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Original scientific paper

An Analysis of the Experimental Configuration of a Standalone PV System

Perumal SARAVANAN*, Kumar CHERUKUPALLI, Ramesh JAYARAMAN, Nattanmai Balasubramanian PRAKASH

Abstract: This research presents an experimental setup for analysing the power flow in a standalone photovoltaic (PV) system, encompassing both DC and AC loads. The study aims to investigate the effectiveness of the system by examining power transfer to a DC load and battery, as well as an AC load and inverter. Experimental analysis and simulation results were compared, demonstrating the successful implementation of the system. The theoretical calculations and software-based computations were utilized for design, comparison, and assessment of the standalone PV system. The findings revealed a linear relationship between incident irradiation and power output, highlighting the direct influence of radiation on PV system performance. Furthermore, the evaluation encompassed Array power, Charge Controller efficiency, Inverter efficiency, and battery charging across various irradiance levels. This research provides valuable insights into power flow analysis, offering a deeper understanding of standalone PV systems behaviour and efficiency. The outcomes contribute to the optimization of PV system designs, facilitating enhanced power generation and utilization for both DC and AC applications.

Keywords: DC and AC load; MPPT; solar PV shading; solar tilting; standalone photovoltaic

1 INTRODUCTION

Solar power is the process of converting solar energy. Photovoltaic (PV) cells allow for the direct conversion of solar energy into electricity, making solar power an important participant in the global energy market. Solar energy has been widely adopted thanks to falling solar cell prices, making it an economical and low-carbon technique for obtaining renewable energy [1]. With the earth's surface absorbing approximately 71% of solar radiation, there is immense potential for harnessing solar energy to meet the world's electricity demands [2].

India, in particular, has recognized the vast potential of solar energy and has implemented various subsidy schemes to promote its development [3]. The country is home to the world's largest solar power plant, located in Kamuthi, Tamil Nadu, with an installed capacity of 648 MW [4]. India's commitment to solar power is further demonstrated by its goal to provide solar energy access to over 60 million homes by 2020 [5]. Additionally, the installation of floating solar power plants, such as the one in Banasura Sagar Reservoir in Kerala, showcases innovative approaches to maximizing solar energy generation [6].

The global solar market is experiencing rapid growth, with India positioned as one of the key players. As solar power continues to expand, advancements in technology, such as the use of concentrated solar power and hybrid systems, further enhance the efficiency and reliability of solar energy generation. Furthermore, initiatives such as robotic cleaning systems, as seen in the Topaz Solar Farm in California, contribute to the optimization and maintenance of solar power plants [7].

Overall, the contributions of solar power to the energy sector are significant. It offers a sustainable and clean solution to meet growing electricity demands while reducing carbon emissions. The progress in solar technology, coupled with supportive government policies and innovative projects, ensures a promising future for solar power generation on a global scale.

This research focuses on the analysis of a standalone PV system, examining its power flow to both DC loads and batteries, as well as AC loads through an inverter. The primary objective is to investigate and evaluate the system's performance under different irradiance levels and load conditions. The experimental setup enables the validation of theoretical calculations and software simulations, ensuring accurate assessment and design of the standalone PV system.

The key contribution of this research lies in the comprehensive evaluation of power flow, including the examination of Array power, Charge Controller efficiency, Inverter efficiency, and battery charging efficiency. By analyzing these parameters, a deeper understanding of the system's behavior and efficiency is obtained, enabling the identification of areas for improvement and optimization.

2 RELATED WORKS

Several studies have focused on various aspects of solar power generation and its applications, contributing to the overall understanding and advancement of the field. The following works are relevant to the research presented in this paper:

