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FUJECE

Sürdürülebilir Enerji Çözümü için FV Sistemlerinin Etkin Kullanımı: Bir Vaka Çalışması

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Öz

Dünyada nüfus artışı ile birlikte enerji talebi de hızla artış göstermektedir. Çevre üzerinde bozucu etkiler oluşturmuş olan fosil yakıtlar yerine teknoloji alanındaki ilerlemeler sayesinde yenilenebilir enerji kaynaklarının kullanılmasının önünü açılmıştır. Güneş enerjisi, birçok yenilenebilir kaynak arasında gittikçe önemi anlaşılan ve gelecekte de kullanımı daha da artacak olan bir kaynak türüdür. Fotovoltaik (FV) güneş panelleri özellikle uzak yerleşim yerlerinde müstakil evlerin elektrik yüklerinin ihtiyaç duyduğu elektrik ihtiyacını karşılamalarına olanak sağlamaktadır. Bu FV sisteminde üretilen enerjinin istenilen seviyedeki enerji miktarına dönüşümünü sağlayan en önemli bileşen DA-DA dönüştürücüdür. FV panelinden en yüksek miktarda gücü alabilmek için en uygun yöntemlerden biri de DA-DA dönüştürücüye Maksimum Güç Noktası İzleme (MPPT) tekniği uygulamasıdır. FV panellerin üretim yapmadığı zaman dilimlerinde enerji ihtiyacının karşılanması için batarya sistemleri kullanmak bir çözüm olmuştur. Bu çalışmada, MPPT algoritması yardımıyla ile beş adet paralel bağlı FV panelden azami şekilde elde edilen elektrik enerjisinin bir kısmı yükün ihtiyacını karşılarken diğer kısmı ise Li-Ion tipi bataryada depolanması amaçlanarak verimli bir çalışma yapısı oluşturulmuştur. Böylece kesintisiz bir enerji akışı sağlanması düşünülmüştür. Sistem tasarımı ve simülasyonu için MATLAB/Simulink yazılımı kullanılmıştır. Güneş ışınım verileri olarak Edirne ili Enez ilçesinin yaz dönemine ait veriler seçilmiştir. Batarya tipi olarak Lityum-İyon tip kullanılmıştır. Sonuçlara baktığımızda, gün doğumunun ilk saatlerinde FV panelden gelen enerjinin yetersiz olduğu ve bu noktada enerjinin bataryadan karşılandığı belirli bir saatten sonra ise panelin ihtiyaç duyulan enerjiyi karşıladığı ve fazla üretilen enerjinin bataryada depolandığı görülmektedir. Bu sayede enerji yönetim sistemiyle kesintisiz enerji akışı en yüksek güçte ve en uygun teknikle sağlanmış olmaktadır.

Anahtar kelimeler: FV sistem, MPPT kontrol, Batarya, Kesintisiz enerji

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Effective Use of PV Systems for a Sustainable Energy Solution: A Case Study

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Abstract

Energy demand is rapidly increasing alongside global population growth. Instead of relying on fossil fuels, which harm the environment, technological advances have enabled the use of renewable energy sources. Solar energy is increasingly recognized as a vital resource among many renewable options, and its usage is expected to grow even more in the future. Photovoltaic (PV) solar panels enable detached houses, especially in remote settlements, to meet their electricity needs. The most important component that converts the energy produced in this PV system to the desired level is the DC-DC converter. One of the most effective methods to obtain the highest amount of power from the PV panel is the application of the Maximum Power Point Tracking (MPPT) technique to the DC-DC converter. Additionally, battery systems have proven to be a viable solution for meeting energy demand during periods when PV panels do not produce electricity. In this study, an efficient working structure has been developed using the MPPT algorithm to meet the load's needs while storing a portion of the electrical energy obtained from five parallel-connected PV panels in a lithium-ion battery. Ensures an uninterrupted energy flow at the highest power output using the most appropriate technique. MATLAB/Simulink software was employed for system design and simulation. Solar radiation data from the summer period of the Enez district in Edirne province were selected for analysis. A lithium-ion battery type was utilized in the system. The results show that energy from the PV panel is insufficient during the early hours of sunrise, at which point energy demand is met by the battery. After a certain hour, the PV panel satisfies the required energy demand, and any excess energy is stored in the battery. This system demonstrates an efficient energy management structure that ensures continuous power supply for off-grid households.

