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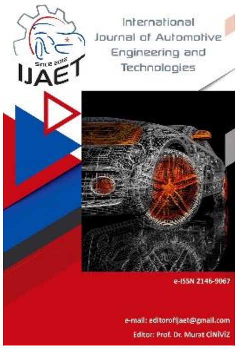

Original Research Article

Solar-powered off-grid charging station design for electric vehicles

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ABSTRACT

In today's world, the increase in Greenhouse Gas (GHG) emissions into the atmosphere, as well as the natural result of the global warming issue, have detrimental consequences. It is known that gas emissions such as CO_2 should be reduced in order to reduce these effects. Internal combustion engines (ICE) that use fossil fuels play a major part in the release of these harmful emissions into the environment in today's transportation industry. For this reason, in order to achieve a cleaner environment, it is aimed to increase the number of Electric Vehicles (EVs) by completely removing fossil fuel vehicles from the market. Thus, it is expected that harmful gas emissions such as CO_2 will reduce considerably and the impact of such hazardous GHG in the transportation industry will be minimal. However, it is known that as the number of EVs grows, the energy demand for the electricity grid will increase and some grid problems will occur. Morever, it is well recognized that as the number of EVs grows, so will the energy demand for the electricity grid, causing potential grid difficulties. This study proposes a clean, environmentally friendly, renewable EV charging station approach to overcome potential grid issues. This system comprises a renewable energy source Photovoltaic (PV) based, off-grid, EV charging model with its own storage system, in rural areas where there is no/insufficient electricity grid or where grid load needs to be minimized. This model is simulated in MATLAB, and the findings are presented graphically.

Keywords: Electric vehicles (EVs), Photovoltaic (PV), Charging station, DC-DC converter, Renewable energy, Off-grid

1. Introduction

Increased air pollution, depletion of energy sources, and challenges such as global warming all represent a threat to human and environmental health in modern world. In parallel with the increasing world population, there are rapid developments in the vehicle industry sector. It has become essential to seek solutions to existent and potential challenges in order to protect the health of living things and the environment and to ensure long-term energy availability [1]. To assist in the solution of these challenges, it is expected that the usage of ecologically friendly and more efficient EVs, rather than traditional fuel vehicles, will become more widespread [2]. However, despite rise in EVs, the deficiencies in the infrastructure of EV charging stations and the long charging times limit the prevalence of EVs [3].

EVs provide high efficiency, reduced noise and

negligible emission advantages [4]. EVs can be classified as Battery EVs (BEV), Hybrid EVs (HEV) and Fuel cell EVs (FEVs) [5]. Since BEVs get their power from the batteries, these batteries need to be charged [6]. EVs, unlike ICE vehicles, do not release any GHG and are a smart way to reduce dependence on the environment [7].
EVs are the future of transportation since they substantially minimize the consumption of fossil fuels. EVs are being promoted in both developed and developing countries as a way to improve energy efficiency and green energy technologies. Solar energy is one of the most environmentally friendly ways to charge an EVs battery [8]. Solar energy production is possible in two ways: thermal sourced production and Photovoltaic (PV) sourced generation. However, PV panels, on the other hand, are the most common method as it's less costly [9]. Some literature on renewable EV charging station models are given in Table 1.
In this study, an environmentally friendly, renewable energy sourced, PV-based off-grid EV charging station has designed for EVs. The designed EV charging system consists of PV panels, boost converter, Maximum Power Point Tracker (MPPT) algorithm, bidirectional converter, and backup batteries (battery storage system). The EV charging system has increased the voltage generated by the PV panel by using the MPPT controller through the boost converter. Next, the boosted voltage is directed to a DC bus. The system controller placed at the DC bus output performs switch control by taking measurements by the EV, battery storage system, and panel connected to the system. In cases where solar radiation is sufficient, both the EV battery and the backup batteries of the system (battery storage system) are charged, with the priority being the EV battery. In cases where the solar radiation is low, the power demanded by the EV battery is insufficient. Thus, in this case, the pre-charged backup batteries sends the required power demand to the EV battery via the bidirectional converter.

Table 1. Some literature on renewable EV charging station models

Source type	Grid connection status	Application area	Technical specifications	Ref.
PV	On-grid	Car park	500 V - DC	[10]
PV	On-grid	Housing	220 V - DC	[11]
PV	On-grid	Workplace	750 V - DC	[12]
PV	On-grid	Car park	540 V - DC	[13]
PV	On-grid	Car park	400 V - AC	[14]
PV+hydrogen +wind	Off-grid	Car park	540 V - DC	[15]

2. PV System Components

The main components are shown in Fig. 1.

