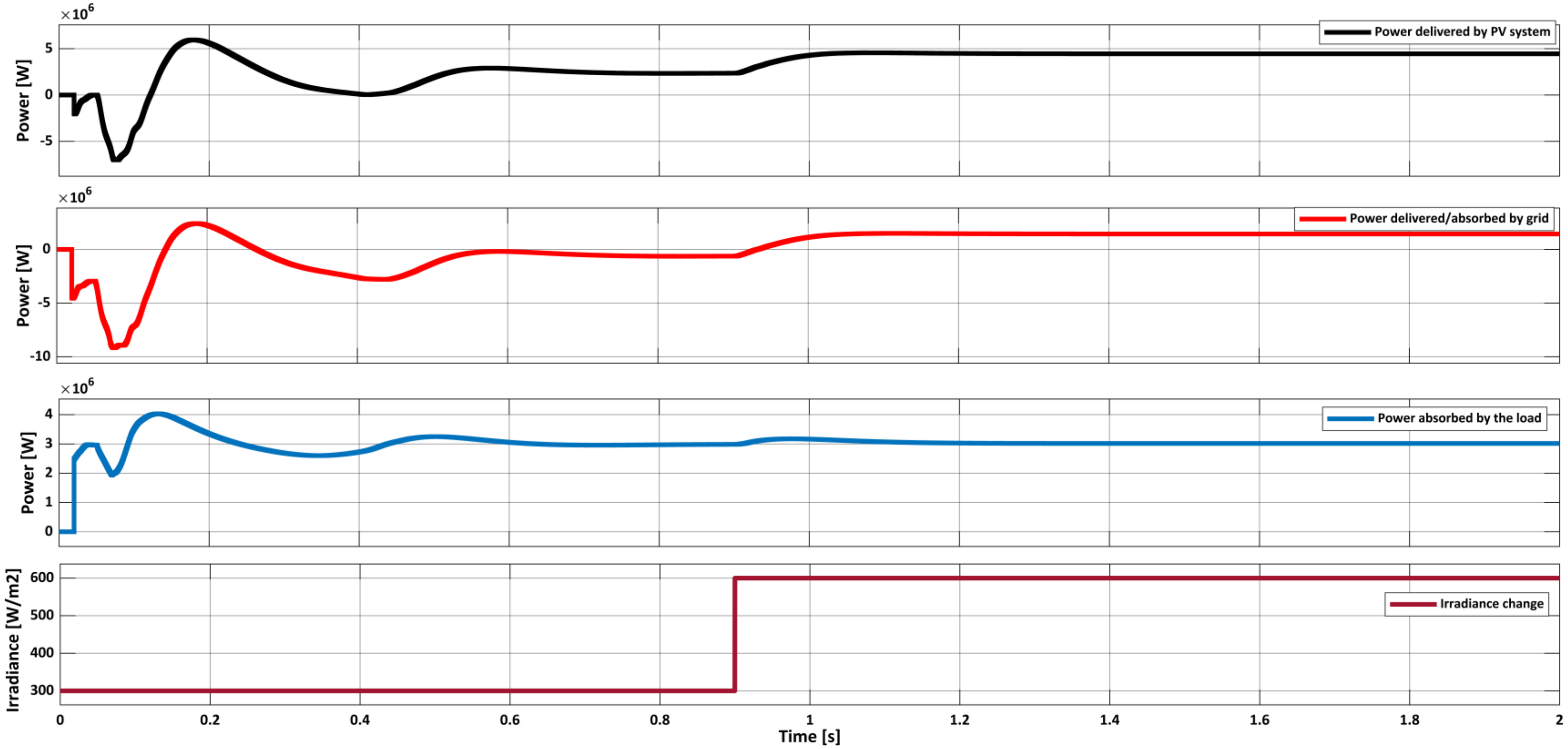


Fig. 42. HRES behavior to step change in irradiance.