Miller et al. (2021) conducted a review on the integration of solar photovoltaic systems with energy storage technologies. They explored different storage options and their impact on enhancing the reliability and performance of PV systems. Hafez, A. Z., et al. (2018) performed a comprehensive review of solar tracking systems. They discussed various tracking techniques and their impact on improving the energy yield of PV systems by optimizing the incident sunlight. Akrofi, M. M., et al. (2022) focused on the application of solar energy in buildings and urban environments. They discussed the integration of PV systems into building structures, urban planning, and energy management strategies. Maka, A. O., et al. (2021) conducted a review on the challenges and opportunities of large-scale solar power plant deployment. They discussed policy frameworks, technological advancements, and financial considerations for the successful implementation of utility-scale solar projects. Kabir, E., et al. (2018) explored the potential of solar energy in developing countries. They discussed the socioeconomic and environmental benefits, along with the challenges and policy frameworks necessary to promote solar energy adoption in developing nations. Muteri. V., et al. (2020) conducted a comprehensive review of PV system monitoring and control methods. They discussed the use of advanced monitoring technologies and control algorithms to improve the efficiency and reliability of PV systems. Das, U. K., et al. (2018) focused on the optimization of PV system operation and maintenance (O&M) strategies. They highlighted the importance of effective O&M practices in maximizing the performance and lifespan of PV systems.

The problem addressed in this research is the limited understanding of the long-term performance and reliability of photovoltaic (PV) systems under varying environmental conditions. While significant advancements have been made in PV technology, there is still a lack of comprehensive studies that examine the degradation mechanisms and durability of PV modules over extended periods of operation. This knowledge gap hinders accurate predictions of energy output and impacts the economic viability of solar power projects. Additionally, the impact of specific environmental factors on PV module performance, such as temperature, humidity, dust deposition, and extreme weather conditions, remains inadequately understood. The lack of comprehensive research in these areas restricts the development of effective strategies to enhance the durability, reliability, and maintenance practices of PV systems. Addressing these knowledge gaps is essential for maximizing the efficiency, longevity, and overall performance of solar power systems.

3 EXPERIMENTAL SETUP DESCRIPTION

A comparative performance analysis is performed between the experimental setup and the simulation results. The experimental Standalone PV system arrangement is seen in Fig. 1 and comprises two 40 Wp PV modules. The cells are of polycrystalline silicon type [16].

Figure 1 Experimental setup of standalone PV system

In Fig. 2 [17], a single module is made up of 36 solar cells connected in series. Connecting the two modules in series will increase the output voltage of the PV array, while connecting the modules in parallel will increase its output current.

The PV modules are illuminated by artificial halogen lamps of 1800 W with a regulator. A POT (variable resistor) of 200 ohms is connected across the modules acting as a load. The change in resistance has an effect in the output current and voltage. The output of a single PV module is sufficient to charge a 12 V battery. So, two batteries are required to store 24 V from the PV modules when they are connected in series. The output of PV modules is connected to supply a DC Load or charge a battery or can also feed an AC Load through an inverter. The parameters of a single solar module of model MS1240 is given in Tab. 1 (Courtesy: Micro Sun Solar Tech Pvt Ltd) [18].

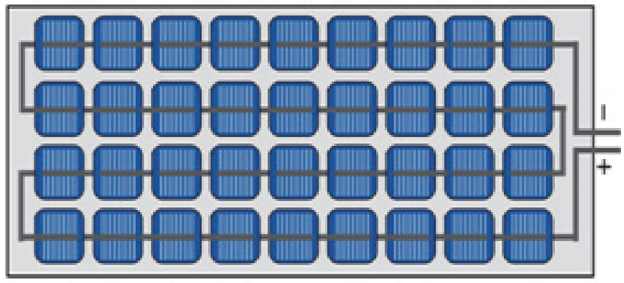

Figure 2 Single PV module

Table 1 Parameters of the solar module

S. No.	Parameters	Range
1.	Open Circuit Voltage (V_{oc})	22.32 V
2.	Short Circuit Current (I_{sc})	2.24 A
3.	Maximum Voltage (V_{mp})	18.1 V
4.	Maximum Current (I_{mp})	2.21 A
5.	Maximum Power at STC (P_{max})	40 Wp
6.	Maximum System Voltage (V_{DC})	600 V
7.	Operating Temperature	–200-900 °C
8.	Normal operating Cell Temperature (*NOCT*)	470 °C +/– 2K
9.	Current Temperature Coefficient	+0.66% / K
10.	Voltage Temperature Coefficient	–0.36% / K
11.	Power Temperature Coefficient	–0.43% / K

Tab. 2 provides the experimental results for a single PV module at an irradiation of 200 W/m^2 and 280 °C for voltage, current, and power. Figs. 3 and 4 provide graphical representations of a single module's VI and PV characteristics. The experimental analysis is performed on Eco sense Solar Photovoltaic Training & Research kit.