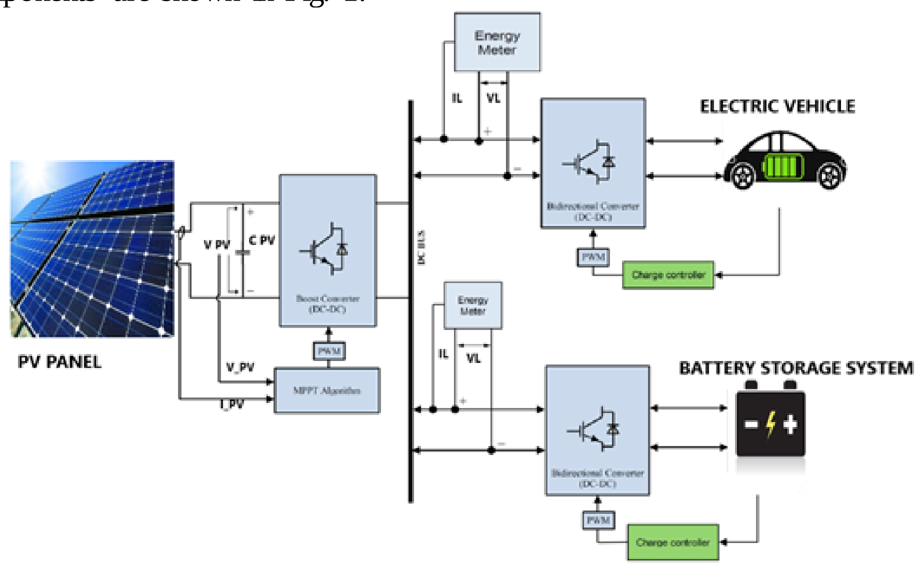

Figure 1. Main components of PV-based off-grid EV charging system

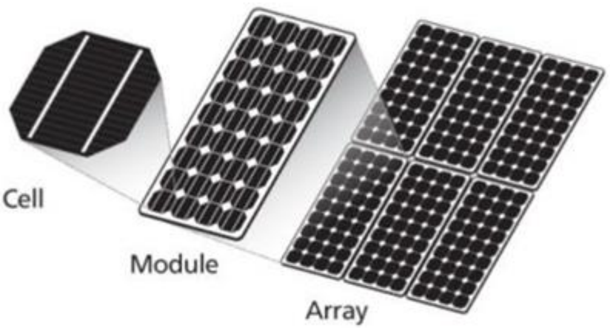

Figure 2. The components of a solar array [17]

2.1. PV Panel

PV panels are made up of a large number of PV cells, which are semiconductor-based components that create electricity using the energy they receive from the sun. The cells convert the sun rays, called photons, into Direct Current (DC) electrical energy with the help of the semiconductor material they contain. They have extremely thin layers that can only be measured using a micrometer. Their shapes are generally square, rectangular or circular, and their area measures are around 100 cm^2. Since a single PV cell produces so little energy, the cells are connected in series or parallel to form modules, and the modules are then combined to form panels. They connect the panels together to form a solar PV array so that the electricity produced is even more [16]. The components of a solar array are shown in Fig. 2.

The most important feature of PV panels is that they are made of non-moving parts, so they work silently and their maintenance needs are at a minimum level. When these systems are compared with other production methods in terms of energy production, they are at the lowest level in terms of negative effects on the environment and human health. In areas where the electricity distribution network does not reach and which is costly to reach, off-grid systems are used to supply the electricity need, as well as on-grid systems that are used as backup or support to the grid in areas where the electricity grid is available [18, 19]. The comparison of the effects of electricity generation methods is shown in Table 2.

The efficiency of PV systems depends on factors such as the level of solar radiation, the temperature of the cells and the load condition. As shown in Fig. 3, the PV panel characteristic is defined as the Current-Voltage (I-V) characteristic. The intensity of solar radiation is expressed in Watts/m^2. Short-circuit current I_{SC} and open-circuit voltage V_{OC} are important points in the characteristic and at these two points the PV panel power is equal to zero. The MPP point of the PV system is the point where the zero slope is on the I-V curve, and the value of current and voltage at this point constitutes the maximum power [20-22]. I-V characteristic of a PV cell is shown in Fig. 3.