Keywords: PV system, MPPT control, Battery, Uninterruptible energy

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1. Introduction

Today, societies no longer see energy as an indicator of social or economic development, but as a part of human life. [1]. Renewable Energy Sources (RES) are among the best options to address the technical, environmental, and financial issues caused by conventional fossil-fueled power plants. Solar energy systems are particularly advantageous compared to conventional power plants due to their low environmental impact, low installation costs, and high availability [2]. In PV panel technologies, maintaining and controlling the stability of the system against variations in input energy and load requires various methods [3]. This is especially important in off-grid PV systems, where investigating the battery charging algorithm is crucial since it is the only power storage device. There are several methods for battery charging algorithms, and these methods depend on the battery's charge level. Therefore, a charge controller is needed to manage the battery's charging and discharging effectively [4]. Since the voltage obtained from the PV system is unregulated, it is first adjusted to a desired voltage level. The MPPT technique is then employed to obtain and control the maximum power to be shared between the battery and the load [5]. The MPPT control technique increases the efficiency of PV systems by effectively monitoring the Maximum Power Point (MPP). In addition, this control technique can reduce operating costs and achieve maximum performance by operating in both transient and steady-state operating modes [6]. MPPT algorithms are crucial for optimizing solar energy harvesting in PV systems. Several MPPT techniques have been developed to address the nonlinear characteristics of PV systems under varying environmental conditions [7]. These techniques can be categorized into several groups based on factors such as monitoring methods, controllers, hardware, and ease of implementation. Traditional gradient-based techniques include perturb and observe (P&O), hill climbing (HC), and incremental conductance (IC) [8]. In the literature, a control algorithm has been developed for the power management of an off-grid PV system combined with battery energy storage. This algorithm monitors the solar panel's MPP to prevent overcharging of the batteries under varying loads and different solar radiation conditions [9]. Microcontroller-based implementations of MPPT algorithms, such as those using Arduino UNO, have shown promise in maximizing power output from solar modules in both simulated and real-life scenarios [10]. In an experimental study of a standalone hybrid microgrid system, an energy management strategy based on the State of Battery Charge (SOC) was developed. This strategy was experimentally implemented using speed and Single Input Fuzzy Logic (SIFL) controllers to achieve MPPT and maintain energy balance, respectively [11]. A novel Energy Valley Optimization (EVO)-based MPPT algorithm is compared with several other algorithms to extract maximum power from the sun. The results show that the proposed MPPT controller successfully overcomes the shortcomings of existing MPPT methods [12]. A system consisting of a grid-connected PV panel, a battery energy storage system (BESS) and an EV charging station is constructed. In order to manage the power of this system, a PI controller and a Neuro-Fuzzy Inference System (ANFIS)-based MPPT are applied and the maximum output power, reactive power, grid current and grid voltage are obtained through MATLAB/Simulink program [13]. MATLAB / Simulink software has been applied to test the efficiency and accuracy of MPPT control in solar energy systems, one of the most common uses of RES technologies. [14]. To overcome the limitations of wind speed capacity and the emission of photons from sunlight in a hybrid system consisting of PV panels and wind turbines, the Incremental Conductance (IC) algorithm has been implemented. This algorithm can control the converter duty cycle and the switching of the buck-boost converter, achieving maximum MPPT efficiency [15]. To reduce peak demands, the power generated from a system consisting of a rooftop PV panel, a Battery Storage System (BSS), a hybrid control system, and a grid-connected inverter is continuously monitored, revealing that the power generated from solar panels meets 100% of the energy required by each residence [16]. A methodology using fuzzy logic has been developed to optimize the maximum power-generating capacity of the system, and the entire system has been simulated using a simplified model with a battery and a fuel cell as backup [17]. A Fuzzy Logic-based inverter controller is modeled and simulated on the MATLAB/Simulink platform to obtain constant AC voltage and frequency from an off-grid battery storage PV system, considering various operating conditions such as varying PV power and load scenarios [18]. The proposed standalone PV-battery charging model, which includes MPPT and a charge controller, utilizes a PIC16F877A-based microcontroller to regulate the battery charge by limiting the overcharge current and protecting the battery from overcharging [19]. A hybrid MPPT method based on Particle Swarm Optimization - Adaptive Neuro-Fuzzy Inference System (PSO-ANFIS) helps achieve rapid and maximized PV output power in an off-grid microgrid, in conjunction with battery energy storage control to maintain stable voltage and frequency (V-f). Additionally, coordinated power management has been developed for the microgrid by integrating MPPT, which enhances power generation and conversion efficiency in PV plants [20]. In the presented study, a comparison between the ANN-based hybrid MPPT system and the conventional Perturb and Observe (P&O) MPPT control system is conducted. The results demonstrate that the ANN-based technique outperforms the conventional method in terms of stability, precision, and accuracy in monitoring the MPP, regardless of whether the solar irradiance changes rapidly or slowly [21]. In this paper, a DC micro-grid with autonomous load switching system is proposed to increase the speed of electrical energy provision in off-grid rural areas [22].

In contrast to the aforementioned studies, this research monitors the maximum power transfer between the battery and the load through the MPPT controller. This controller is regulated by the current and voltage variables derived from the energy harvested from the PV system, utilizing real irradiance data at an off-grid location alongside the backup system. By employing the P&Q tracking loop, the MPPT controller can be precisely managed. The battery control system prevents overcharging and deep discharging of the battery under varying solar irradiation conditions. To ensure a stable and reliable hybrid system, a Battery Energy Storage System (BESS) is integrated into the system to supply power to the load alongside the PV system. Thanks to this control technique, both the battery charge/discharge control and the amount of energy produced by the panel are controlled, making it possible to operate an off-grid system in areas with limited solar radiation data. The article is structured into three parts: the first provides general information about the system, the second discusses the properties, shapes, and detailed information of the system's components, and the last presents simulation results and their interpretation.

2. Materials and Methods

2.1. System information

This study aims to meet the uninterrupted electricity demand of an existing detached villa that suffers from grid outages during the summer period, especially in the Enez district, which has the highest global radiation value in Edirne province. The villa is located between 40°69'59"north latitude and 26°06'80" east longitude. The satellite image of the location is shown in Figure 1. Since Enez district receives the highest solar radiation value in the province, the necessary studies for the PV panel system to be installed in a detached house are specified.

Figure 1. Satellite image and photograph of the villa location

A PV module implements a control strategy that manages the power flow between the battery and the load. An MPPT scheme is utilized to obtain the maximum power from the PV system. The excess energy remaining after fulfilling the load demand is stored in the battery. This stored energy is then used to address future load demands during power deficits from the PV system, thereby effectively managing the power requirements of the load. The implementation and simulation of the system are conducted using MATLAB/Simulink software. Figure 2 illustrates the block diagram of the designed system, which comprises two DC/DC converters, one PV panel, an MPPT controller, a DC load, and a lithium-ion battery.

