Micro PV Solar Station to Support Home Residential Using Multi-Level Inverter for Stand – Alone Load

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ABSTRACT

This study presents a standalone photovoltaic (PV) system for residential loads using a multi-level inverter. The system optimizes power output through maximum power point tracking (MPPT) control, enhances power conversion efficiency, and considers different weather conditions for reliable operation. The MPPT control algorithm tracks the maximum power point of the PV array, adjusting the operating point to maximize energy harvested from the solar panels. The multi-level inverter converts DC power into AC suitable for residential loads, reducing harmonic distortion and improving voltage quality. It also provides better control over power flow and seamless integration with residential loads. The system considers different weather conditions, such as variations in solar irradiance and temperature, to ensure optimal operation and robustness. The system is verified using MATLAB Simulink simulation software.

Keywords: Standalone PV system, Multi-level inverter, Maximum power point tracking, MPPT control.

Introduction

Energy security and sustainability are crucial worldwide, with renewable energy sources like solar, wind, and biomass being preferred. The International Energy Agency predicts that fossil fuels will account for 70% of global electricity generation by 2020. However, non-renewable energy faces environmental concerns, limited resources, and cost competitiveness. This has led to a shift towards renewable energy-based power generation[1]. The increasing awareness of the need to minimize greenhouse gas emissions and limit human activities' environmental impact is driving a push towards greener sources of power generation. Technological advancements are also being emphasized to reduce fossil fuel demand and achieve energy independence. Hybrid power generation technology, combining multiple sources, can help reduce uncertainty and improve energy storage systems[2].

1.1. Present situation of renewable energy over the world

Renewable energy, derived from natural sources like sun, wind, rain, and geothermal, is increasingly popular due to its environmental benefits, low cost, and energy independence. The use of renewable energy sources for electricity generation has grown significantly in recent years, with hydropower being the largest source. The International Energy Agency (IEA) reported that renewable energy accounted for over 26% of global electricity generation in 2021. Wind and solar energy have seen strong growth due to technological advancements and declining costs. The usage of solar and wind turbines is increasing daily, demonstrating the growing importance of renewable energy sources in a low-carbon, sustainable energy system.

1.2. Objectives and Scopes

The primary objectives for this study are-

- Design and control of photo voltaic (PV) with MPPT control.
- Design and control of battery storage system for the system.
- Modelling a power flow control mechanism for the overall power management.
- Economic analysis of the proposed model

2. Literature Review

2.1. PV technology

Photovoltaic (PV) technology has become increasingly popular due to cost reductions and the demand for clean, renewable energy. Large-scale PV power plants, or PV farms, contribute significantly to the grid. Designing and operating these plants is a complex, multidisciplinary field involving technical, economic, and regulatory issues. A.B Awan et al. [3] reviewed the design and operation of PV power plants, discussing factors like modules, inverters, plant structure, shading, energy storage, and grid integration.

The research optimizes PV power plant design and operation to increase energy yield and minimize operating costs. New design and operation tools will help the renewable energy sector flourish by boosting PV power plant performance and dependability. Researchers conclude. K. Nwaigwe et al. [4] evaluated photovoltaic (PV) power plant grid integration difficulties and solutions. The authors begin by outlining the rapid expansion of PV technology and the growing importance of grid-integrated large-scale PV power facilities. They then discuss grid stability, energy storage, power quality, and system cost as technical, economic, and regulatory hurdles to integration. Advanced control systems, inverters, and energy storage systems are also reviewed by the writers.

M. Egido and E. Lorenzo's study reviews existing methods for sizing standalone photovoltaic (PV) systems, focusing on optimal sizing for off-grid applications. They analyze various methods, identifying key parameters like load profile, solar resource availability, system losses, and battery storage capacity. They propose a new sizing method that considers these parameters, incorporating a detailed energy balance analysis. The authors emphasize the importance of accurately estimating load profile and solar resource data for reliable and cost-effective system sizing. The method's advantages include accuracy and flexibility, and it can be compared with other techniques. The study also discusses potential challenges and future research directions in PV system sizing for standalone applications[5, 6].

3. Methodology

This thesis employs a methodology that incorporates photovoltaic (PV) battery storage technologies to investigate the efficacy and potential of a hybrid power generating system. This study's major goal is to evaluate the viability and effectiveness of the hybrid power production system in meeting the needs of various applications for a steady and renewable supply of electricity. The hybrid power generation system's performance under varying operating situations, such as variable weather conditions and load demands, will be evaluated through simulation and analysis. The hybrid power production system's overall cost-effectiveness in comparison to conventional power sources will also be evaluated through economic analysis.