Table 2 Experimental values of V, I for single PV module

S. No	Temperature	Voltage	Current	Power
1	28	0.2	0.27	0.054
2	28.4	4.5	0.26	1.17
3	28.5	6.9	0.26	1.794
4	28.6	8.7	0.25	2.175
5	28.7	10.1	0.25	2.525
6	28.9	11.7	0.24	2.808
7	29.0	13.1	0.24	3.144
8	29.0	15.8	0.23	3.634
9	29.2	17.3	0.21	3.633
10	29.2	18.6	0.16	2.976
11	29.3	19.3	0.09	1.737
12	29.8	19.7	0.05	0.985
13	29.9	20.1	0.02	0.402

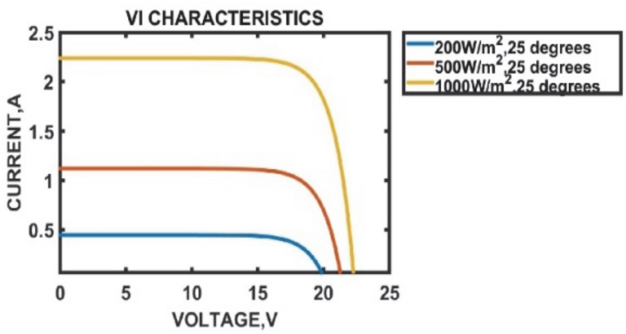

Figure 3 VI characteristics of a single PV module

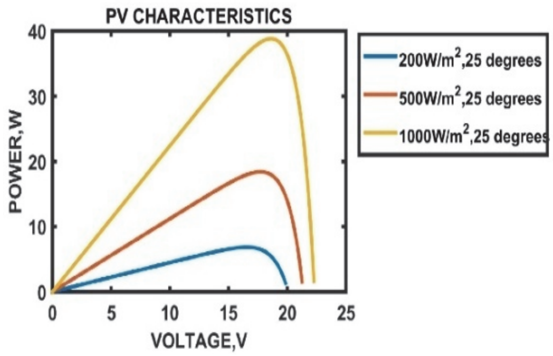

Figure 4 PV characteristics of a single PV module

The 36 solar cells are linked in series with the parameters listed in table 1 in the PV circuit seen in Fig. 5. This circuit was created using Matlab software.

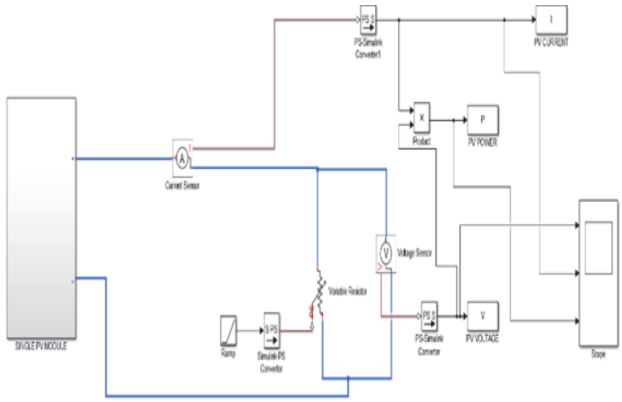

Figure 5 Single PV module simulation circuit

It is possible to acquire the VI and PV characteristics of a single module for 1000 W/m, 2500 W/m, and 2200 W/m^2 at 250 °C. The simulation's outcomes are displayed in Figs. 6 and 7.