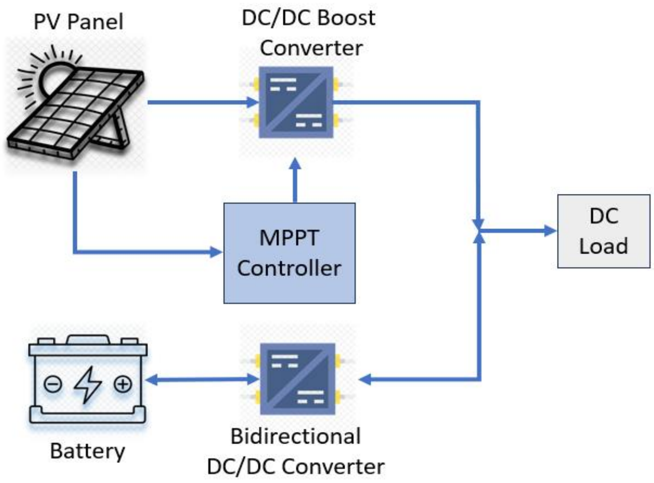


Figure 2. System block diagram

The system operates with the maximum power transfer obtained by considering the impedance matching between the PV panel and the load. MPPT is a different version of a DC/DC switching voltage regulator. Here, the impedance matching of the DC/DC converter can be done by adjusting the duty cycle of the switch. Achieving maximum power transfer may require adjusting the load's voltage and current levels. For this purpose, voltage and current sensors connected to the voltage supply loop are commonly used together with a boost converter.

2.2. System components

2.2.1. Overview of pv side

Solar radiation data is directly related to the power that can be obtained from the PV panel [23]. Figure 3 presents the hourly solar irradiation data for the Enez district, which is essential for the operation of the PV system, collected over a day during the summer period. Analyzing this data, it shows that solar radiation occurs between 07:00 in the morning and 20:00 in the evening, reaching its highest level at 13:00.

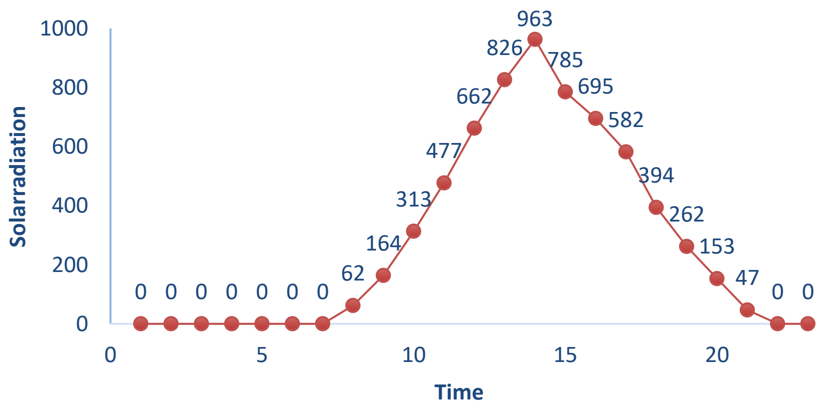


Figure 3. Daily solar radiation data applied to the PV panel

An ideal PV cell consists of a parallel diode and a DC current source. The PV cell, or solar cell, is made up of a p-n junction fabricated with a thin semiconductor wafer. By adding series and shunt components to the PV cell model, it ensures that internal losses are accurately calculated by accounting for the current flow towards the ground resulting from leakage current. Voltage can be increased by adding series-connected PV panels, while the output current can be increased by adding parallel-connected PV panels [24]. The single-diode PV cell equivalent circuit is the simplest representation, consisting of a current source connected in parallel with a diode, a series resistor *Rs*, a parallel (shunt) resistor *Rsh*. The series resistor is an important parameter that affects irradiance and cell temperatures [25]. The PV cell equivalent circuit is shown in Figure 4.

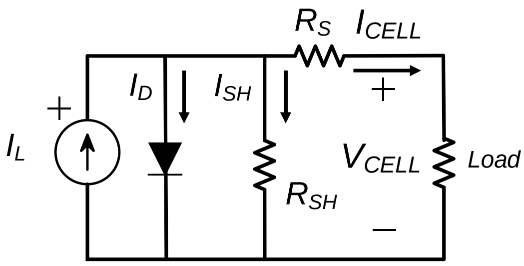


Figure 4. PV cell equivalent circuit

Applying Kirchhoff's current law, the output current of the PV cell is expressed by the following equations as follows.

$$I = I_L - I_D - I_{sh} \tag{1}$$

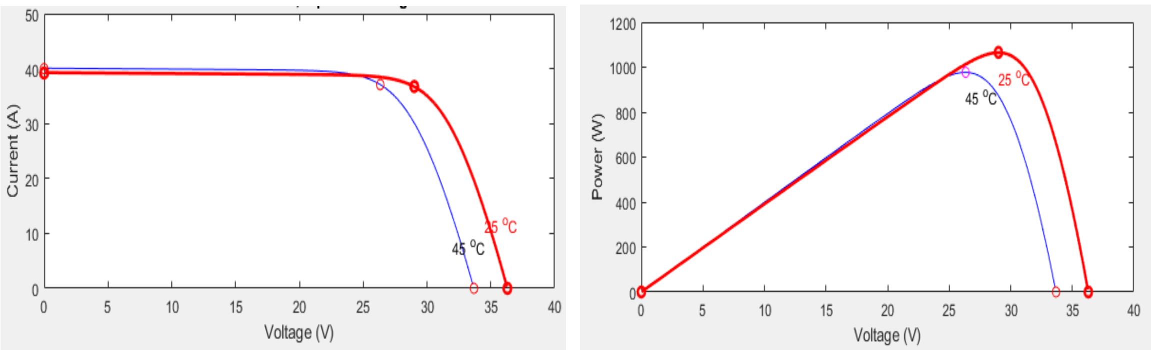
$$I_D = I\left\{exp\left[\frac{q(V+IR_S)}{AkT_C}\right] - 1\right\} \tag{2}$$