3.1. PV array

The photovoltaic (PV) technology, discovered in the late 19th century, converts light into electricity. It was first used in the 1950s and 1960s for powering satellites and space equipment. Initially, PV systems were large and expensive, limiting their use to specialized applications. However, the 1970s oil crisis and energy independence led to increased research funding and increased efficiency. Residential and small-scale commercial installations began in the 1980s, and the PV industry grew rapidly in the 1990s and 2000s. PV cells, made of semiconducting materials like silicon, convert light into electrical charge, which is collected by electrodes. When connected together, they form a photovoltaic array, capable of powering homes, businesses, and large power plants.

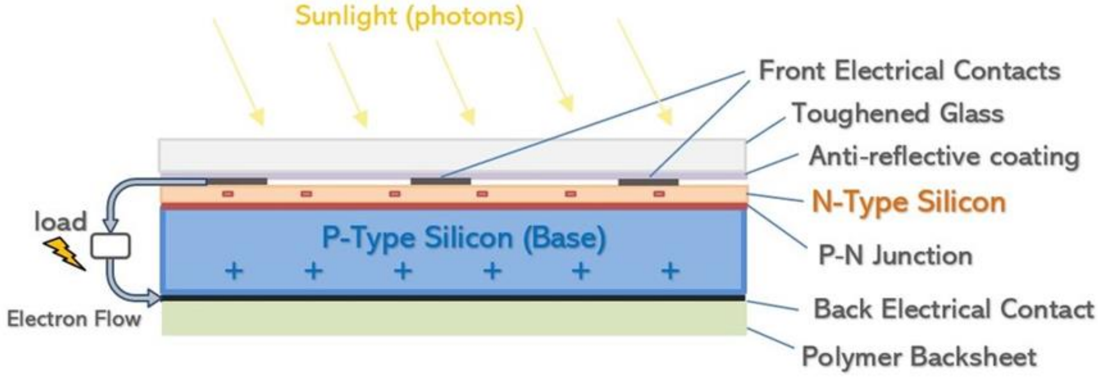


Figure 1: PV cell construction

3.1.1. PV Panel modelling

The mathematical modelling approaches used to simulate the behavior of photovoltaic (PV) cells include single diode modelling, double diode modelling, and current-voltage (IV) characteristic modelling. The single diode model describes the behavior of PV cells as a function of light intensity and temperature, accounting for the impact of diode idealist factor, shunt resistance, and series resistance on efficiency. The two-diode model represents the recombination of charge carriers in a PV cell, accounting for recombination losses, temperature effects, and shading losses on performance. The current-voltage characteristic model provides a graphical representation of the PV cell's power output vs input voltage and current, allowing analysis of performance in different illumination, temperature, and shading scenarios. The choice of model depends on accuracy and intended usage.

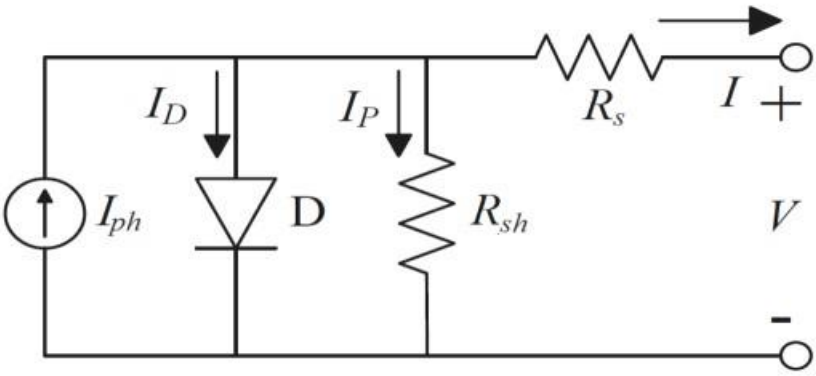


Figure 1: Single diode model

The single diode model takes account of current and voltage relationship which helps to track maximum power point effectively. As my thesis is intended to achieve maximum efficiency so single diode model is more effective for analysis. From Figure 3.2, single diode model output current equation is

$$I_{pv} = I_{ph} - I_o\left[\exp\left(\frac{V_{pv} + I_{pv}R_s}{n_s m V_t}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_s}{R_s} \tag{3.1}$$

$$\text{And } V_t = \frac{kT_c}{q} \tag{3.2}$$

Where, I_p= output current, I_{ph} = photo current, I_{diode} = diode reverse saturation current, T_c = boltzmann constant, V_p = output voltage, R_s = series resistance, V_t = thermal voltage, m = diode ideality factor, n = number of cells in series, k = boltzmann constant, R_p = shunt resistance and q = electron charge. I_{ph} is defined by module temperature T_c, the solar irradiance G_c and temperature coefficient α. [7]. Moreover, the photo current I_{ph} is evaluated by the solar irradiance G_c, module temperature T_c, as well as temperature coefficient α comprehensively. Where we can write:

$$I_{ph} = \frac{G_c}{G_r}[\, I_{cc} + \alpha(T_c - T_r)] \qquad (3.3)$$

Where T_r = temperature and I_c = standard irradiance short circuit current, G_r = the standard solar irradiance and temperature. I_{diode} is determined by the diode ideality factor m, T_r, module temperature T_c, and thermal voltage. Where:

$$I_o = I_{or}\left(\frac{T_c}{T_r}\right)^{\frac{3}{m}} \exp\left[\frac{V_g\left(\frac{T_c}{T_r} - 1\right)}{mV_t}\right] \qquad (3.4)$$