MODELING OF THE DESIGNED HRES IN SIMULINK

➢ Effect of load variations

- The simulation results for step change are shown in the fig

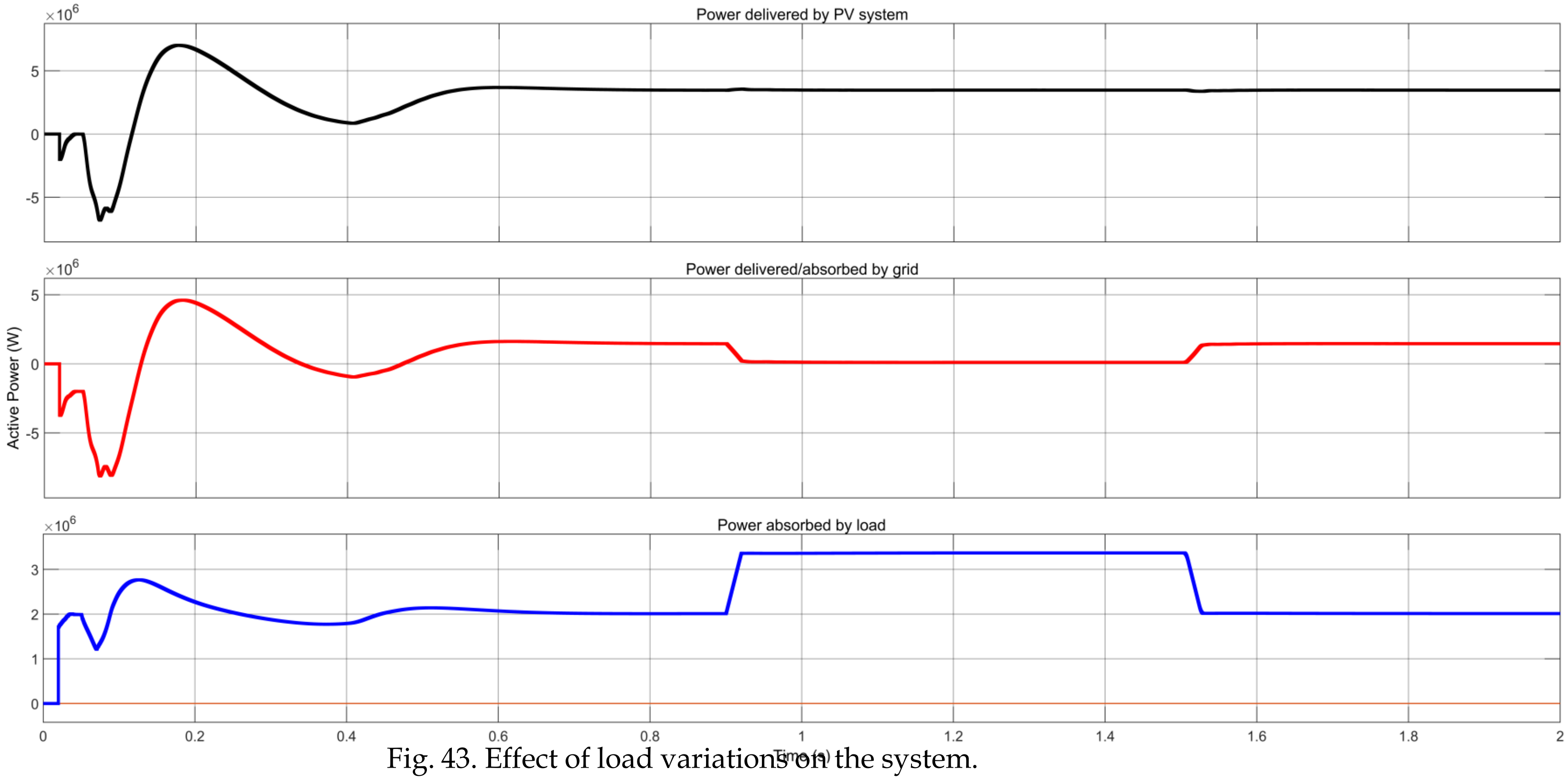


Fig. 43. Effect of load variations on the system.

Low-Cost, Open Source Emoncms Based SCADA System for a Large Grid Connected PV System

SCADA

- Monitoring, control, and data acquisition are all referred to as SCADA.
- All these functions are comprised of both hardware and software components.
- In SCADA system, a human-machine interface (HMI) is used to interact with sensors and devices, and log 34 files are generated.
- A PLC or RTU is a micro-computer that communicates with objects of various types, a factory machine, a human machine interface, a sensor, or an end device.
- Finally, the SCADA system is used in some process and utility applications to enhance the performance of system.