Table 2. Comparison of the effects of electricity generation methods [19]

	Acid contamination	CO_2	CH_4	Human health and safety.	Heavy metals	Disaster	Waste material	Visual pollution	Noise	Space requirement
Passive solar energy	0	0	0	0	0	0	0	1	0	0
Photovoltaic	0	0	0	0	1	0	1	1	0	1
Wind power	0	0	0	0	0	0	0	3	1	1
Biomass	1	0	3	1	1	0	1	1	1	3
Geothermal	1	1	1	1	1	0	2	1	1	0
Hydroelectric	0	0	0	0	0	2	0	3	0	3
Tidal energy	0	0	0	0	0	1	0	3	0	1
Wave energy	0	0	0	0	0	1	0	1	0	0
Coal	4	4	2	1	2	1	2	2	1	3
Oil	3	4	1	1	1	2	1	1	0	1
Natural gas	1	4	1	1	1	2	1	1	0	1
Nuclear	1	1	0	1	0	3	3	2	0	1

0: Negligible **1:** Negligible/ Important **2:** Important **3:** Important /Large **4:** Large

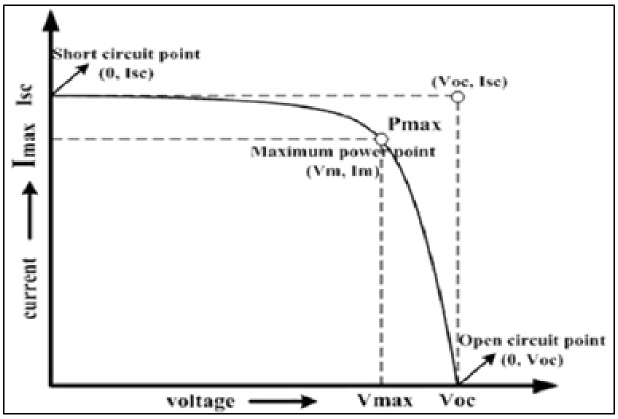

Figure 3. I-V characteristic of a PV cell [23]

In Fig. 4, a solar panel with PV cells in series or parallel is illustrated, providing solar energy to be converted into DC electrical energy. The solar cell equivalent circuit consists of a parallel current source, a diode, a parallel resistor and a series resistor [24, 25]. A PV panel equivalent circuit is shown in Fig. 4.

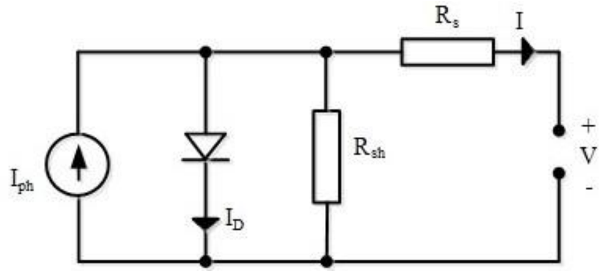

Figure 4. PV panel equivalent circuit [25]

$$I_D = I_0\left(e^{\frac{qVD}{AkT}} - 1\right) \quad (1)$$

$$I_{ph} = I_0\left(e^{\frac{q(V_{ph}+I.R_s}{AkT}} - 1\right) + \frac{V+I.R_s}{R_{sh}} \quad (2)$$

where, R_s is the series resistor, R_{sh} is the parallel resistor, I_{ph} is the current created by the photon, I_D is the diode current, I is the short-circuit current, I_0 is the reverse saturation current, V or V_{ph} is open-circuit voltage, V_D is the diode voltage, A is the diode factor [25].

2.2. DC-DC Boost Converter

In MPPT control approaches, boost type converters are often used. This type of converter is used for controlled boosting of the input voltage. The boosting process is determined according to the duty cycle of the switching signal applied to the switching element (MOSFET) [26].

The basic circuit model of the converter, which boosts the voltage applied to its input at the desired output, is shown in Fig. 5. DC-DC boost converters allow the instantaneous use of the energy produced in PV panels because the switch draws current from the source both when it is on and off state, thus they are widely used in PV systems [27, 28]. Basic circuit model of DC-DC boost converter is shown in Fig. 5.

The electrical energy obtained from solar panels varies during the day. However, depending on the type of load from solar systems, it is expected to give a constant output voltage. In order to provide this demand, a converter must be used. The structure of the converter to be used in the system is determined by the difference between the input voltage *(V_i)* obtained from the solar panels and the output voltage *(V_0)* of the converter. Thus, in this study, a boost converter is used so that the voltage produced by the solar panel can be higher at the output.

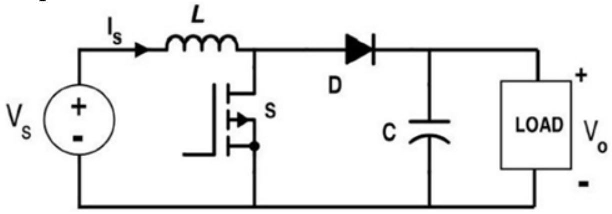

Figure 5. Basic circuit model of DC-DC boost converter [29]

Power values at input and output are given in Eq. (3) and Eq. (4);

$$P_{IN} = \left[\frac{(I_{max}+I_{min})}{2}\right] V_s \quad (3)$$

$$P_{OUT} = \frac{V_0^2}{R} = \frac{V_s^2}{(1-D)^2} R \quad (4)$$

Where, D is the fill rate, R is the load resistor, I_{max} is the maximum current, I_{min} is the minumum current, V_0 is the load voltage, V_s is the source voltage [29].