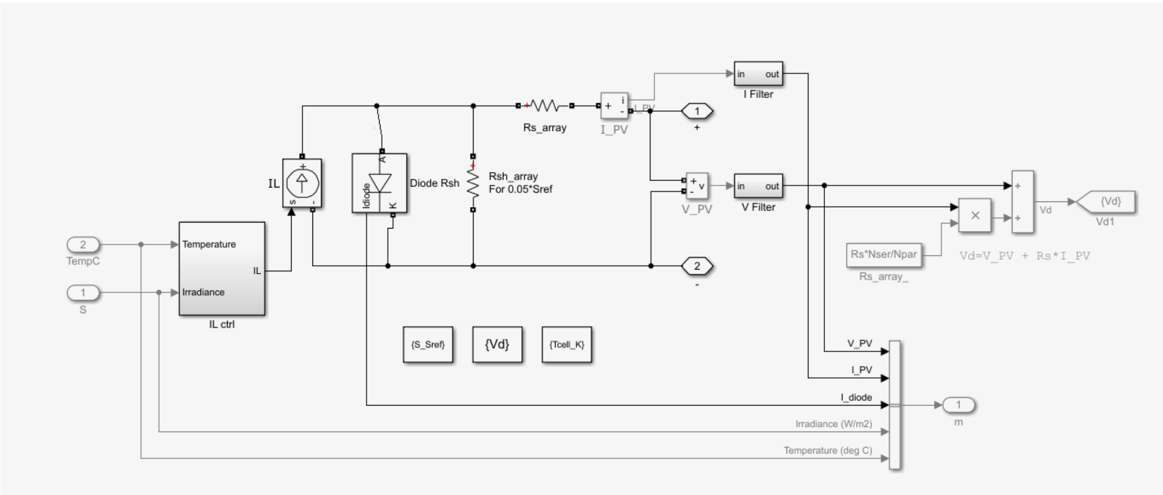


Figure 2:MATLAM Simulink model of Single PV module

I_{0r} presents the reverse saturated current for standard temperature and V_g defines the energy gap. The power output of a PV module could be presented as:

$$P_{pv} = V_{pv} I_{pv} \qquad (3.5)$$

Where I_{pv} is output current, V_{pv} is operating voltage of PV module, and P_{pv} is output power of PV module. The simulation model that are used is given in fig 3. In this simulation 1Soltech 1STH-215-P model PV cell is used. The specification of this model PV cell is given in table 1.

Table 1 Single PV module specifications

Parameter	Value
Max power output	213.15 W
Cell per module	60
Open circuit voltage	36.3 V
Short circuit current	7.84 A
Voltage at max. power point	29 V
Current at max. power point	7.35A