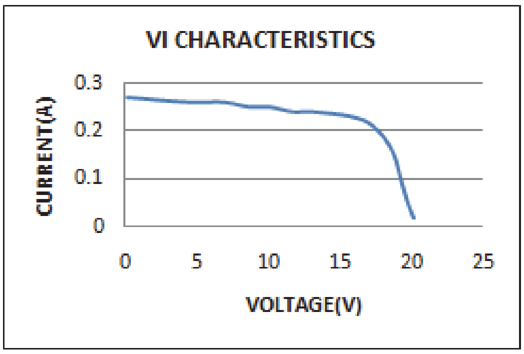

Figure 6 VI Characteristics of a single PV Module

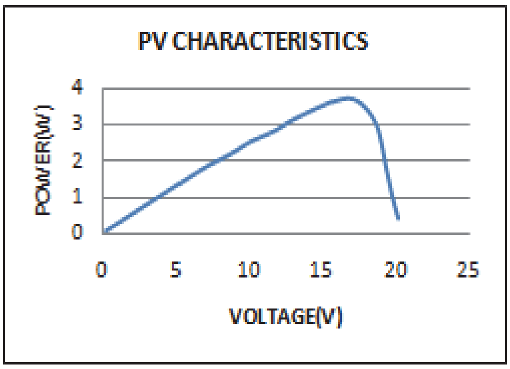

Figure 7 PV Characteristics of a single PV Module

As depicted in Fig. 8, the simulation model comprises PV array of 1 parallel string with 2 modules of 36 cells in series per string. The PV module is designed with the parameters as given in Tab. 1. The DC to DC buck converter, which has a 50 W output power and a 12 V output voltage, is linked to the PV array's output and charges a 100 Ah/12 V battery that serves as the storage component. For the MOSFET switch in the converter to operate at maximum output, a solar charge controller is coupled to provide the gating PWM pulse. Perturb and Observe, the Hill Climbing method, the Incremental Conductance method, and other soft computing techniques are examples of further MPPT algorithms.

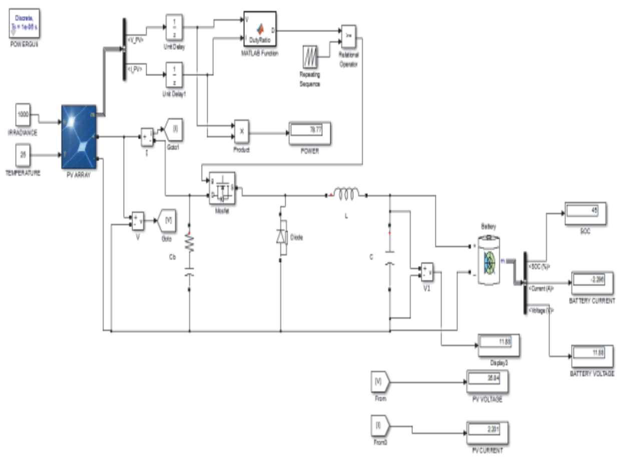

Figure 8 Implementation of PV system

The Perturb and Observe MPPT algorithm is being used in this design's controller. The output power of the PV array, which is exhibited from the battery measurement and is denoted by a negative sign, is roughly 79W, and the PV array charges the battery. The current and voltage sensor's output, Imp and Vmp, roughly matched the characteristics listed in the module's datasheet. Through the use of an inverter, the PV array's output may also power either an AC or DC load [19].

3 MODELLING EQUATIONS AND CHARACTERISTICS

PV cells are made from a variety of materials. Mono- and polycrystalline silicon crystal structures are the two most popular types. To get the required output voltage, numerous solar cells are connected in series to form a solar panel. A typical solar cell only generates about 0.5 V and less than 2 W. Thus, the panels are a part of an array. A series connection between two arrays results in a high output voltage. The PV cell operates as a p-n junction diode if solar radiation is not present at all times. As a result of the interaction between the light photons and the cell atom, when solar radiation impacts the PV cell, pairs of electron holes are produced. The electric field produced by the cell junction splits the photogenerated electron-hole pair, with the electrons and holes floating to the n region and p region of the cell. A photo current is produced by this movement, and it is mostly reliant on the quantity and type of solar energy [20]. A PV cell transforms into a *p-n* junction diode and turns into inactive if solar radiation is not reaching it, as was previously said. PV cells are unable to generate current or voltage in this circumstance. However, when a cell is linked to a larger external supply than the cell voltage, a current ID known as black current is generated. The PV system used for power conversion is made up of the tracking controller, several series and parallel configurations of PV modules, a DC-DC converter, and an inverter. A DC-DC converter and an inverter can both be used to boost the DC voltage generated as a result and convert it to AC. The load rating of the PV panel should be taken into consideration. The electrical equivalent diode model of the PV cell shown in Fig. 9 is given below.

