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Designing a Solar PV−Battery based on Electric Vehicle Charging Station

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ABSTRACT: Increasing transport demand necessitates higher oil consumption, resulting in an increase in carbon dioxide (CO2) emissions, which is a major cause of air pollution. The use of electric vehicles (EVs) is becoming more common around the world. Recent advancements in lithium-ion battery technology have increased the improvement of EVs. In this work, a solar photovoltaic (PV) battery-based EV charging station is designed. Meanwhile, the overall system comprises a battery energy storage system (BESS), solar PV module, grid and EV charging station. Thus, the primary source for the charging station is the PV source but due to less power during the night, we included battery storage as a backup. Grid source is also recommendable for an uninterruptable power supply. An artificial neural network strategy is developed in MATLAB/Simulink for proper power management of the solar PV-battery based EV charging station connected to the AC grid. Moreover, by employing an adaptive neuro-fuzzy inference system (ANFIS) and PI controller-based MPPT, the grid voltage and current, real/reactive grid power and the maximum output power are obtained. The overall system is evaluated under different scenarios of irradiance level and temperature with a state of charge (SOC) greater than 10 % for simulation purposes. The result shows that during the night hour due to less power from the PV source, an artificial neural network begins to regulate the grid power so that it supplies power to the stationary storage and EV battery.

Keywords: Solar PV, Electric vehicle, Stationary storage, ANFIS MPPT, PI controller, Neural network.

1. INTRODUCTION

Nowadays, EVs are gradually replacing typical IC engines [1, 2]. For instance, IC engines have several disadvantages, for example, high greenhouse gas (GHG) emissions that can be resolved by EVs. As mentioned in Ref [3], EVs promise more environmentally friendly, noise-free operation, greater energy efficiency and require less maintenance than IC engines. Additionally, renewable energy sources (RES) should be employed in EVs to provide electrical power to meet growing future needs. Amongst the different RES available such as; the solar PV system, fuel cell-based generation, hydropower and wind energy, solar PV generation is the most useful option for EV charging since it's available nearly everywhere regardless of whether the location is urban or rural [4-6].

Most of the research papers focus on issues like; (1) grid-connected solar PV based EV charging stations. (2) fast charging stations and control approaches for solar PV with AC grid. (3) an off-grid solar PV based EV charging stations, etc. Ref [7] demonstrated an effective design and power management approach of a PV-battery based EV charging station connected to an AC grid using MATLAB software. Ref [8] focuses on issues like; (1) energy management approach of converter control multi-port EV battery charging from solar PV source. (2) maintaining the dc bus voltage constant during overload in the grid power. (3) reducing the charging time. Ref

[9] demonstrates the design features and application of a modern PV-based level-2 EV charging station regulated by a type-1 vehicle connecter using MATLAB and PROTEUS software. In Ref [10], the authors present a charging station strategy for fast DC charging using MATLAB software. Moreover, a DC bus is developed by connecting to the power grid through converter. Then the converter was developed to such a degree that the power factor was close to unity and the line current harmonics are maintained to a minimum. Ref [11] proposed, designed and presented an off-grid charging station for EV and hydrogen vehicles (HV) using GAMS and MATLAB software. In addition, both EV and HV are charged simultaneously. Ref [12] investigates an ideal PV-based EV charging station design from a technical and economical perspective under various irradiance using HOMER software. Ref [13] proposed an ideal charging and discharging management technique of V2G, G2V and BESS for EV charging station using a demand response (DR) program. It suggested that it's possible to reduce the challenges of an optimization problem by using a distributed computing system.

In this study, a solar PV-battery based EV charging stations connected to an AC grid has been designed. The characteristics of the implemented system, which employs ANFIS+PI controller-based MPPT, are specified in Table. 1. In addition, the entire model was simulated with different scenarios of irradiance level and temperature. At maximum irradiance, the PV power provides power to the stationary storage and EV battery. Then, the stationary storage discharges to fulfill EV demand when the PV power is low, especially during the night. Moreover, a neural network was developed in MATLAB for grid control purposes and to guarantee an uninterruptible power supply. Eventually, this paper is structured in such a way. Section 2 presents the system design. The control strategy is discussed in section 3. The simulation result is investigated in section 4. Conclusion remarks are stated in section 5.