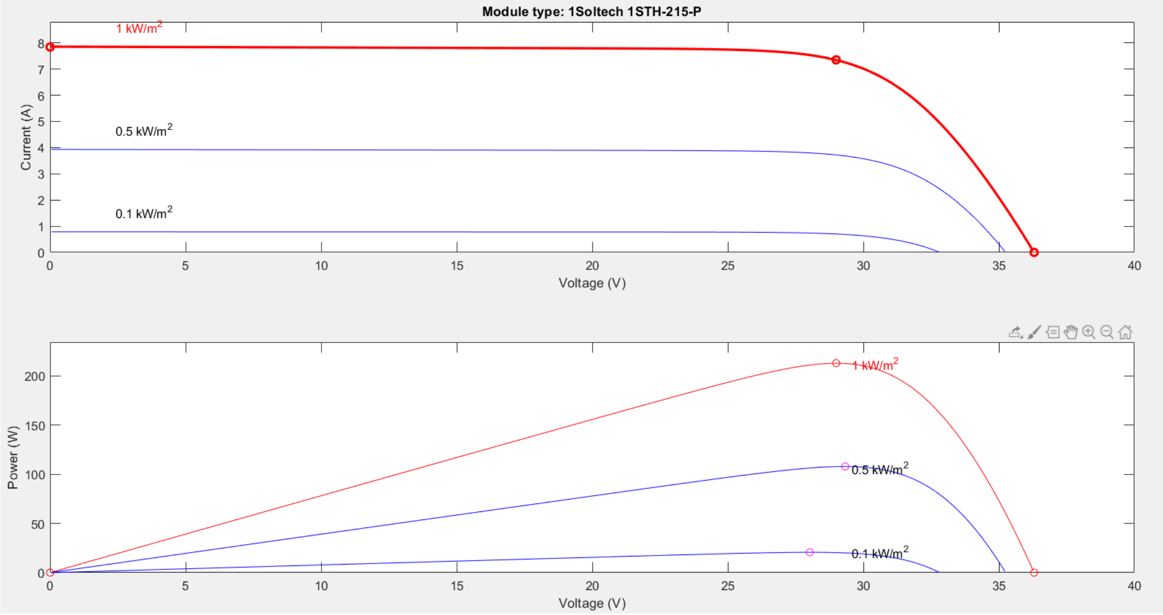


Figure 3: Characteristic Curve of single PV module

In Figure 4 the I-V and P-V curve of a single PV cell is shown. In conclusion, PV cells are the essential component of photovoltaic systems, and they work by converting sunlight into electricity through the photovoltaic effect [8, 9, 10]. They are a crucial part of the transition towards clean and renewable energy sources, and as technology improves, the efficiency and affordability of PV cells will continue to improve, making solar energy a more accessible and practical solution for power generation.

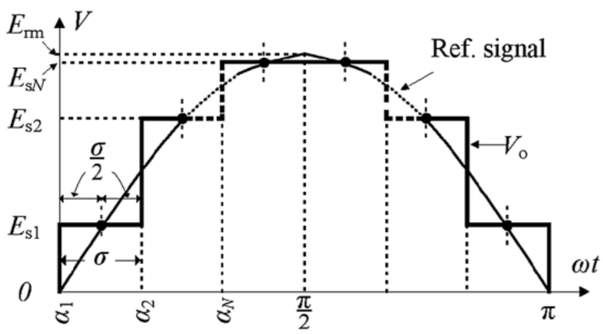
3.2. Multilevel inverter

Multi-level inverter have emerged as a promising technology for various power electronic applications. These converters offer several advantages over conventional two-level converters, making them increasingly popular in a wide range of industries. The concept of multi-level inverter involves the generation of output voltage with several discrete voltage levels, achieved through the combination of several power semiconductor devices. This innovative approach allows for improved waveform quality, reduced harmonic distortion, higher power efficiency, and enhanced control flexibility [11-15]. At its core, a multi-level inverter consists of multiple voltage levels, typically achieved by connecting power semiconductor devices in a series or parallel configuration. Each voltage level is generated by the combination of semiconductor switches, such as insulated gate bipolar transistors (IGBTs) or metal-oxide-semiconductor field-effect transistors (MOSFETs), along with the appropriate control strategy [16]. The distinctive feature of multi-level inverter is their ability to generate a staircase-like output voltage waveform, where the number of steps or levels determines the overall performance of the converter.

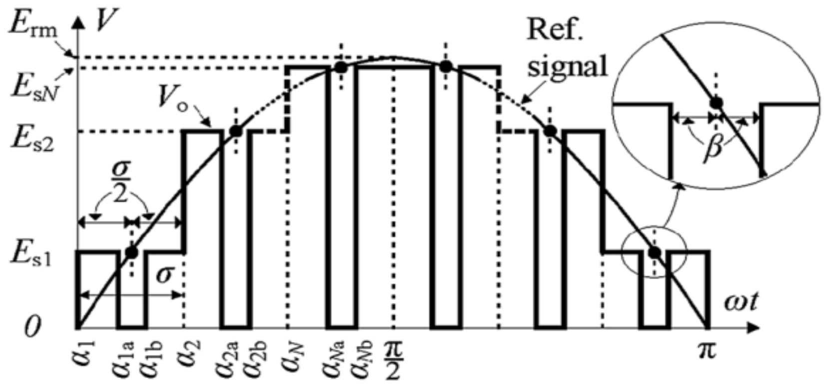
$$E_{si} = \sum_{j=1}^{i} E_{dcj}, \quad i = 1, 2, 3 \ldots \ldots \ldots n \qquad (3.11)$$

$$E_{dc1} = E_{s1}$$

$$E_{dci} = E_{si} - E_{s(i-1)}, \quad i = 2, 3, \ldots \ldots \ldots \ldots n \qquad (3.12)$$



(a)



(b)

Figure 6: Working principle of proposed SHE-PWM method: (a) selection of voltage rating of dc sources and (b) the output voltage control by adding switching notch. [12]

Figure 6 a shows sinusoidal reference signal having a peak amplitude of V_{rm} and inverter output voltage. To control the output voltage, a switching notch having width of 2β is inserted at mid-point of each rectangle in the waveform shown in fig 6a. Resulted waveform of output is presented in Figure 6b. The output voltage can be controlled by varying the value of β. In fig 3.10 a basic 3 level inverter is shown.