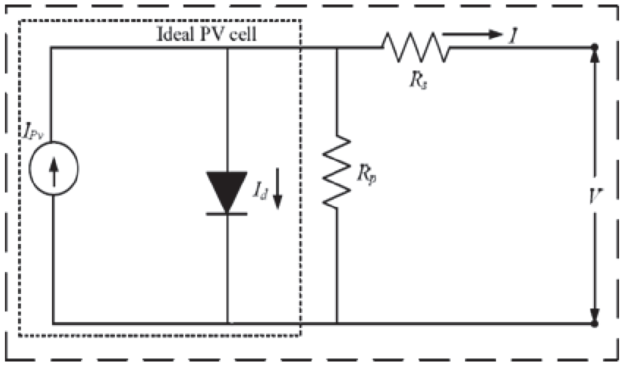

Figure 9 Equivalent circuit of PV cell

Current source, diode shunt resistance R_p, and series resistance R_s make up the PV model. The cell surface leakage via the edges is represented by the shunt resistance R_p.

The overall current I is the difference between the currents generated by a light source (I_{pv}), a diode (I_d), and a resistor (R_p) is given by Eq. (1).

$$I = I_{pv} - I_d - I_{sh} \tag{1}$$

Diode current I_d and Shunt Resistance current I_{sh} is presented by Eqs. (2) and (3).

$$I_d = I_0 \left\{ \exp\left[\frac{q}{mkT_c} \left(V + IR_s \right) \right] - 1 \right\} \tag{2}$$

$$I_{sh} = \frac{V + IR_s}{R_p} \tag{3}$$

where, m - idealizing factor; k - Boltzmann constant; T_c - absolute temperature of cell; q - charge of electron; V - potential across cell; I_0 - cell reverse saturation current.

By utilizing Eqs. (2) and (3) in (1) is shown below

$$I = I_{pv} - I_o \left\{ \exp\left[\frac{q}{mkT_c} \left(V + IR_s \right) \right] - 1 \right\} - \frac{V + IR_s}{R_p} \tag{4}$$

Since PV cells often have large shunt Resistance R_p, $\frac{V + IR_S}{R_P}$ is deleted. Hence,

$$I = I_{pv} - I_0 \left\{ \exp\left[\frac{V + IR_s}{A} \right] - 1 \right\} \tag{5}$$

where, A - curve fitting parameter.

$$A = \frac{mkT_c}{q} \tag{6}$$

Calculating the phase current I_{pv}. It shows that the output current under typical test conditions is

$$I = I_{pv} - I_0 \left[\exp\left(\frac{V}{a} \right) - 1 \right] \tag{7}$$

When a PV cell shorts out,

$$I_{sc} = I_{pv} - I_0 \left[\exp\left(\frac{0}{a} \right) - 1 \right] = I_{PV} \tag{8}$$

Eq. (8) is only true in an ideal situation. The equality is thus untrue. Eq. (9) has the notation,

$$I_{pv} \approx I_{sc} \tag{9}$$

Irradiance and temperature both affect the photocurrent.

$$I_{pv} = \frac{G}{G_{\text{ref}}} \left(I_{pv} + \mu_{sc} * \Delta T \right) \tag{10}$$

where, G - irradiance; G_{ref} - irradiance at standard testing conditions calculating the shunt and I_0 - through the use of three standard conditions, resistance which is frequently significant for all applications is eliminated. Open circuit voltage ($I = 0$, $V = V_{oc}$). Short circuit current ($V = 0$, $I = I_{sc}$). The following equation is constructed using the maximum power voltage (V_{mp}) and current (I_{mp}).

$$I_{sc} = I_{pv} - I_0 \left[\exp\left(\frac{I_{sc} \cdot R_s}{A} \right) - 1 \right] \tag{11}$$

$$O = I_{pv} - I_0 \left[\exp\left(\frac{V_{OC}}{A} \right) - 1 \right] \tag{12}$$

$$I_{pm} = I_{pv} - I_0 \left[\exp\left(\frac{V_{pm} + I_{pm} R_s}{A} \right) - 1 \right] \tag{13}$$