2. SYSTEM DESIGN

This work presents a solar PV- battery to charge EVs that employs a boost converter using ANFIS and PI controller. The PV-battery is designed in a system with a 40 Ah lithium-ion battery rated capacity and 300 V open circuit voltage (Voc). Figure 1 represents the overall block diagram of a PV-battery based EV charging station. Hence, the block diagram comprises; (1) a PV module along with the DC-DC converter and MPPT algorithm. (2) stationary storage (BESS) with a bi-directional DC-DC converter and voltage controller. (3) grid supply and (4) EV battery with DC-DC converter.

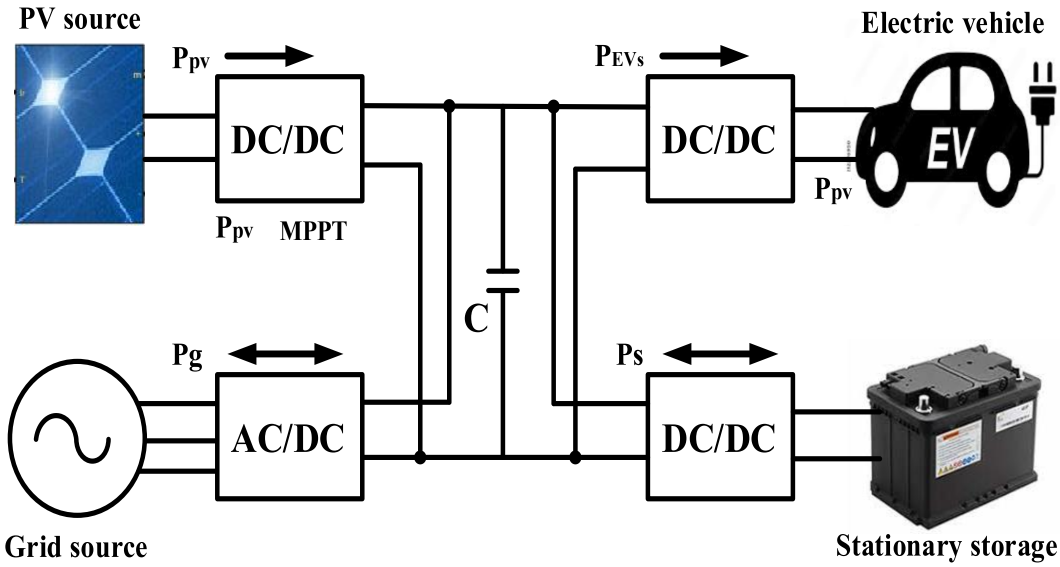

Figure 1. Block diagram of PV-battery based EV charging station.

Thus, the primary source for the charging station is the PV source. Therefore, the power available in the PV goes to charge the stationary storage element and EV battery. If power generation is unavailable in the PV source, the stationary storage provides power to the EV battery. Besides, a grid source is also recommendable for an uninterruptable power supply.

2.1. Photovoltaic Module

Solar systems use PV panels to concentrate solar radiation to generate sunlight into electricity [14]. In this work, the PV system is directly linked to a load (EVs) or stationary battery via DC-DC converter. Hence, the system's operational point is crossing between the I-V curve of the PV and the load line. Normally, these operational points are not at the maximum power of the PV system. Therefore, a neural network-based ANFIS MPPT and PI controller are applied to achieve the maximum power available from the PV array. The generalized circuit diagram of the PV system is represented in Figure 2 and the output current can be given as [15].

$$I_A = N_p I_{ph} - N_p I_s \left\{ exp\left[\frac{q\left(\frac{V}{N_S}+I\frac{R_S}{N_p}\right)}{nKT}\right] - 1 \right\} - \left[\frac{V\left(\frac{N_p}{N_S}\right)+IR_S}{R_{sh}}\right] \quad (1)$$