SCADA Parts

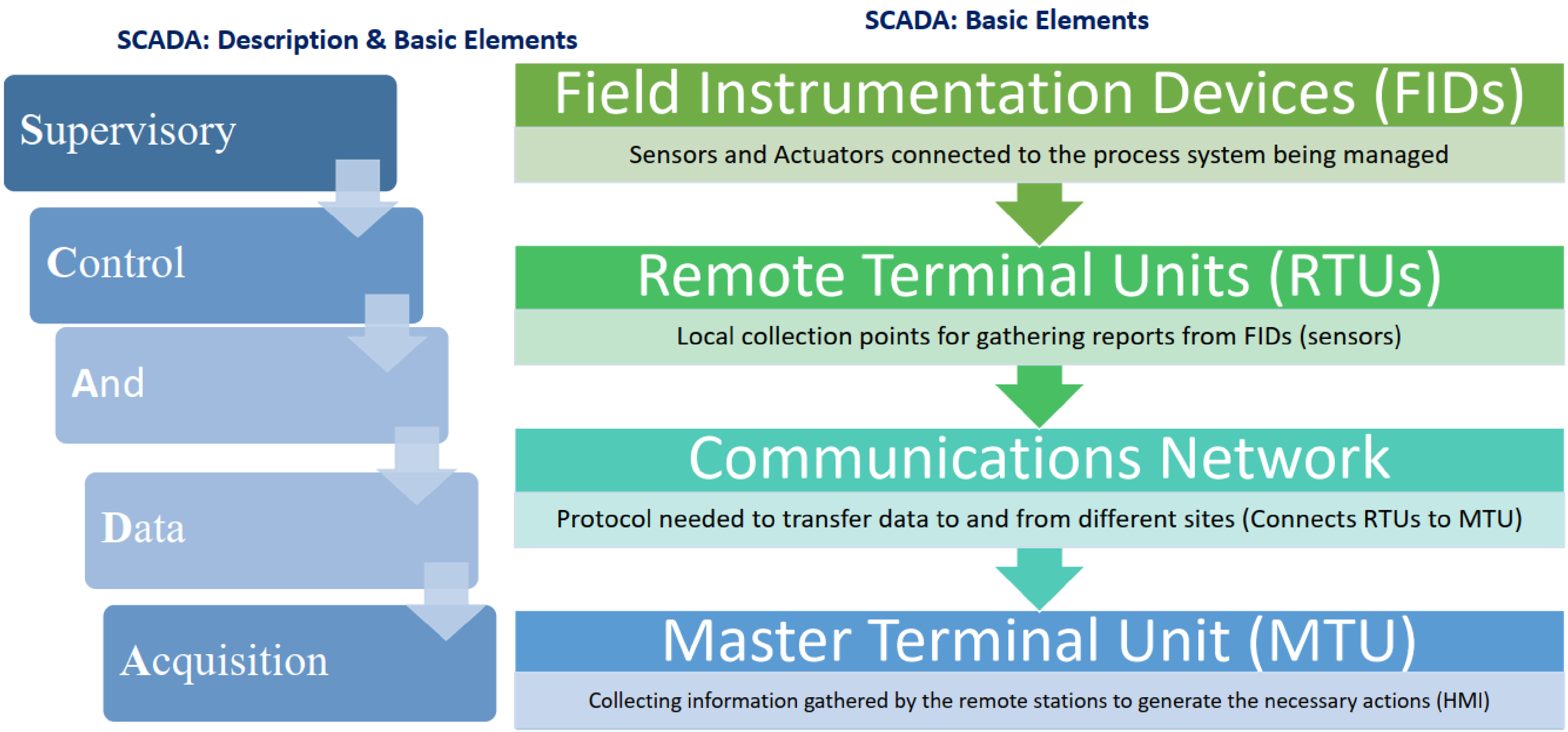


Figure 44: System components.

System Description

- The designed SCADA system for PV plant is depicted in figure 45, which has 15 rows and 313 columns of a PV modules.
- Arduinos Mega 2560 which act as remote terminal units (RTUs) are used for taking the data from PV field sensors.
- In the design configuration, an low cost DELL computer is along with Raspberry Pi software.
- For this purpose, 32-bit Debian having kernel version of 5.10 is installed on the x86 processor.

System Description

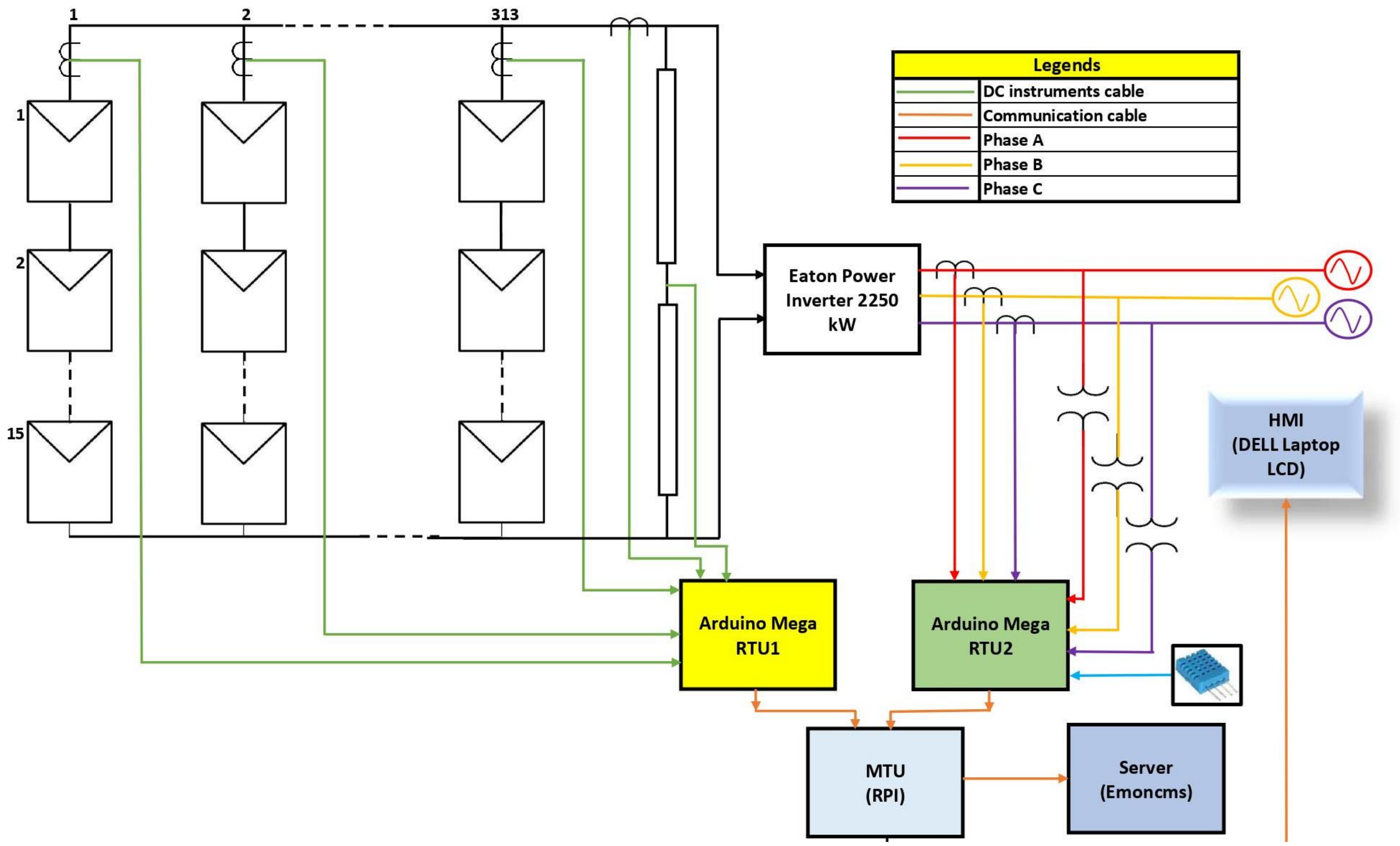


Figure 45: Schematic of PV monitoring system.