Since term (–1) is so little in comparison to exponential term, it is deleted. Eq. (13) with (I_{pv}) substituted in accordance with Eq. (14) and we get Eq. (15).

$$0 \approx I_{sc} - I_0 \exp\left(\frac{V_0}{A} \right) \tag{14}$$

Hence,

$$I_0 = I_{sc} \exp\left(\frac{-V_{OC}}{A} \right) \tag{15}$$

4 POWER FLOW EVALUATION OF A PV SYSTEM OF DC LOAD WITH BATTERY

The evaluation of power flow in the PV system when a DC load [21-23] is connected along with the battery is analyzed in this section which is demonstrated using the experimental setup.

The Solar Charge Controller and battery for measurement and DC load is present in the Main Controller. Eight 1W lamps (Blue Color Lamp) in the Main Controller act as the fixed DC load as shown in Fig. 10.

The modules are linked in a manner that is parallel. The halogen bulbs are turned on, and their intensities are adjusted. The radiation meter's measurement of the irradiation constant is maintained constant. The DC load current and voltage, battery current and voltage, and array current and voltage from the PV module are all measured in the Main Controller module. The module voltage needed by the battery bank or DC load is controlled by the solar charge controller. The required parameters are measured as the radiation is gradually changed. The DC load's intensity varies depending on the irradiation. The Array power for the PV modules is calculated using the formula:

PV Array power = load power + battery power + Power loss by Charge Controller.

Figure 10 Experimental setup of parallel connection of PV modules with DC load

The experimental analysis was performed and from the analysis it was noted that as the irradiation was varied, the intensity of the Lamp which is acting as DC load is also changed which is regulated by the Charge Controller. The PV array, DC load, Battery voltage and current are measured for 200 W/m^2 as tabulated in Tab. 3.

The below Fig. 11 shows the simulation of Parallel connection of PV modules with DC Load and Fig. 14 shows the output voltage of DC load.