$$I = I_L - I\left\{exp\left[\frac{q(V+IR_S)}{AkT_C}\right] - 1\right\} - \frac{V+IR_S}{R_{sh}} \tag{3}$$

$$I_{RS} = \frac{I_{SC}}{e^{\left(\frac{qV_{OC}}{N_S AkT_C}\right)}-1} \tag{4}$$

where I is the output current of the solar cell, I_L is the photocurrent, I_D represents the current through the diode, R_s is the Series resistance, R_{sh} is the Shunt resistance, I_{sh} is the current through the R_{sh}, A is the ambient factor, K is the Boltzmann constant, and q is the electron charge.

Figure 5 presents graphs of the current-voltage and power-voltage characteristics of the PV panel, which comprises one series and five parallel cells utilized in the system. It is noted that as temperature increases, the current and power generated by the panel decrease. The electrical characteristics and specifications of the selected PV panel system model for implementing the proposed system are displayed in Table 1.



(a) (b)

Figure 5. a) Temperature graphs of the system PV panel. (a) Current and voltage changes (b), voltage and power changes

Table 1. PV panel characteristics

Parameters	Value
Parallel strings	5
Series-connected modules per string	1
Maximum Power (W)	213.15
Cells per module (Ncell)	60
Open circuit voltage *Voc* (V)	36.3
Short-circuit current *Isc* (A)	7.84
Voltage at maximum power point *Vmp* (V)	29
Current at maximum power point *Imp* (A)	7.35
Temperature coefficient of *Voc* (%/deg.C)	-0.36099
Temperature coefficient of *Isc* (%/deg.C)	0.102

2.2.2. Battery energy storage side

In an off-grid system, the battery supplies power to the loads during periods when the solar panels cannot generate electricity. While the battery discharges to feed the load when no production occurs from the PV panels, it charges when production is high and demand is low. Battery depletion is prevented by continuously monitoring its charge level. If the charge falls below 25%, the load is disconnected from the battery using a breaker [26]. Having a battery in a PV system helps reduce power generation instability and can be economically advantageous [27]. In a lithium-ion battery composed of rechargeable cells, lithium ions flow from the negative electrode to the positive electrode through an electrolyte during discharge and move in the opposite direction during charging. The characteristics of the lithium-ion batteries used in the system are shown in Table 2.

Table 2. Battery characteristics

Parameters	Value
Nominal voltage (V)	24
Rated capacity (Ah)	50
Initial state-of-charge (%)	45
Battery response time (s)	1
Internal resistance (Ohms)	0.0048
Maximum capacity (Ah)	50
Cut-off Voltage (V)	18
Fully charged voltage (V)	27.9357
Nominal discharge current (A)	21.7391

2.2.3. Power electronics side

A boost converter topology is utilized here to increase the solar voltage to the necessary level to achieve a higher output voltage [28]. In off-grid PV systems, the use of a bidirectional DC-DC converter to connect to the battery energy storage system has been favored. Unlike conventional buck-boost converters, this type of converter transfers power in both directions by increasing or decreasing the voltage and transmitting the power forward or reverse. Bidirectional DC-DC converters function as power flow regulators for the DC bus voltage in both directions. Wind turbines and solar power systems produce erratic output due to fluctuating climatic conditions. These energy sources are not dependable as stand-alone systems because of significant output fluctuations. Consequently, these circuits, along with energy storage devices such as batteries, work in conjunction to mitigate this unreliability [29]. Bidirectional and boost converters are used collaboratively in the system. Figure 6 illustrates the MATLAB model of the buck-boost converter that optimizes the highest voltage from the PV system supplying the load.

The equations of the values used in Buck-Boost converters are given below.

$$M = \frac{-D}{1-D} \tag{5}$$

$$L = \frac{DV_{PV}}{f_s \Delta I} \tag{6}$$

$$C = \frac{DV_B}{f_s \Delta V} \tag{7}$$

where, V_{PV} is PV voltage, V_B is bus voltage, f_s is system frequency, ΔI is equal to the ripple current, ΔV expresses the ripple voltage, M states the gain ratio, and D denotes the duty ratio [30].