2.3. MPPT controller

MPPT is a control algorithm that extracts maximum power from the PV module and transmits maximum power from the PV module to the load. MPPT, in general, are electronic systems that change the electrical operating point of the module so that the modules can provide the maximum usable power [30].

Many MPPT algorithms are employed in existing applications, with the Perturb and Observe (P&O) algorithm being the most widely used. This method does not use physical hardware or a mechanical structure, but rather electronic hardware that monitors the PV system's current and voltage values and utilizes an algorithm structure to control the voltage at the output. In the PV characteristic curve shown in Fig. 7, the points dP/dV=0 or dP/PI=0 where the slope is zero are defined as the MPP. Projections of the MPP to the power, voltage or current axes represent PMPP, VMPP, and IMPP values [20]. Power curve of the PV panel is shown in Fig. 6.

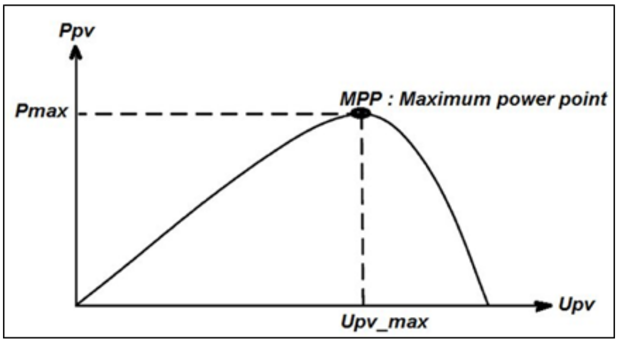

Figure 6. Power curve of the PV panel [31]

The P&O algorithm is based on the principle of monitoring the calculation of the change in power by sampling the PV panel current and voltage values. Perturb & Observe (P&O) algorithm is shown in Fig. 7.

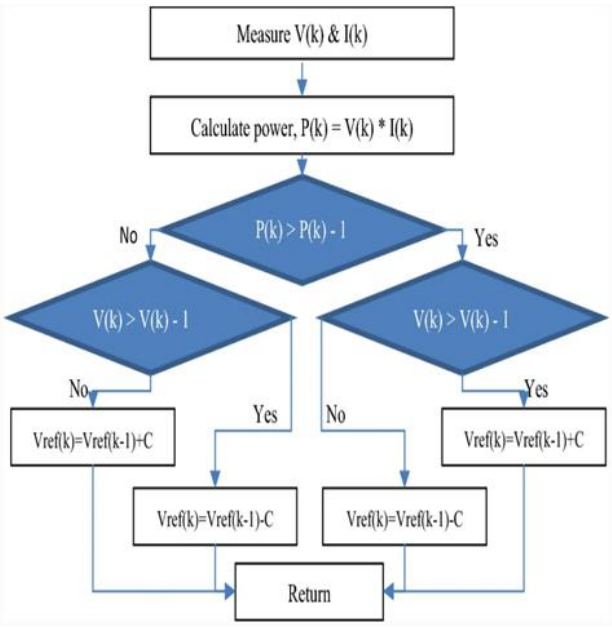

Figure 7. Perturb & Observe (P&O) algorithm [32]

3. Solar-Powered Off-Grid EVs Charging System

This section presents solar-powered off-grid EVs charging system. PV panels, boost converter, MPPT algorithm, bidirectional converter, and backup batteries (battery storage system) are all part of the proposed EV charging system. In the first stage of the system, solar energy is converted into electrical energy by using PV panels. In the second stage, the voltage is increased by MPPT controller and boost converter. In the third stage, the boosted voltage is sent to a DC bus. In the fourth stage, it is a system controller placed at the DC bus output that performs switch control by taking measurements by the EV, battery storage system, and panel connected to the system. MATLAB model of the EV charging system is shown in Fig. 8.

It has been observed in the literature that EV batteries are determined as 48V, 100Ah on average, and charging processes are carried out with 16A output current. Thus, in this study, considering these values, a 3.9kW charging station with 240V, 16A was designed.