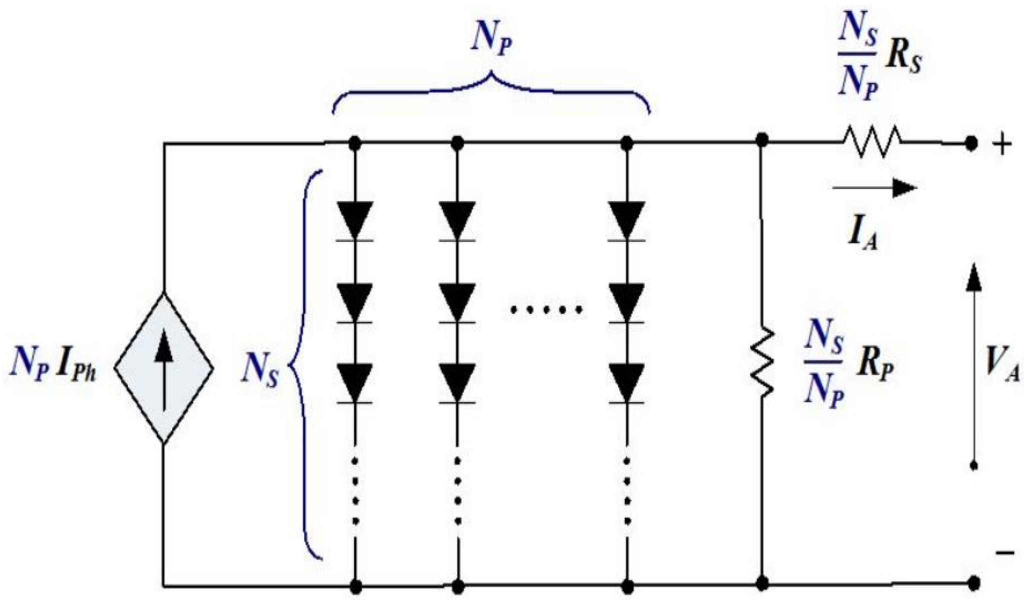

Figure 2. Generalized circuit diagram of the PV array [15].

where N_s and N_p are the number of cells connected in series and parallel. I_A and V are the PV module output current (A) and voltage (V). I_{ph} is the photon current. I_s is the saturation current equal to 3.2328e-10 A. K is Boltzmann's constant. n is the ideality factor equal to 1.045. q is the number of charges of electrons equal to 1.602e-19 C. R_s and R_{sh} are series and shunt resistance equal to 0.22828 and 47.9694 ohms respectively [16].

Figure 3 represents the I-V and P-V curve of the PV system and maximum output power (P_m) can be given as [17]:

$$P_m = V_m I_m \quad (2)$$

where, V_m is the maximum voltage and I_m is the maximum current.

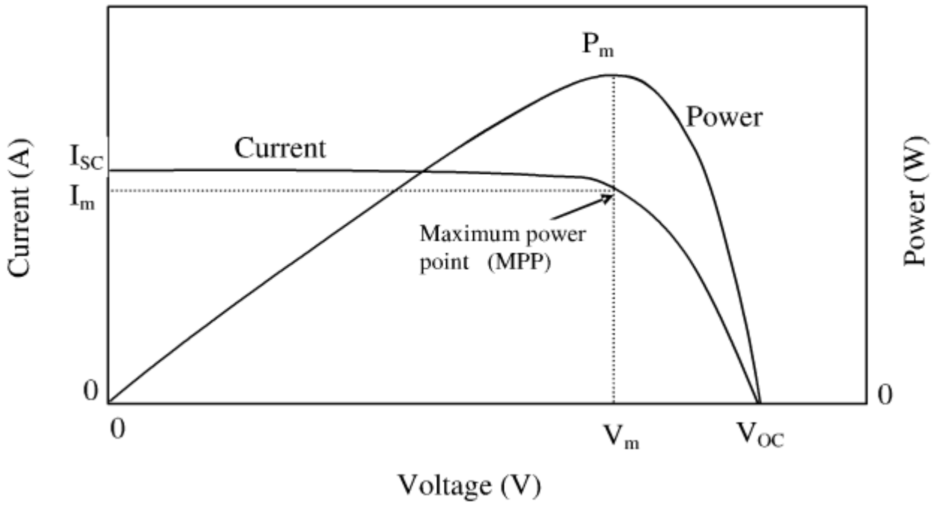

Figure 3. I-V and P-V curve of the PV array [17].