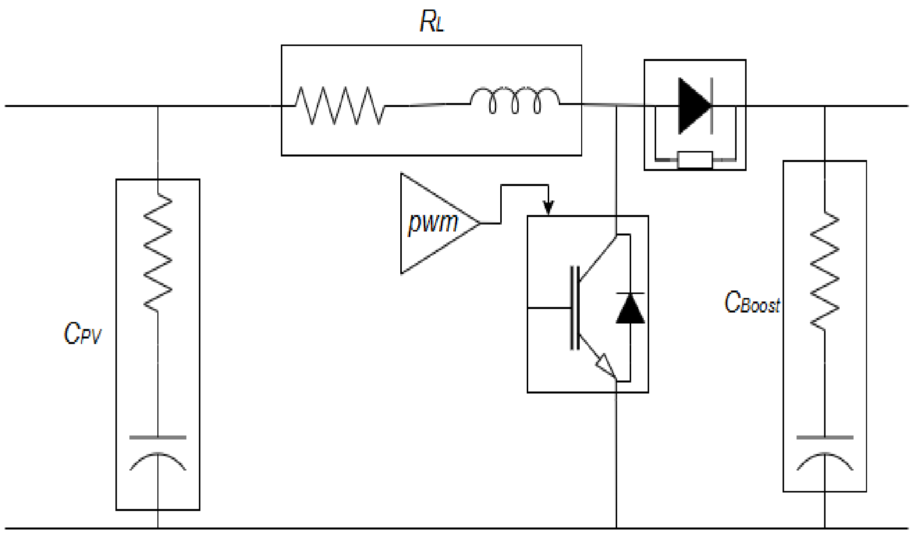


Figure 6. MATLAB model for buck-boost DC-DC converter

2.2.4. MPPT controller side

The efficiency of MPPT is a very important aspect of all PV systems. Coordination between the PV panel and the DC-DC converter is primarily achieved through MPPT. Using the MPP technique in solar panels is tricky because the current-voltage relationship of the PV operating curve is not straightforward, and changing weather, like differences in sunlight and temperature, affects it. To mitigate this, the MPPT control technique must be applied carefully. As PV panels are exposed to continuously fluctuating solar radiation levels, it becomes increasingly challenging to use this control method effectively. The literature contains numerous studies on MPPT algorithms focusing on operation at the optimal MPP [31]. Considering the P-V and I-V output characteristics of the PV panel, Perturbation and Observation (P&O) algorithms have been developed using direct duty cycle control techniques based on voltage reference or current reference. Figure 7 expresses the flowchart of the P&O algorithms.

The P&O algorithm is preferred for determining the duty cycle of the boost converter, thereby enabling the system to operate at the MPP. This algorithm operates by introducing a small perturbation that alters the power output of the module. If the power increases due to the perturbation, the perturbation continues in that direction. Once the power reaches its maximum point, it starts to decrease, causing the perturbation to reverse. When steady state is achieved, the algorithm oscillates around the maximum point [32]. To charge the battery, a device is required that can supply power to the battery until it is fully charged. Additionally, once the battery is at full capacity, controlling the power and current in the charger is crucial to prevent overcharging and protect the battery cells from depletion [33]. A battery controller regulates the battery charging process based on the output power of the PV panels. The bidirectional DC-DC converter connected to the battery can manage the DC-link voltage. Consequently, the bidirectional DC-DC converter can also serve as the MPPT controller for the system. This eliminates the need for an additional MPPT, thereby reducing costs. The *Vref* from the P&O algorithm will act as the reference voltage for the battery controller, facilitating the regulation of the PV voltage at the specified *Vref*. This configuration will then function as the MPPT converter for the PV system [34].