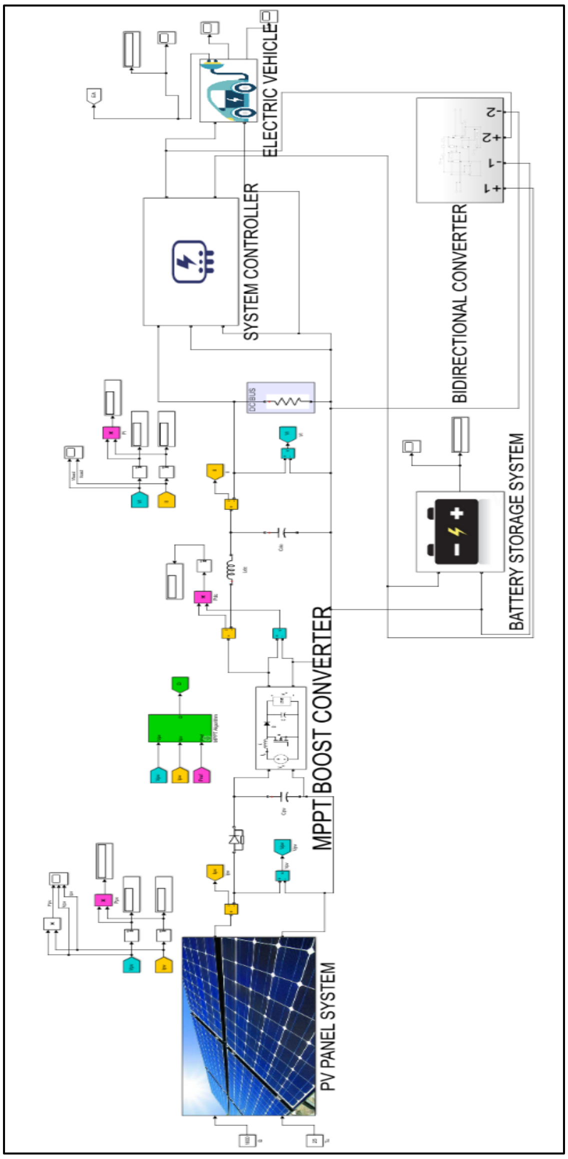

Figure 8. MATLAB model of the EV charging system

Panels with a maximum power of 340 W are used in the system. PV panels were selected from the panel library in the MATLAB and the panel parameters are given in Fig. 9.

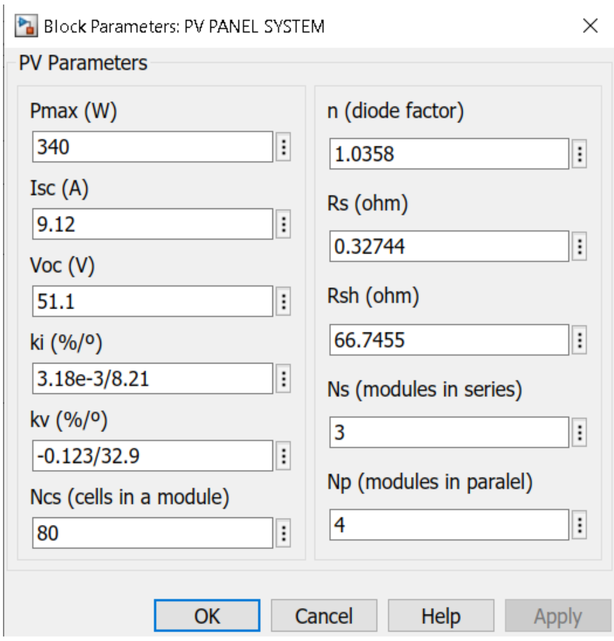

Figure 9. PV panel parameters

PV panels are composed of 3 series and 4 parallel strings and are 12 in total. The power value produced by the system is 340 W * 12 = 4080 W. The power value at the panel output was approximately 4039 W due to the panel resistance values, and the voltage and current values were observed as 125 V and 32 A, respectively. The power, current and voltage parameters of the PV panel output are shown in Fig. 10.

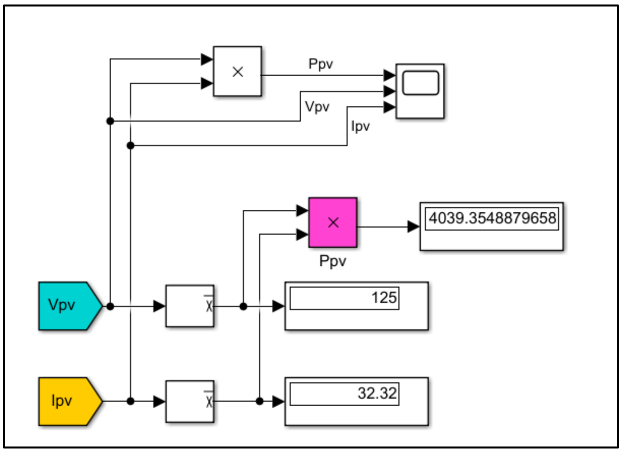

Figure 10. The power, current and voltage parameters of the PV panel output

The MPPT point must be identified in order to transfer power from the panel output to the boost converter completely and reliably in the system. Thus, MPPT point tracking was performed with the P&O method. The PWM control of the boost converter was also provided with this method. MATLAB diagram of MPPT system and MATLAB model of MPPT P&O method are shown in Fig. 11 and Fig. 12, respectively.