Components of the designed system

➢ **DC current and voltage sensor**

- CR5210 is used as a dc current sensor and CR5310 is dc voltage sensor.
- Both provide the output dc signal in the range 0-5 Vdc which is directly proportional to the input signal.
- The input voltage range of CR5310 is 0-600 Vdc and input current range of CR5210 is 200 Adc

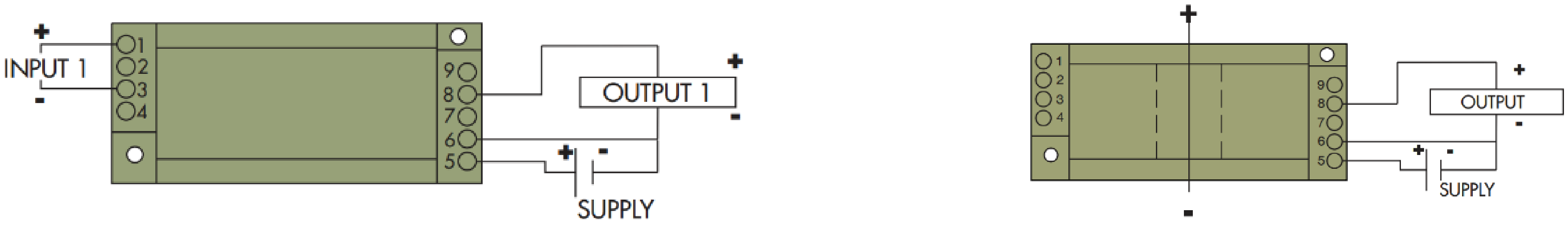
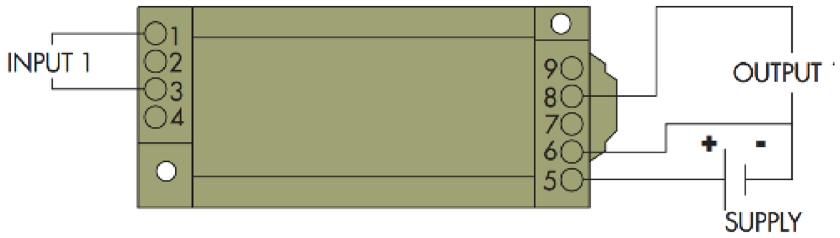


Figure 46: Wring of DC transducer: (a) Voltage sensor CR5310; (b) Current sensor CR5210.

Components of the designed system

➢ **AC current and voltage sensor**

- CR4500 is used as an AC current sensor and CR4310 is AC voltage sensor.
- Same as dc sensors, these also provide the output dc signal ranging from 0-5 Vdc which has a direct linear relationship with the input parameter along with the 24 V power supply



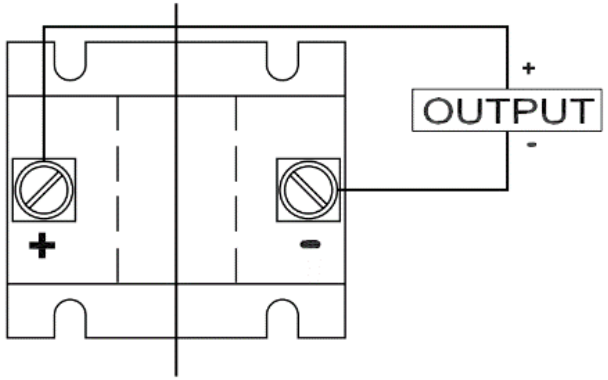


Figure 47: Wring of DC transducer: (a) Voltage sensor CR5310; (b) Current sensor CR5210.

Components of the designed system

- **Environmental sensor**

- DHT11 sensor has been used for measuring both parameters.
- DHT has a calibrated signal output and guarantees long-term stability and excellent reliability.
- It has a resistive type of humidity measurement component for humidity and NTC thermistor for temperature

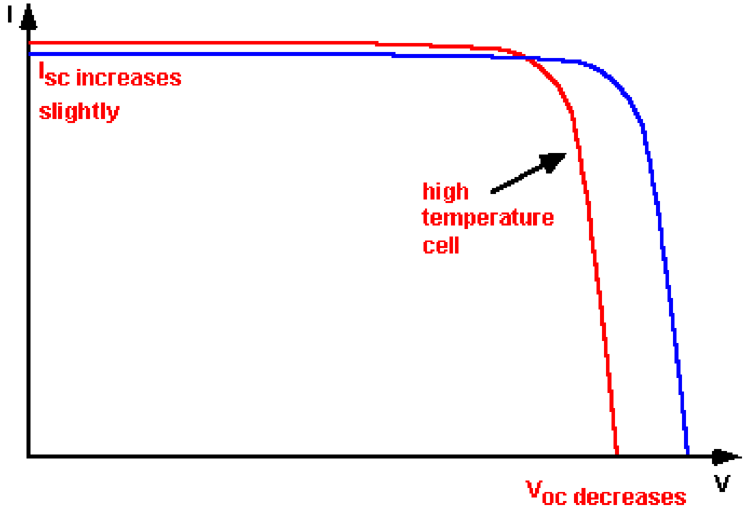


Figure 48: Effect of temperature on PV module characteristics.