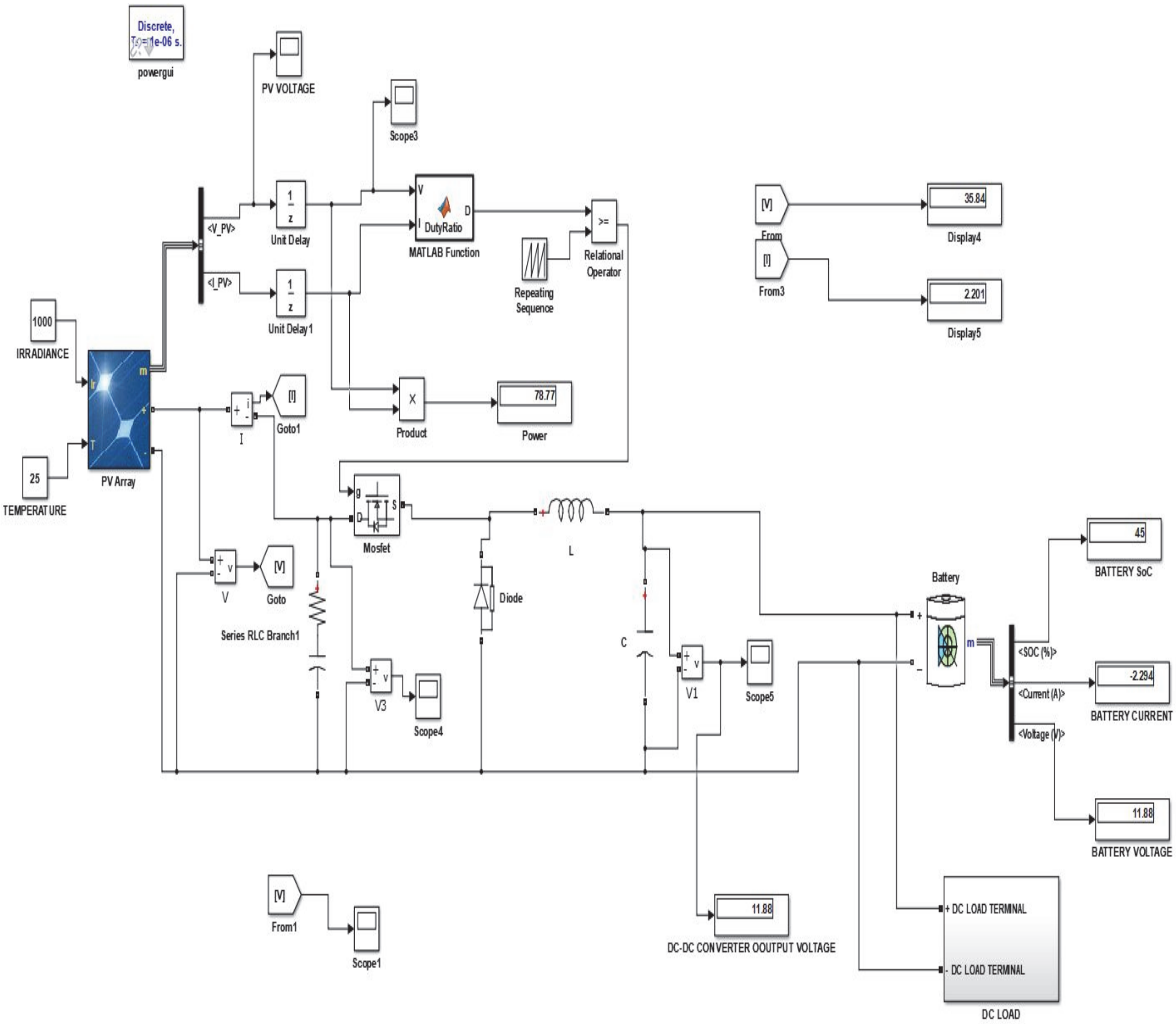

Figure 11 Simulation of Parallel connection of PV modules with DC Load

Table 3 Experimental values of parallel connection of PV modules with DC load

Array Current / A	Array Voltage / V	Array Power / W	Load Current / A	Load Voltage / V	Load Power / W	Battery Current / A	Battery Voltage / V	Battery Power / W
0.16	20.5	3.28	1.1	12.5	13.7	0.008	13.7	0.1096

5 POWER FLOW EVALUATION OF A PV SYSTEM OF AC LOAD

The power flow in the PV system when an AC load is connected through an inverter is evaluated and discussed in this section. The experimental standalone setup includes PV module, ammeter, voltmeter, Solar Charge Controller and battery for measurement and AC load which is present in the Main Controller and an Inverter. White Color Lamp in the Main Controller acts as the fixed AC load as shown in Fig. 12. The halogen lamps are switched on and the intensity of the lamps are varied using the regulator. The irradiation is kept constant which is measured by the Radiation meter.

The charge controller controls the voltage produced by the PV modules, and an inverter converts the battery's controlled DC power from DC to AC. The input current and voltage of the inverter, the current and voltage of the AC load, the current and voltage of the battery, and the array current and voltage from the PV module are all measured in the main controller module. The irradiation is varied in steps and depending upon the irradiation, the intensity of the AC load is varied. The Array power and the inverter efficiency are calculated and tabulated in Tab. 4.

Table 4 Experimental values of Parallel connection of PV modules with AC Load and Inverter

Array Current / A	Array Voltage / V	Array Power / W	Inverter *I*/*P* Current / A	Inverter *I*/*P* Voltage / V	Inverter *I*/*P* Power / W	Battery Current / A	Battery Voltage / V	Battery Power / W
0.43	12.0	5.16	0.42	8.9	3.738	0.021	8.9	0.1869