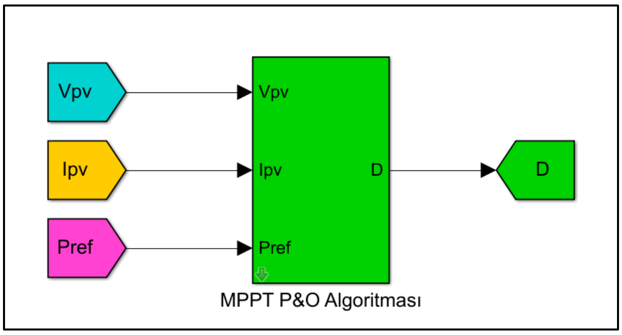

Figure 11. MATLAB diagram of MPPT system

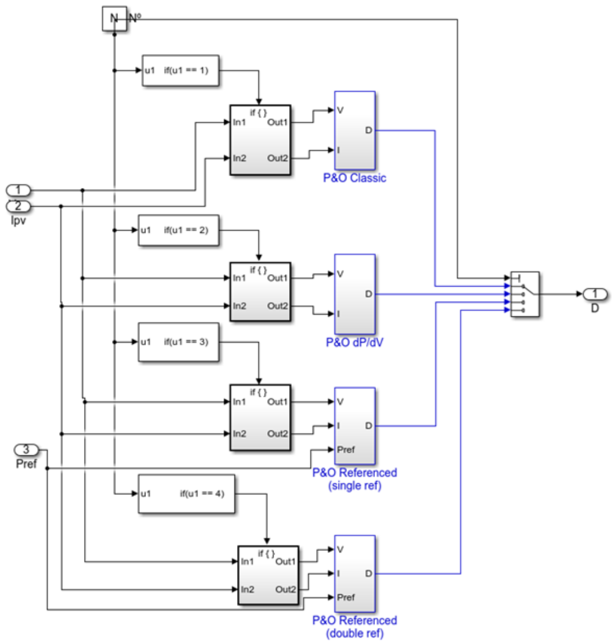

Figure 12. MATLAB model of MPPT P&O method

The boost converter is switched with the signal received from the MPPT output. The MATLAB model of the boost converter is given in Fig. 13.

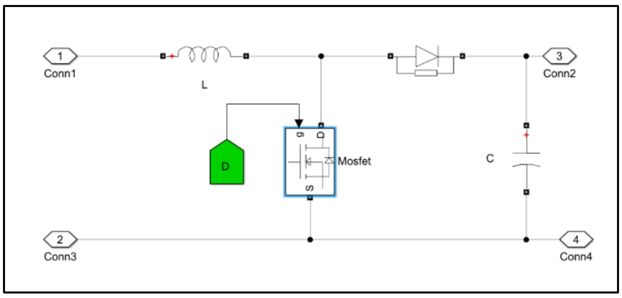

Figure 13. MATLAB model of boost converter

The boost converter is designed to charge the EV and battery storage system via the DC bus by increasing the 125 V applied to its input to 240 V. The values measured from the DC bus at the boost converter output are shown in Fig. 14. A control system is modeled for the PV system to control the charge and operate the system efficiently. The system controller measures the battery charge rates to manage the EV charging system and the battery storage system, then manages the charging priority with the help of switches according to this measurement status. This part consists of logic circuits and switches that make on-off. MATLAB model of the system controller is shown in Fig. 15.