EMONCMS

- Emoncms is an open-source platform and provide versatile packages.
- The main objective is to display the data on HMI for visualization and observing the behavior of system.
- It also offers an easy package data is stored on the remote server which limits the data storing capabilities along with exposing that data the hacker which compromises the security and reliability of system

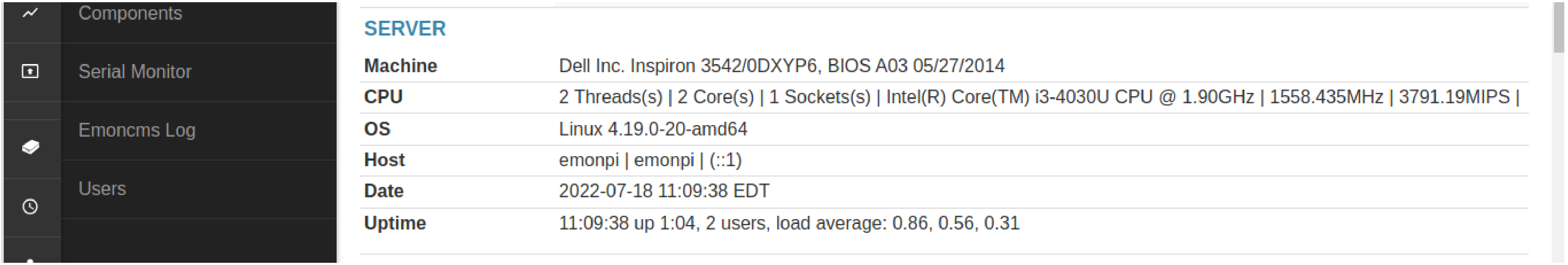


Figure 49: Dell laptop as local server.

EMONCMS

- Emoncms interconnectivity of different modules, in which the main module is EMONHUB

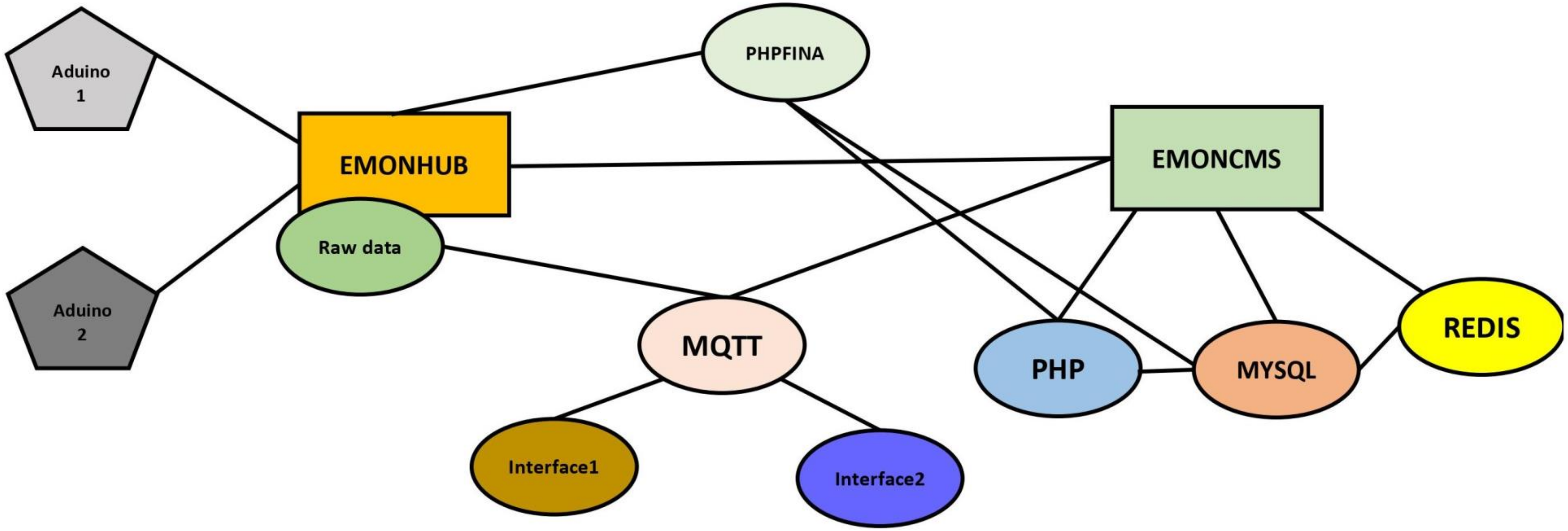


Figure 50: Emoncms connectivity modules.

Implementation Methodology

Algorithm 1: Arduino Sensor Data Reading Algorithm

```
Initialization;
1. Set the baud rate of 38400 bps;
2. Define the DHT libraries;
3. While read and store the AC current Sensor CR43100;
    4. Read and store the AC Voltage Sensor CR4510;
    5. Take and store the temperature and humidity value from DHT11;
     if sample are equal to 10
         7. Take average store all data in final variables;
     else
         9. Parse the data in JSON format;
         10. Push parsed data to the MTU;
         11. Go to step 3;
     end
  End
```

Implementation Methodology

Algorithm 2: Data Logging Algorithm

Initialization;
1. Read Field devices values on Arduino Mega 1 (RTU1) analog PIN 0,2,4;
2. Read Field devices values on Arduino Mega 2 (RTU2) analog PIN 0,2,4;
3. Connect the Both RTU to the MTU with Serial Cable;
4. Login into the Emoncms;
5. Detect the Read Only or Read & Write API keys;
6. Format the data in JSON format;
7. Push data to serial port;
8. While Start Emonhub
    9. Receive data into the Emonhub;
    10. Check the status of Emonhub data transmission;
    If no data receipt
        11. Display message in status screen;
    Else
        12. Go step 1;
    End
End

Prototype design and Results

- Different power supplies are used for generating the desired voltage.
- 24 V supply is used for proving the Vcc and ground to all sensors.
- For providing the dc voltage variable supply is used whose output voltage varies between 0-60 Vdc .
- 12 V dc incandescent bulb and rheostat are used as a dc load for generating the load current.
- 100 W incandescent bulb is used on the AC side as a load.