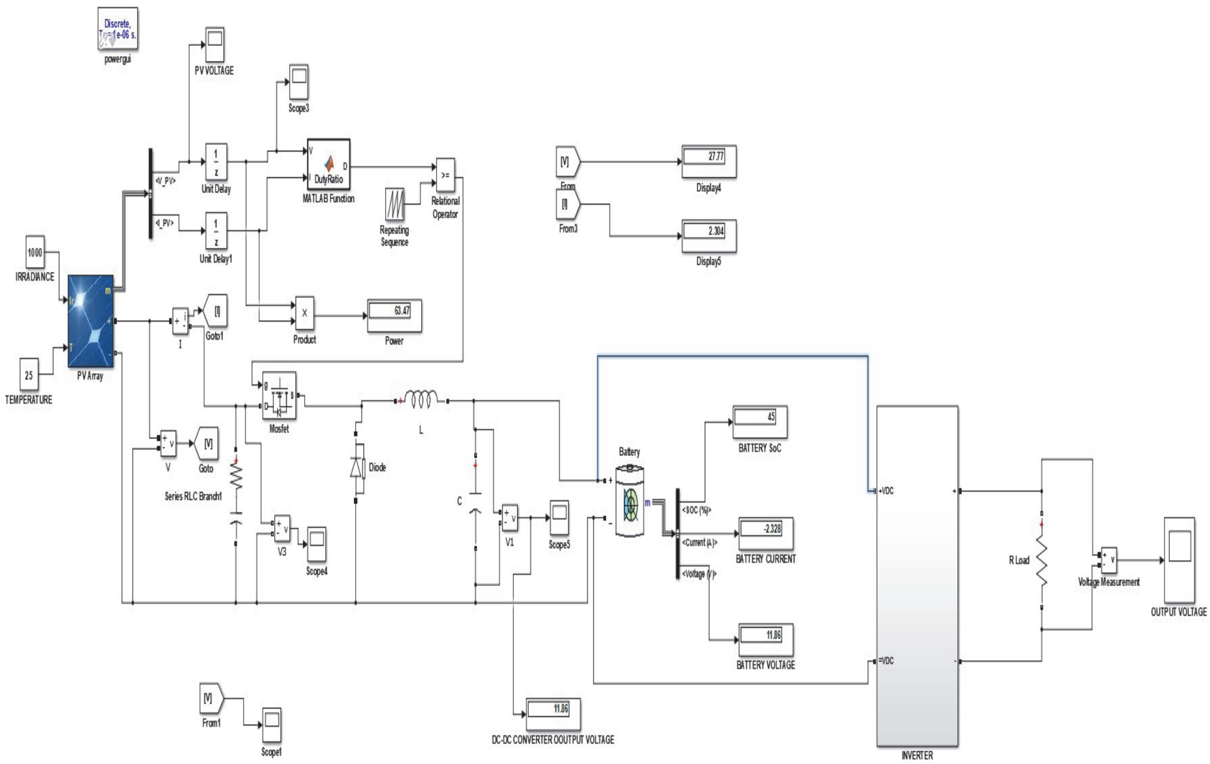

Figure 12 Simulation of parallel connection of PV modules with AC load and inverter

6 CONCLUSION

This research gives an experimental setup for analyzing the power flow from a PV system to a DC load and battery as well as an AC load and inverter. An experimental examination was conducted, and the findings showed that the estimated values and the outcomes of the simulation matched each other, proving that the system was effectively created and could be used. The theoretical calculations and software-based computations are used to design, compare, and assess the standalone PV system. The relation between the radiation and power output is found to be linear. Performing the evaluation of power flow, the Array power, Charge Controller efficiency and the Inverter efficiency, battery charging was also analyzed for different irradiance levels. It is suggested that a design of off-grid PV Solar system for a commercial building should be carried out; when heavy loads are subjected to the system without any diversity factor. All these changes in loads application will result in more conclusive and pronounced outcomes for the future optimization of off-grid PV systems.

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Contact information:

Perumal SARAVANAN, Professor and Head
(Corresponding author)
Sree Sakthi Engineering College,
Karamadai, Coimbatore - 641104
E-mail: dr.sara_p@outlook.com

Kumar CHERUKUPALLI, Associate Professor
Department of Electrical and Electronics Engineering,
PVP Siddhartha Institute of Technology,
Vijayawada, Andhra Pradesh - 520007
E-mail: kumarcherukupalli77@gmail.com

Ramesh JAYARAMAN, Associate Professor
Department of Electrical and Electronics Engineering,
Velagapudi Ramakrishna Siddhartha Engineering College,
Vijayawada, Andhra Pradesh - 520007
E-mail: jramesh@vrsiddhartha.ac.in

Nattanmai Balasubramanian PRAKASH, Professor
Department of Electrical and Electronics Engineering,
National Engineering College,
Kovilpatti, Tamilnadu - 628503
E-mail: nbprakash26@gmail.com