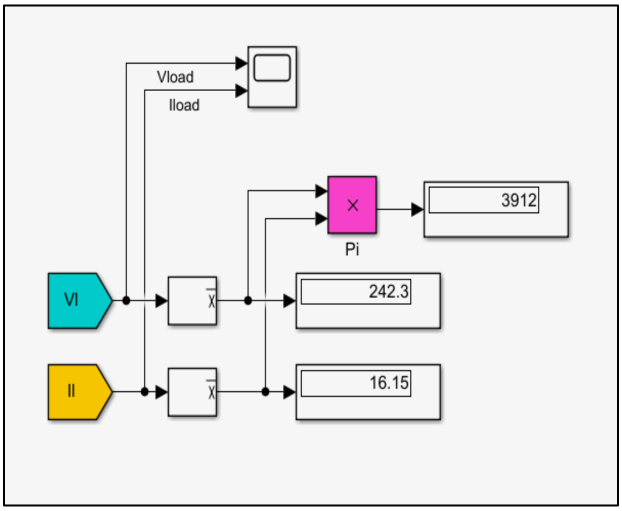

Figure 14. Voltage and current values at boost converter output

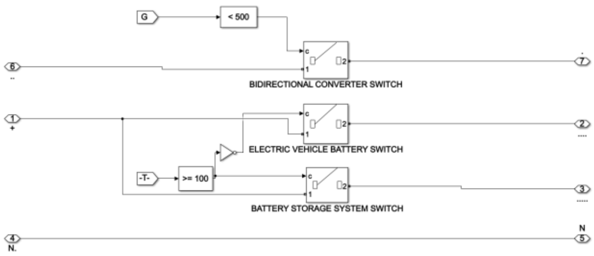

Figure 15. MATLAB model of the system controller

3.1. Operating cases of the EV charging model

In order to monitor the performance of the designed EV charging model, performance analysis was carried out by establishing three distinct operating cases.

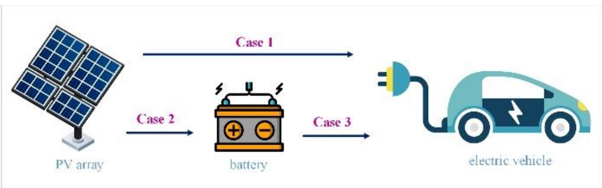

Figure 16. Operating cases of EV charging model

3.1.1. Case-1

In Case-1, once an EV is connected to the system, the charge level of the EV battery is first measured, and if the charge state is less than 100%, the charging operation for the EV battery begins. In this study, the charge rate of the EV battery was determined as 20% and the system started to charge the EV battery. The EV battery charge voltage is 51.85 V and the current value is 31.83 A. The EV battery was simulated for 5 seconds and the SOC value increased from 20% to 20.044%. The time required for the EV battery to be fully charged is approximately 2.5 hours. EV battery parameters (Case-1) is shown in Fig. 17.

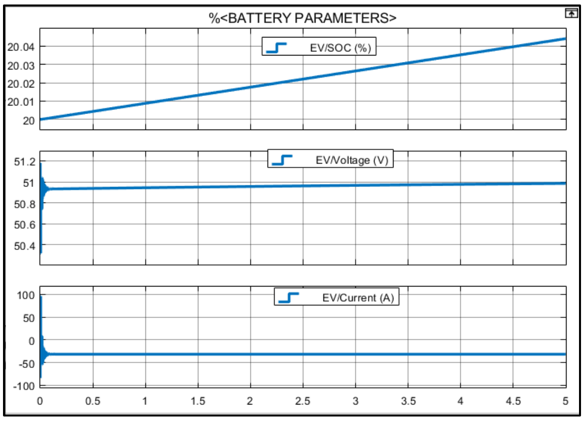

Figure 17. EV battery parameters (Case-1)

3.1.2. Case-2

In Case-2, backup batteries (battery storage system) are charged with the energy produced by the PV system. That is, if there is no EV waiting to be charged in the system or the EV battery is fully charged, the system controller charges the battery in the battery storage system. EV battery parameters (Case-2) is shown in Fig. 18.

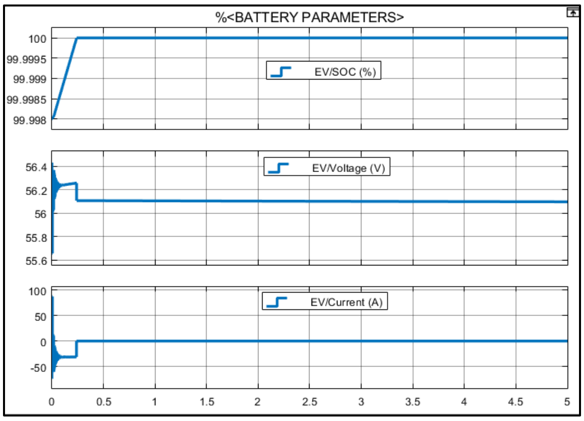

Figure 18. EV battery parameters (Case-2)

The battery charge rate of the storage system has been determined as 60% and the system has started to charge the storage battery. A 99% EV battery charge rate is provided to validate the system. The system has ended the EV charging process once the simulation is completed and the EV battery charge reaches 100%. Thus, the storage system battery started to charge and reached from 60% to 60.04% in 5 seconds. The time required for the storage system to be fully charged is approximately 1.38 hours. Storage system battery parameters (Case-2) is shown in Fig. 19.