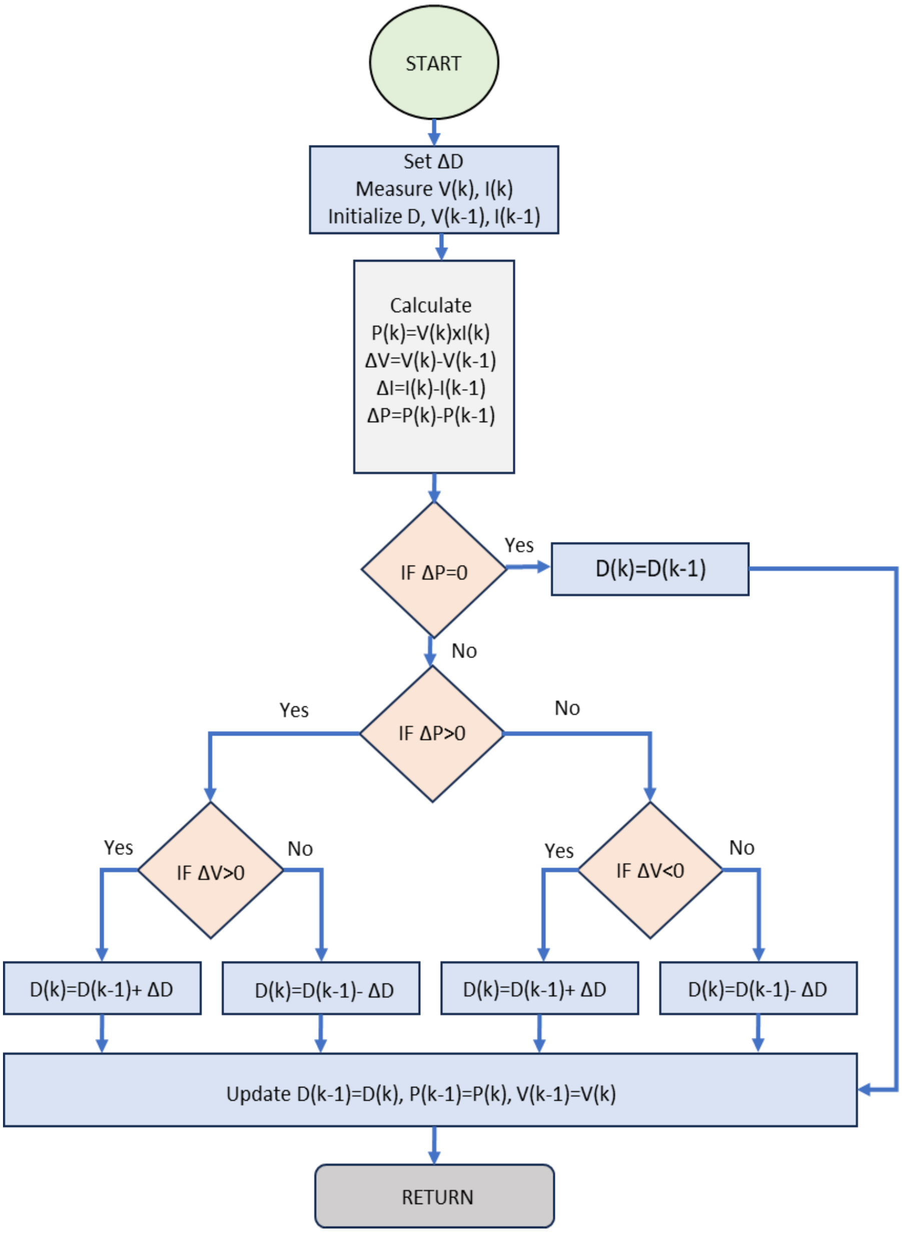


Figure 7. Flowchart of the MPPT P&O algorithm utilized in the system

2.2.5. Load side

On the load side of the system, a resistive load is used as 6 Ω in the system, powered by the PV panel during times of high solar irradiance and by the battery at other times. The load operates with a constant bus voltage of approximately 48 V, drawing a current of about 20 A.

3. Simulation Modeling

In this study, we have utilized the MATLAB/Simulink environment for system simulation, comprising four structures as depicted in Figure 8: the primary circuit, measurement blocks, the PV control block, and the battery control block. The parameters of the circuit elements utilized in the system are provided in the tables above. Real solar radiation data from the geographical information system, along with input values, were input into the PV system under a constant temperature of 25°C. The load in the system is powered by the energy received from the panel and the DC load. During periods of insufficient solar radiation data, the system draws energy from the battery. Algorithm was implemented in MATLAB's editor according to the algorithm for the MATLAB Function used for MPPT control in the system.

4. Findings and Discussion

The entire system was modeled and simulated in MATLAB/Simulink. Simulink's built-in blocks simulated each component. An internal lithium-ion battery model represented the batteries used for energy storage. Variables such as solar irradiance, bus and reference voltages, battery state of charge, bus and reference currents, PV panel current, PV panel power, and PV panel voltage were monitored through the measurement blocks based on the irradiance values throughout the day.