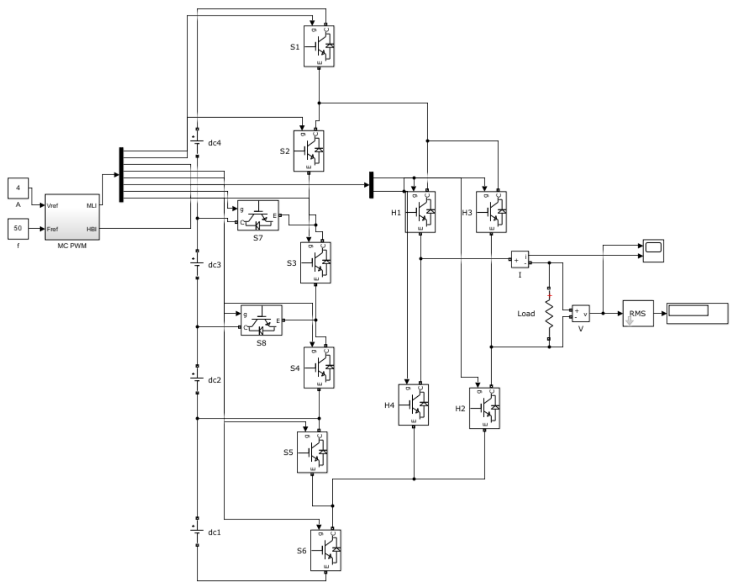


Figure 7: MATLAB Simulink model of multi-level inverter

In figure 7 MATLAB Simulink model of a multilevel inverter is shown. In this model input AC side voltage is 400 and output DC side voltage is 250V. there are in total 4 level which wave shape is shown in figure 7.

$$voltage\ step\ size\ \Delta V = \frac{AC\ side\ voltage}{No.of\ step - 1} \quad (3.13)$$

$$modulation\ index\ M = \frac{0.5 \times AC\ side\ voltage}{\Delta V}\ and \quad (3.14)$$

$$carrier\ frequency\ F_c = No.of\ level \times fundamental\ frequency = 4 \times AC\ line\ frequency \quad (3.15)$$

Multi-level inverters are a type of power electronic system that can significantly reduce harmonic distortion in output voltage and current waveforms. This is particularly important in applications requiring high-quality power, such as renewable energy systems, motor drives, and grid-connected converters. Multi-level inverters also offer improved power efficiency compared to traditional two-level converters, as they reduce harmonic distortion and lower switching losses, leading to higher energy conversion efficiency. The modular design of multi-level inverters also allows for better thermal management, reducing the need for complex cooling systems and enhancing system reliability.

Moreover, multi-level inverters offer enhanced control flexibility, allowing for more precise and adjustable power delivery. They also offer improved fault-tolerant capabilities, ensuring continuous operation of the converter. As research and development in this field continue, multi-level inverter technology is expected to continue improving, leading to more efficient and reliable power electronic systems in the future.

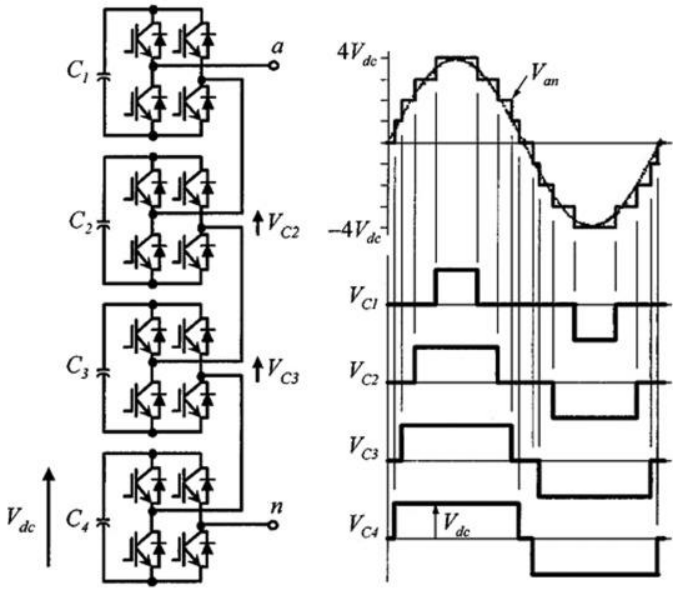


Figure 8: Basic Multilevel inverter.