Prototype design and Results

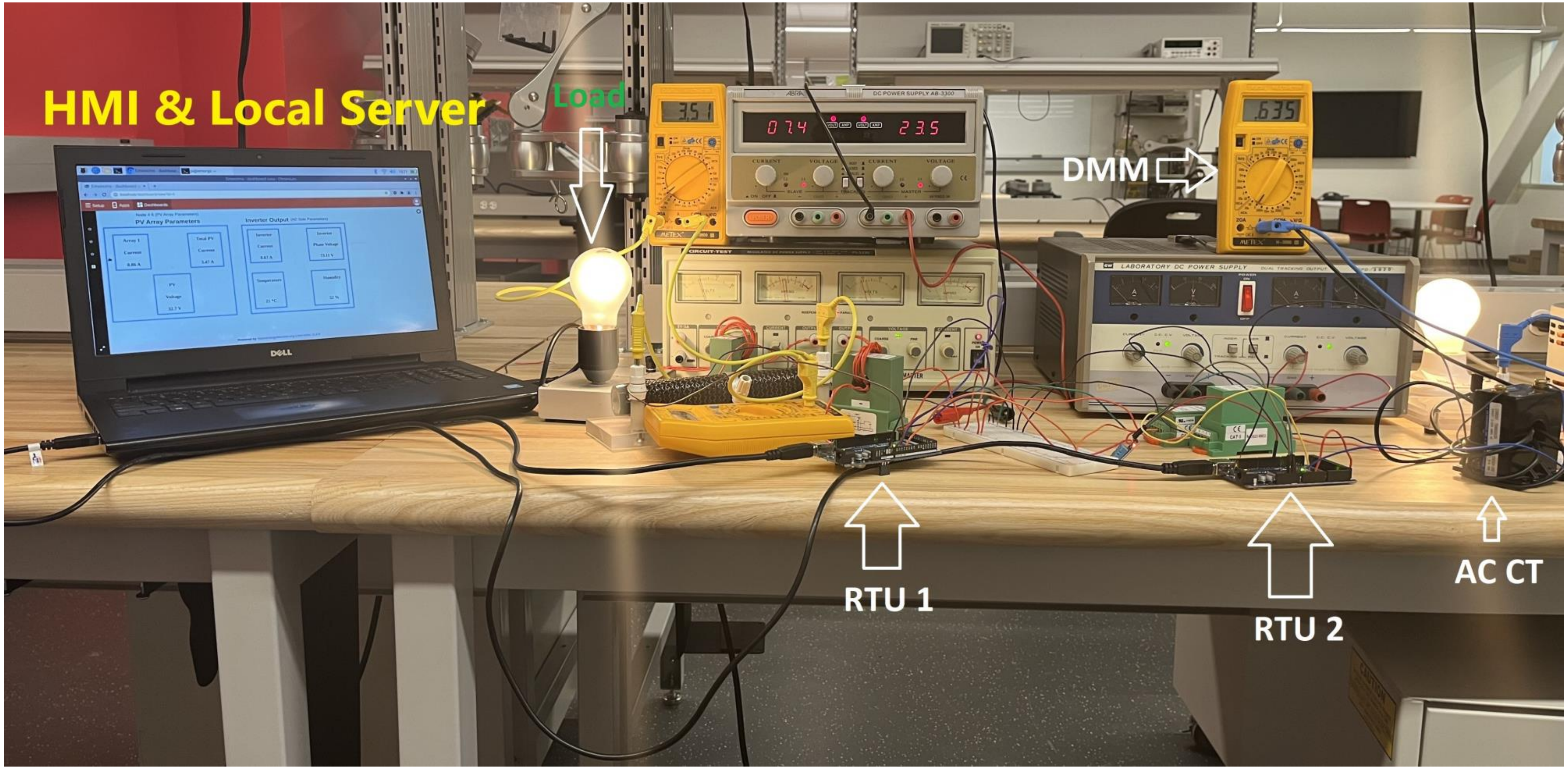


Figure 51: Hardware setup.