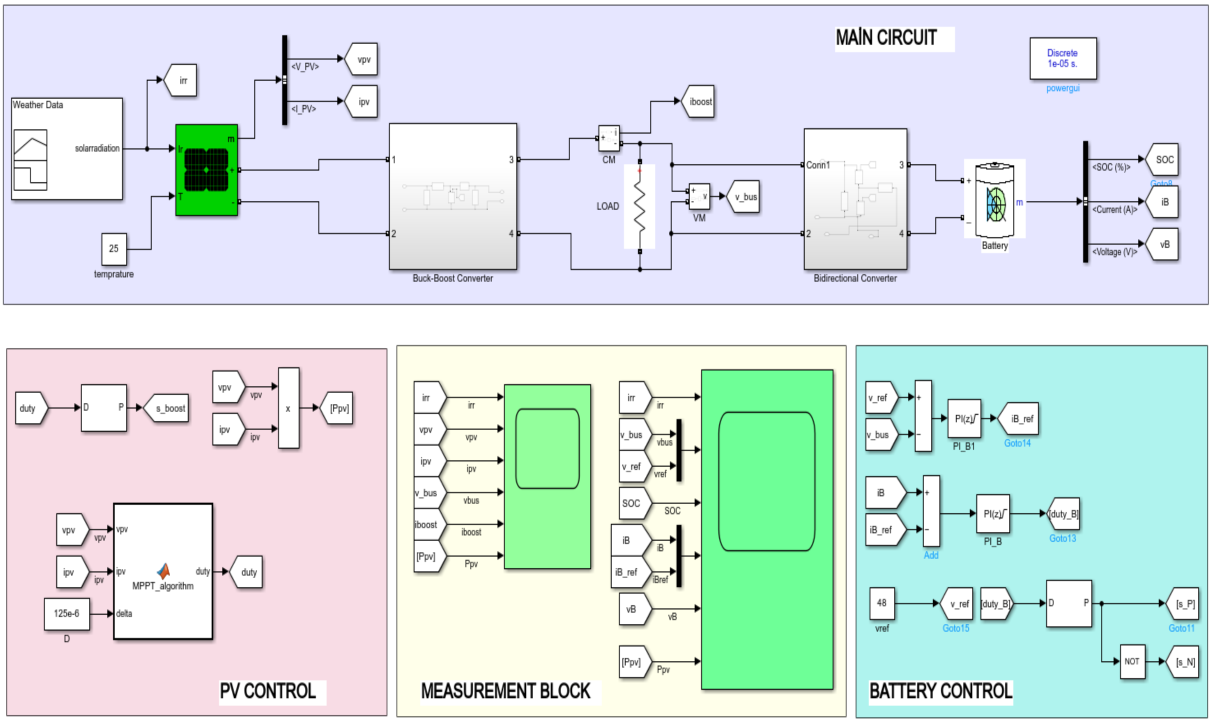


Figure 8. Simulation scheme of the system

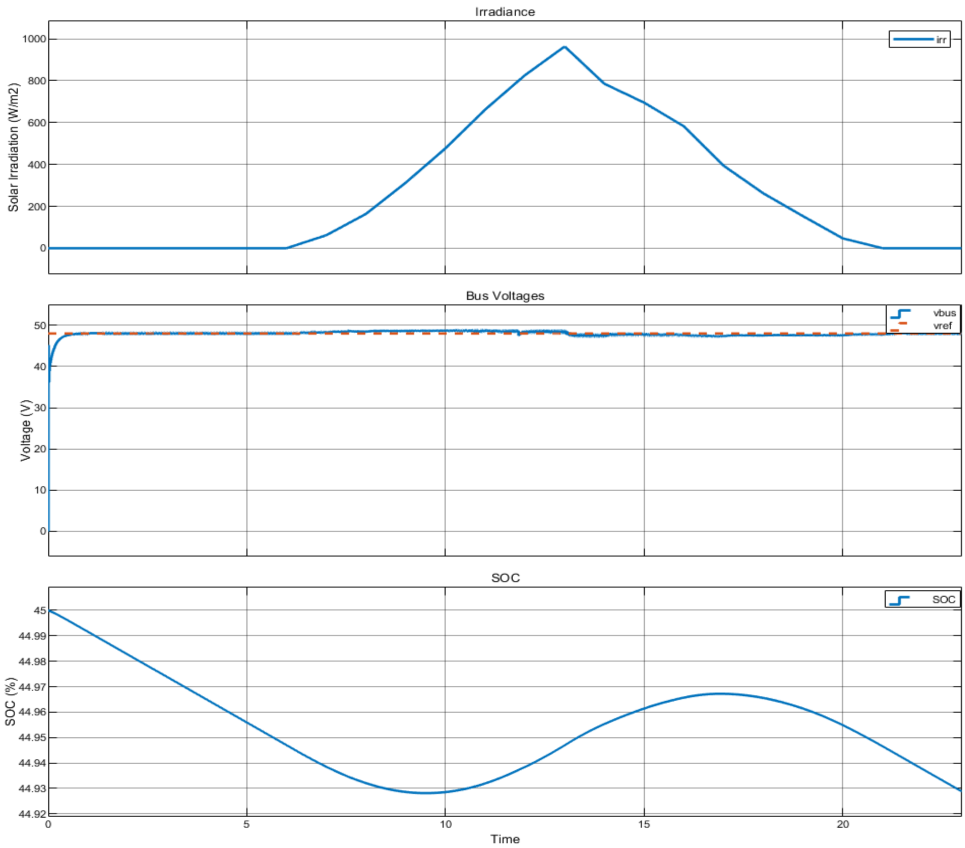


Figure 9. Solar irradiance, bus voltage, and battery charging status

In Figure 9, solar irradiance data peaks at 13:00, at which time there is an oscillation in the voltage value. Additionally, our battery, which powers the load during periods without solar irradiation, reaches its full charge level at 13:00 as the solar irradiation increases. Afterwards, it begins to supply power to the load again. This cycle continues in this manner.

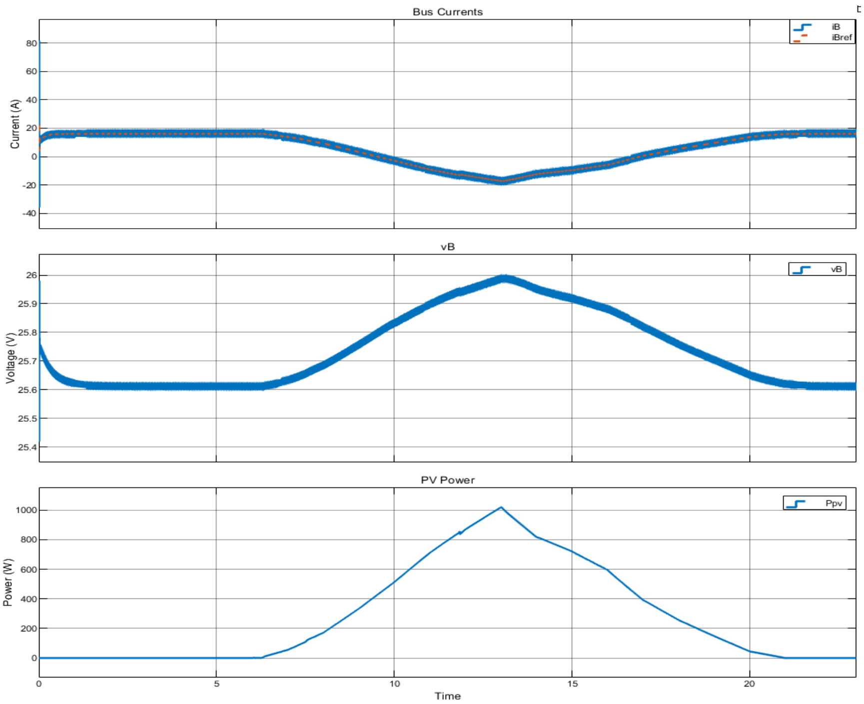


Figure 10. Bus currents, bus voltages, and panel power graphs

In Figure 10, when the solar radiation value is at its maximum, the panel power has also reached its peak, thanks to the MPPT controller. During the periods when the current graph is negative, the battery is charging. At other times, the battery discharges to supply the load. During periods without solar irradiation, the battery supplies power to the load, causing the bus voltage to decrease.