3.3. Proposed system

The stand-alone PV system is designed to convert DC power from a 100KW PV array into AC power for remote or off-grid locations. The system operates independently without being connected to the utility grid. The system has a power capacity of 100KW and uses an incremental conductance MPPT control technique to maximize energy extraction. The DC bus voltage is set at 600V, ensuring efficient power conversion and effective control. The PID control system is implemented for precise regulation of output voltage and current, maintaining stability and reliable power delivery. The AC side voltage is set at 410V peak to peak, ensuring compatibility with load requirements and efficient utilization of generated power. The multilevel inverter generates multiple voltage levels, improving power quality and reducing harmonics. The system can handle a peak load of 70KW and an average load of 50KW, meeting varying power demands while maintaining stable operation. The system can deliver up to 70KW of power during high demand and 50KW during average load conditions, ensuring efficient energy utilization and maximizing autonomy.

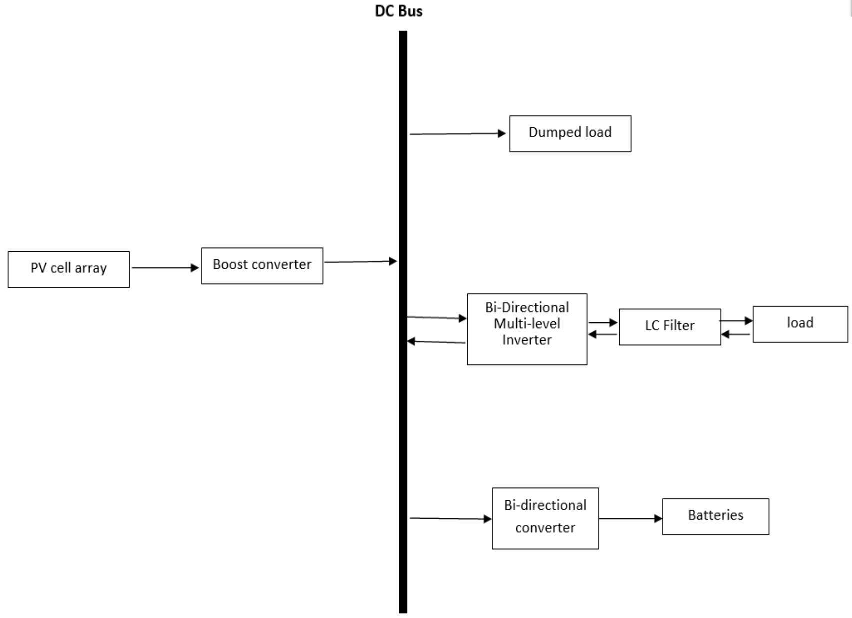


Figure 9: Proposed system block diagram

4. Results And Dıscussıon

4.1. PV Array

Irradiance levels, the amount of solar energy received per unit area, vary annually due to seasonal changes, weather conditions, and the sun's position. Understanding these variations is crucial for assessing the performance and energy production of solar systems, including stand-alone PV systems. Summer months have higher irradiance levels due to longer days, direct sunlight, and reduced atmospheric attenuation. This allows stand-alone PV systems to operate closer to their peak performance, resulting in optimal power generation. Figure 10 shows maximum irradiance levels of 1080 Wm-2 and 100Wm-2 at daytime, with irradiance almost 15 hours.

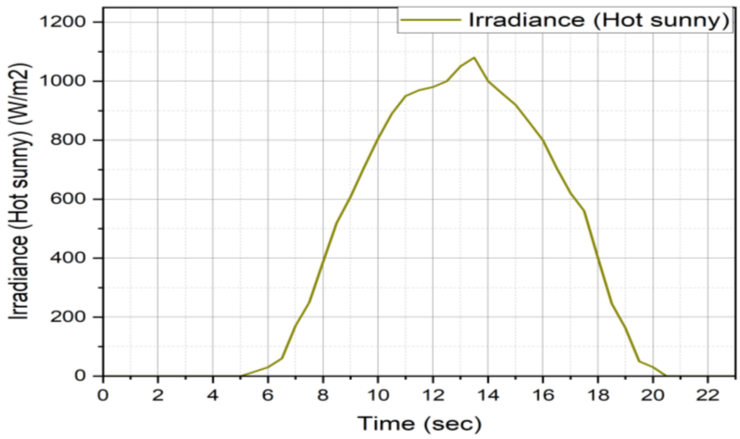


Figure 10: Irradiance level in hot sunny summer day

In contrast, the winter months bring shorter days, lower sun angles, and reduced irradiance levels. The decreased solar radiation can be attributed to the Earth's axial tilt, causing sunlight to spread over a larger area and pass through a greater thickness of the Earth's atmosphere. These factors contribute to lower energy production and reduced power output for stand-alone PV systems during winter. However, it's important to note that even in lower irradiance conditions, modern PV technologies still exhibit reasonable energy conversion efficiency, enabling the system to generate usable power. In figure 11 it is seen that in winter season there are less sun power available during day time compare to other condition. The maximum irradiance level is almost 300Wm^{-2} which means low power production.