Prototype Results

- The system was turned on for 6 hours and data logging is done

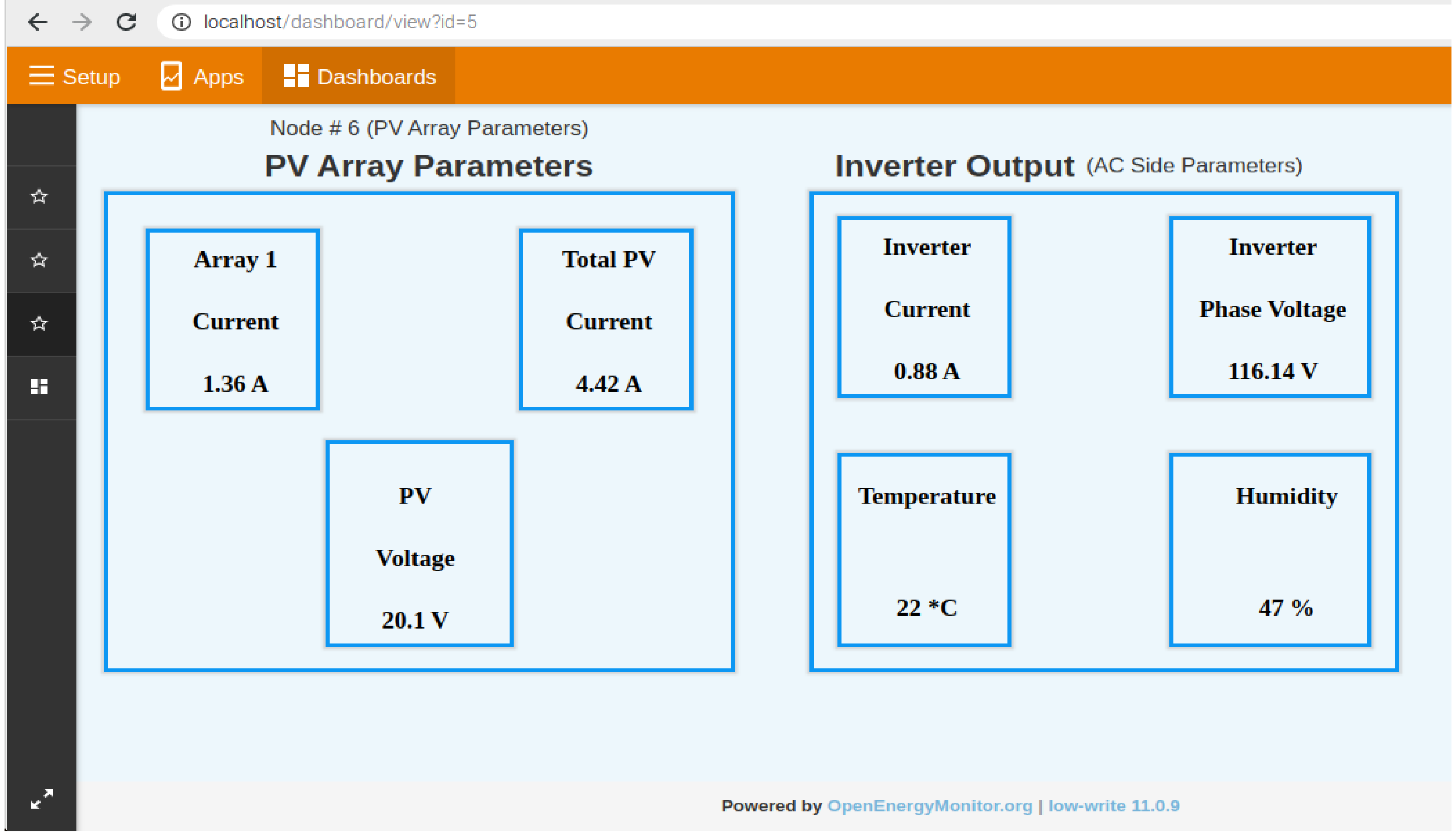


Figure 52: Instantaneous values of field instruments.