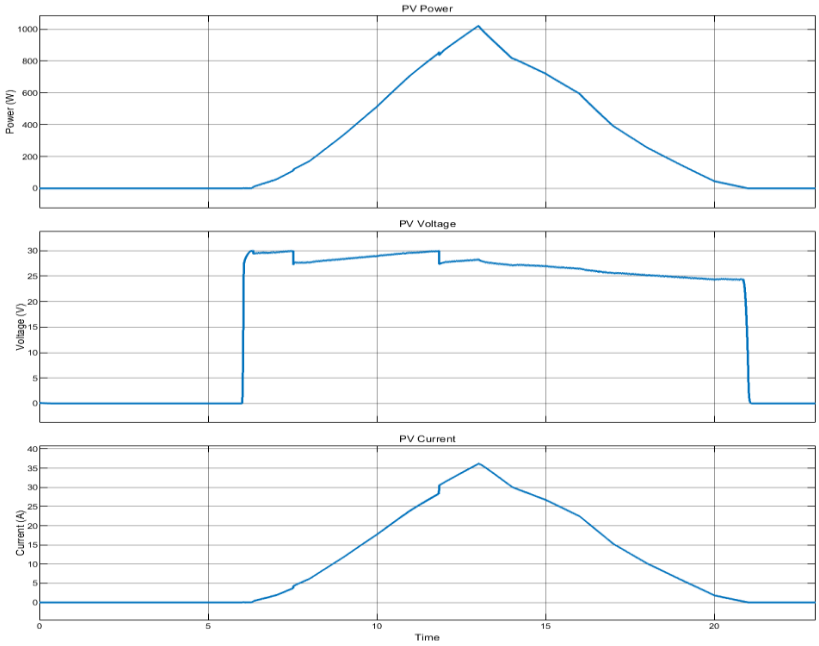


Figure 11. Panel current, voltage, and power changes

In Figure 11, the panel voltage remains constant at 30 V from the beginning to the end of the solar radiation period. The fluctuations at specific points are attributable to the limitations of the control algorithm. The panel current completes the daily process by following a parallel path with the solar irradiance values.

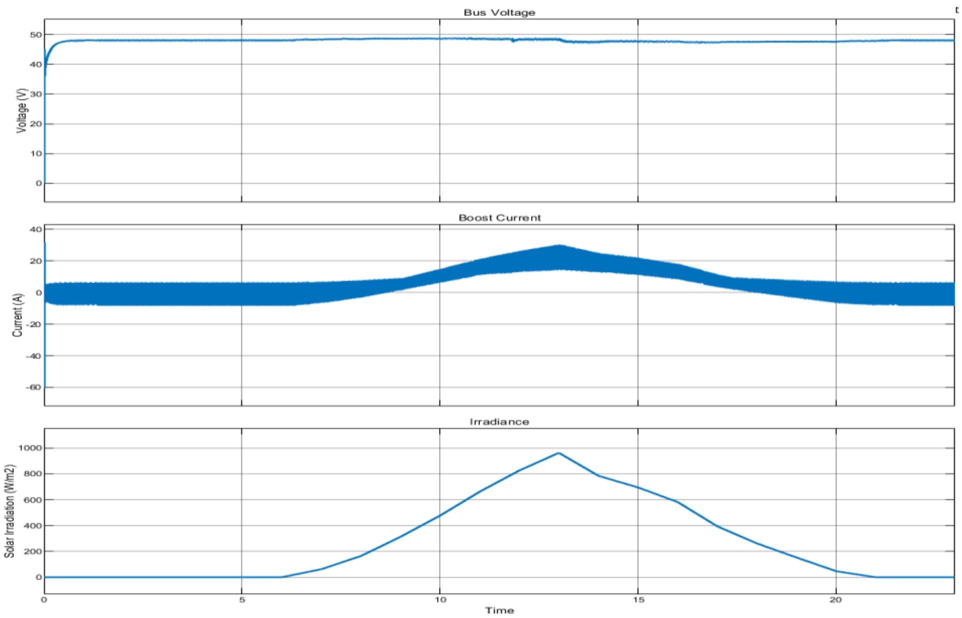


Figure 12. Load current and voltage variations

Figure 12 illustrates the current and voltage values passing through the load. The voltage quickly stabilizes at 48 V, which is essential for the load's operation in terms of voltage stability. The current value remains within specific ranges in parallel with the solar radiation values received by the panel. When the above results are analyzed, the voltage and power values obtained from the panel, in accordance with the hourly changing solar radiation values, exhibit similar graphical characteristics. However, these variable values are not ideal for the electric load. At this juncture, the MPPT control technique comes into play, facilitating efficient operation by maximizing the constant bus voltage and current values required by the electrical load. When there is no electricity generation from the PV panel, the demand load is satisfied by enabling a bidirectional current flow from the battery.

5. Conclusions

In this study, a system consisting of a battery energy storage system (BESS), a bidirectional DC-DC converter and a PV panel with MPPT control technique is modelled and simulated. A DC-DC converter using MPPT control algorithm is designed and modelled to increase the output power of the PV panel. MPPT techniques are implemented using a P&O algorithm. The simulation utilizes real daily insolation data from a villa in the Enez district during the summer period. The simulation results show that the proposed MPPT control prevents the BESS from overcharging, maintains a safe state of charge, and operates with zero wasted energy. Additionally, a battery charging algorithm that regulates the power supply from the battery and the state of charge is implemented. Operating at a constant voltage of 48 V, the load is powered throughout the day. This study contributes by demonstrating constant voltage and maximum power output under varying solar conditions. In other studies, within the literature, grid-connected systems lacking backup systems and sufficient control techniques are examined. This study addresses all these shortcomings and is designed to ensure an uninterrupted constant energy flow. Consequently, the electrical energy required by an off-grid detached villa is supplied in a controlled manner, eliminating all potential drawbacks. These results confirm that the MPPT control strategy enables stable, uninterrupted energy supply for off-grid applications.

6. Author Contribution Declaration

Fikret KAYA contributed to the conception, methodology, literature review and sourcing; Alper Nabi AKPOLAT contributed to the formal analysis, data development and results review; Onur AKAR contributed to the content, evaluation of the results, correction of the methodology, results review and checking of the manuscript.

7. Ethics Committee Approval and Conflict of Interest Statement

Ethics committee approvals are not necessary for the article. There is no conflict of interest with any institution/person in the article.

8. Ethical Statement Regarding the Use of Artificial Intelligence

In this study, no artificial intelligence (AI) tools or applications for preparation, editing, translation, or any other process. All content was created by the author(s) following scientific research methods and adhering to academic ethical principles.

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