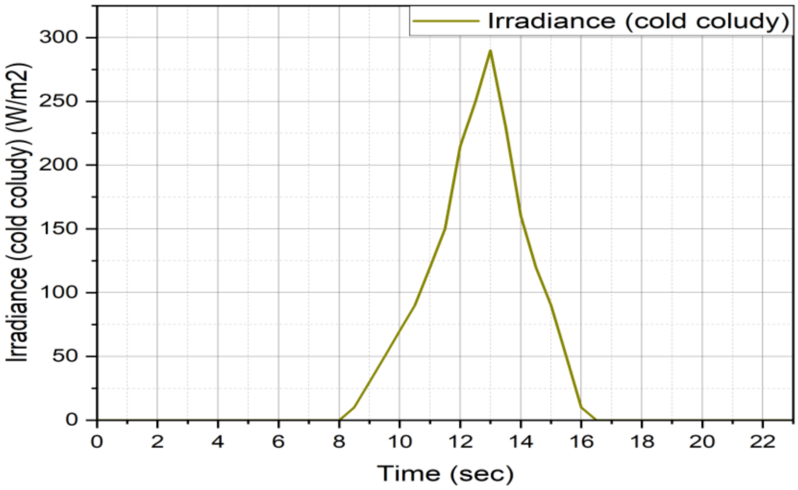


Figure 11: Irradiance level in cold cloudy day

During transitional seasons like spring and autumn, the irradiance levels lie between the extremes of summer and winter. The duration of daylight gradually increases or decreases, affecting the overall solar energy availability. The irradiance levels during these seasons are typically moderate, allowing stand-alone PV systems to operate efficiently and contribute substantial energy.

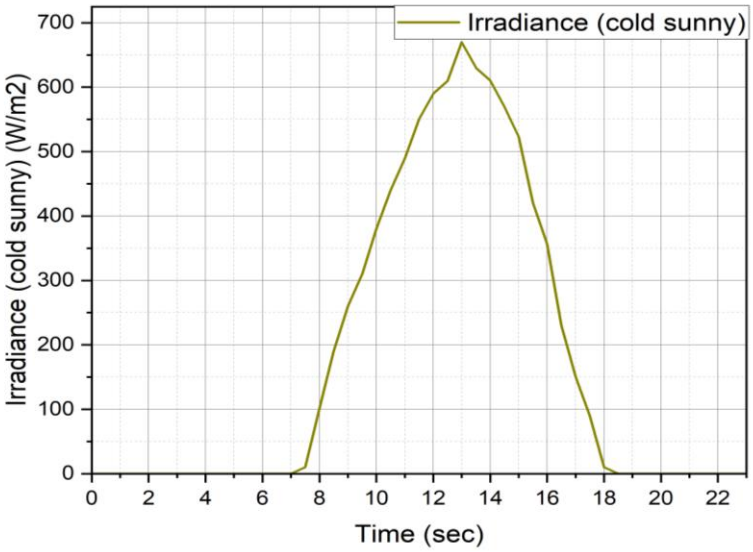


Figure 12: Irradiance in cold sunny day

4.2. Overall Power Flow

The power output of a photovoltaic (PV) system is influenced by varying irradiance levels throughout the year. During high irradiance periods, such as summer, the PV system generates a significant amount of electricity, exceeding the immediate load demand. This excess power is used to charge the battery bank, acting as a storage medium. The battery absorbs the surplus energy for later use when irradiance levels decrease or during peak load periods. In Figure 4.9, high solar irradiance results in high power output and excess energy stored in the battery system.

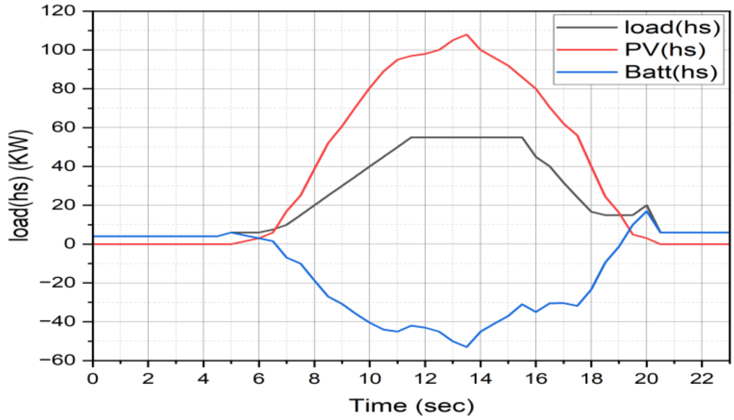


Figure 13: Overall power flow at hot sunny day

As the irradiance level decreases, during winter or cloudy days, the PV power output reduces accordingly which we can see in figure 13. In such situations, the power generated by the PV system may not be sufficient to meet the load demand directly. From the fig 13 it is seen that PV system only can meet the demand for 4 hours. However, the battery bank plays a vital role in bridging this gap. It discharges stored energy to supplement the power generated by the PV array, ensuring a consistent and reliable power supply to the loads. In the low irradiance time battery systems helps to meet the load demand.