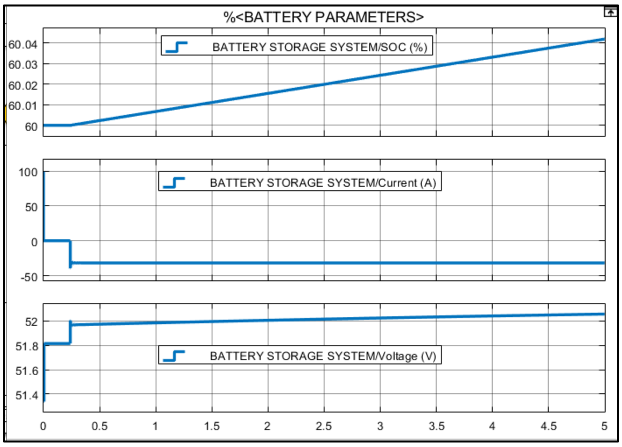

Figure 19. Storage system battery parameters (Case-2)

3.1.3. Case-3

In Case-3, once the PV system is unable to energy generation due to weather conditions, the EV battery is charged by the storage system's system controller via a bidirectional converter. In this system, the storage system battery charge rate is 100% and the EV battery charge rate is determined as 50%. The storage system battery began to discharge and the EV battery began to charge once the simulation was run. The storage system in discharged state (Case-3) and the EV battery in charging state (Case-3) are shown in Fig. 20 and Fig. 21, respectively.

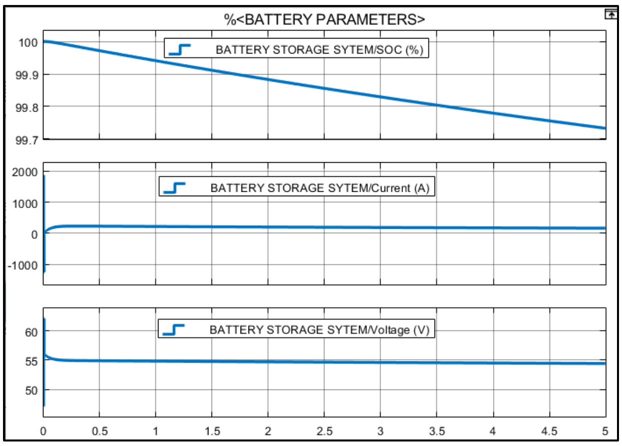

Figure 20. Storage system battery in discharging state (Case-3)

4. Conclusion

Today, it is known that increasing the number of EVs by reducing the ICE vehicles in traffic will be a smart alternative to reduce GHG and global warming. However, the charging process of those vehicles would impose additional loads on the power system network, and their power demands would change throughout the day. This circumstance may cause major problems for the power system network. Renewable energy-based charging station models can offer an alternative and environmentally friendly solution in order not to encounter such problems and to charge the EV battery in rural areas and places where it is difficult to reach the electricity grid.

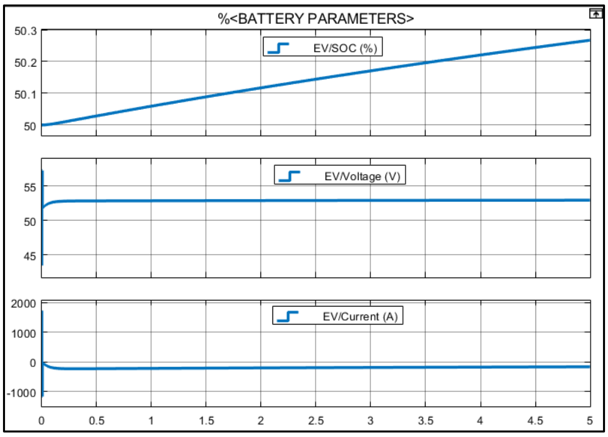

Figure 21. EV battery in charging state (Case-3)

In this study, a solar-powered off-grid EV battery charging system is modeled by using MATLAB/Simulink. The designed system is attractive to residents and places in rural areas without access to the grid. In addition, this system is a completely environmentally friendly, clean and sustainable model. Three distinct operating cases (Case-1, Case-2 and Case-3) have been designed to observe the charging performance of the system. In Case-1, the EV battery is charged with the energy produced by the PV panel. In Case-2, the EV battery is fully charged, so the system starts to charge the backup batteries (battery storage system). In Case-3, the EV battery is effectively charged with the energy in the battery storage system, while there is little or no sun radiation. The charging capabilities of this designed system have been successfully demonstrated in three different operational cases.

In future studies, hybrid (eg PV + wind) charging models including Artificial Intelligence (AI) and smart grid can be modeled.

CRediT authorship contribution statement:

Alper Kerem: Investigation, Writing,

Visualization, Supervision, Conceptualization, Methodology, Formal analysis, Validation. Nurettin Doğan: Writing - original draft, Software, Methodology, Visualization, Validation, Resources. Ahmet Serdar Yılmaz: Supervision, Project administration, Review & Editing.

Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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