Prototype Results

- The system was turned on for 6 hours and data logging is done

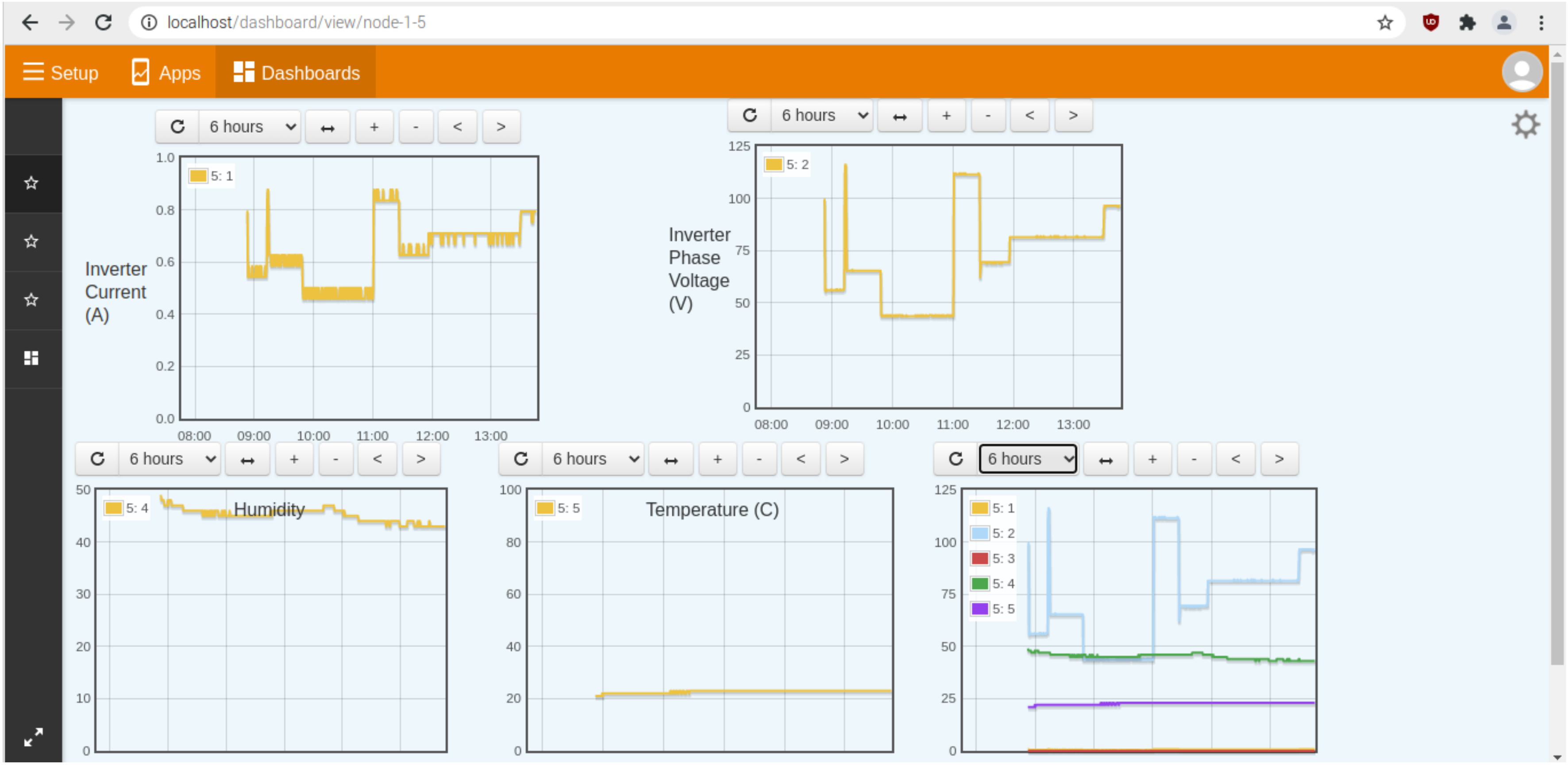


Figure 53: AC side parameters trend.

Prototype Results

- The system was turned on for 6 hours and data logging is done

Figure 54: DC side parameters behavior.

Conclusion

Conclusion

- A detailed sizing, modeling and dynamic analysis of a hybrid power system have been presented in this paper.
- The system provides lowest per unit cost of energy i.e 0.1025 $/kWh.
- The dynamic analysis of the designed system has been done in Matlab/Simulink, which shows the transient and steady-state behavior of the grid-tied PV system under Pakistani conditions.
- The system behavior under disturbance, irradiance step response are presented, which shows the PV system power fed to the grid while maintaining the voltage & frequency within the limit.

Conclusion

- Designed HRES can handle load fluctuations of 1.5 MW.
- The system has fast enough response to tackle 300 W/m^2 step change in irradiance by increasing the power delivered to grid.
- Designed system voltage remain stable at 400 V during any interruption in the system.
- The paper finds the limitation and hurdles in easing the renewable energy integration and suggested the system design to the industrial units in Pakistan.
- Finally, simulation results show that the designed system can handle interrupts and disturbances.

Conclusion

- In the designed system, low-cost, open-source SCADA system has been designed which has IoTs architecture which is the latest one.
- The hardware design of system has also been done which has four major modules, Field Instrumentation Devices, Remote Terminal Units, Master Terminal Units, and SCADA Communication Channel.
- The system voltage & current are changed and a corresponding change in the output has also been observed.
- The system is also storing the data locally and creating .dat and. meta files in this “/var/opt/emoncms/phpfina” directory
- Power consumption of the whole designed SCADA system is less than 35 W

Research Contribution and Future Work

Research Contribution

- A textile unit “ Shafi Texcel Limited” has been chosen for conducting the feasibility study of PV plant.
- Different cases have been discussed and the most feasible and reliable is the 8382 kW gridtied PV system is needed to generate the lowest cost energy.
- The control and dynamic of the above-made feasible system are modeled in MATLAB/Simulink using the Simscape block set.
- For the monitoring and control of a designed system, EMOMCMS open source SCADA system is used which was configured on a Debian Linux which is installed on a local PC

Future Work

- The modeling of the system should be done along with the reduced order dynamic model of system.
- This model will have less computation complexity and can run from months to years on any computer machine.
- The open-source SCADA system based on Emoncms can be upgraded to a wireless system so that the data could be controlled and monitored wirelessly.
- An email alert system can be incorporated into the SCADA system already developed using Swift-mailer.

Publications

➢ Articles in Refereed Publications

- L. Ahsan and M. Iqbal, “Dynamic Modeling of an Optimal Hybrid Power System for a Captive Power Plant in Pakistan,” Jordan Journal of Electrical Engineering, vol. 8, no. 2. ScopeMed, p. 195, 2022. doi: 10.5455/jjee.204-1644676329.
- L. Ahsan M.J.A Baig and M. Iqbal, “Low-Cost, Open Source Emoncms Based SCADA System for a Large Grid Connected PV System,” Sensors 2022.

➢ Refereed Conference Publications

- L. Ahsan and M. T. Iqbal, "Design of an Optimal Hybrid Energy System for a Captive Power Plant in Pakistan," 2021 IEEE 12th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON), 2021, pp. 0820-0826, doi: 10.1109/IEMCON53756.2021.9623260.

Publications

- **Regional Conference Publications**

- Luqman Ahsan and M. Tariq Iqbal, Design of Hybrid Electrical Power System for an Industrial Unit in Pakistan, presented at the 31st Annual IEEE NECEC conference St. John's, November 19th, 2021

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THANK YOU