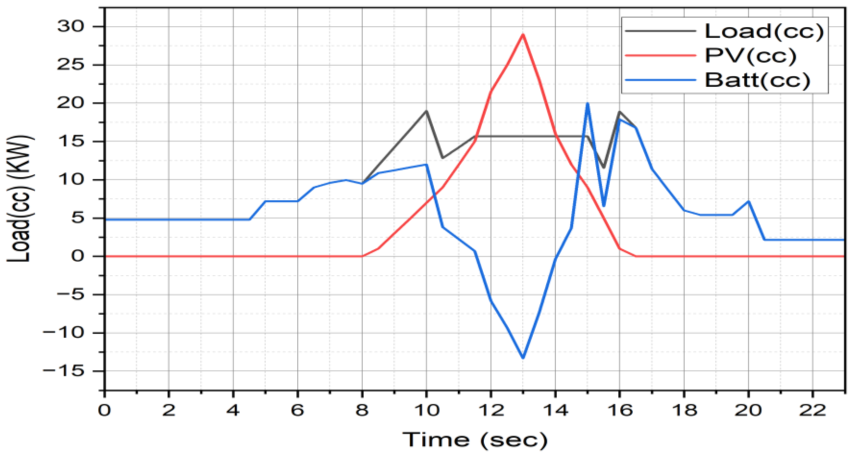


Figure 14: Overall power flow in cold cloudy day

During transitional seasons, when the irradiance levels are moderate, the PV power output and load demand can align more closely. The PV system generates electricity that matches or slightly exceeds the immediate load demand, reducing the reliance on the battery. The battery remains in a balanced state, neither significantly charging nor discharging, as the power output and load demand are relatively well-matched during these periods. From figure 14 and 15, the condition of transitional seasons is shown. In this period solar irradiance is also very from high to low. So, power flow also vary from high to low.

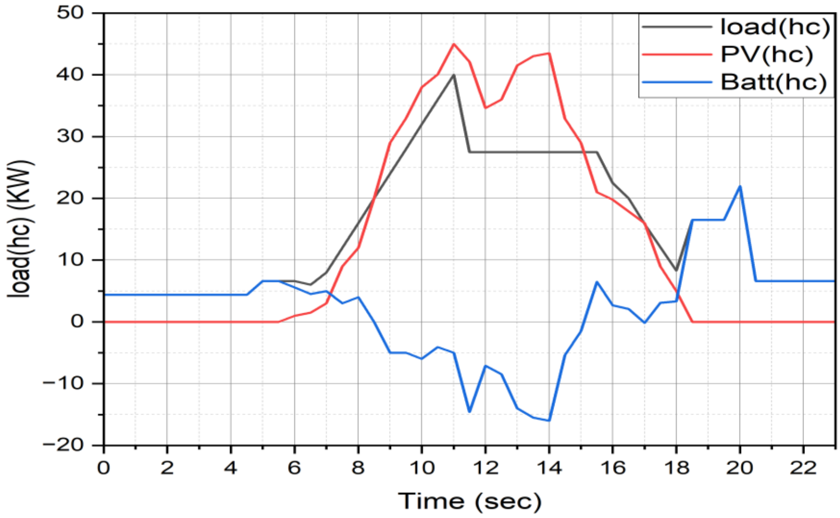


Figure 15: Overall power flow in hot cloudy day

5. Conclusion

The wind-PV-fuel cell and battery storage system-based hybrid power system has been found to be a promising approach for providing sustainable and reliable power to remote areas with limited or no access to grid electricity. The integration of wind turbines and PV panels provides a constant supply of renewable energy, while the fuel cell and battery storage systems provide backup power during periods of low wind or insufficient sunlight. The performance of the hybrid power system was evaluated using different performance parameters, such as energy efficiency, power output, and economic viability. The results have shown that the hybrid system can effectively meet the energy demand of the target system while maintaining stable power supply with minimal environmental impact. Furthermore, the economic analysis has demonstrated that the proposed hybrid system is economically feasible and can compete with conventional power generation technologies in terms of both cost and environmental impact. In conclusion, the wind-PV-fuel cell and battery storage system-based hybrid power system is a promising approach to address the energy demand of remote areas with limited or no access to grid electricity in a sustainable, reliable, and cost-effective manner.

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