2.2. Stationary Storage with Bidirectional DC-DC Boost Converter

Normally, bidirectional DC-DC converters allow energy storage for the battery [18]. There are two types of bidirectional converters: isolated and non-isolated type [19]. In this work, the power from the PV is stored in stationary storage, which charges the EV battery during the night. Moreover, a 240 V, 40 Ah, li-ion battery is selected for the stationary battery. Equivalent circuit diagram of DC-DC boost converter is represented in Figure 4.

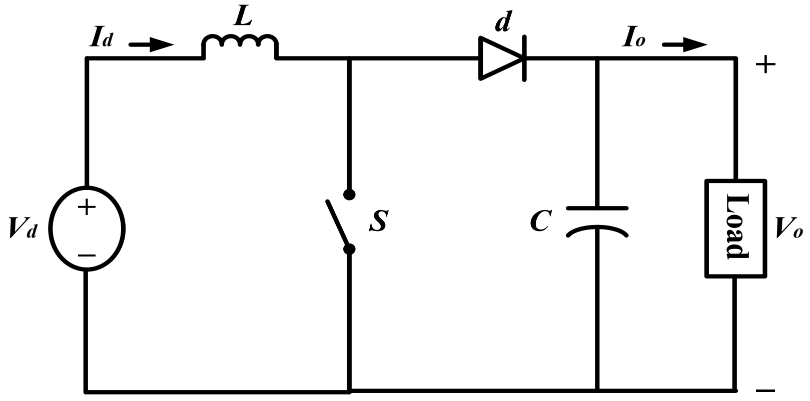

Figure 4. Equivalent circuit diagram of the DC-DC boost converter.

Here, the design of ripple current, inductor and capacitor can be represented as follows:

$$D = 1 - \frac{\eta V_i}{V_o} \tag{3}$$

where D is the duty ratio, η is the efficiency, V_i and V_o are the input and output voltage. Here, ripples current equation will formulated as:

$$\Delta I_L = \frac{D V_i}{L f_s} \tag{4}$$

where f_s is the switching frequency and Inductor (L) is designed as follows:

$$L = \frac{V_i (V_o - V_i)}{\Delta I_L f_s V_o} \tag{5}$$

The capacitor equation can be obtained as:

$$C = \frac{DI_o}{\Delta V_o f_s} \tag{6}$$

where I_o is the output current of the system.

2.3. EV Battery

Batteries are a source of electric power that is used to store electrical energy. Here, the EV battery is considered as a load. Among the different types of rechargeable batteries, lithium-ion batteries are considered in this study. Therefore, a 240 V, 40 Ah, li-ion battery with SOC greater than 10 % is chosen for the EV battery. Hence, the energy in the battery is represented as WH and it's given as follows:

$$WH = V \times AH \tag{7}$$

with EV battery calculated as:

$$EV_{bat} = \frac{V \times SOC \times AH}{100} \tag{8}$$

Where V is the nominal voltage, *SOC* is the initial state of charge and AH (ampere-hour) is the battery's rated capacity.

3. CONTROL STRATEGY

This paper uses an artificial neural network concept for grid control. Moreover, the study uses ANFIS MPPT and PI controllers, to achieve the maximum output power from the PV source.

3.1. Neural Network Strategy

Neural network (NN) is a type of data processing system composed of several basic and interconnected nodes known as neurons, which are similar to human brain cells [20, 21]. The hidden neurons are trained by applying the Levenberg-Marquardt algorithm.

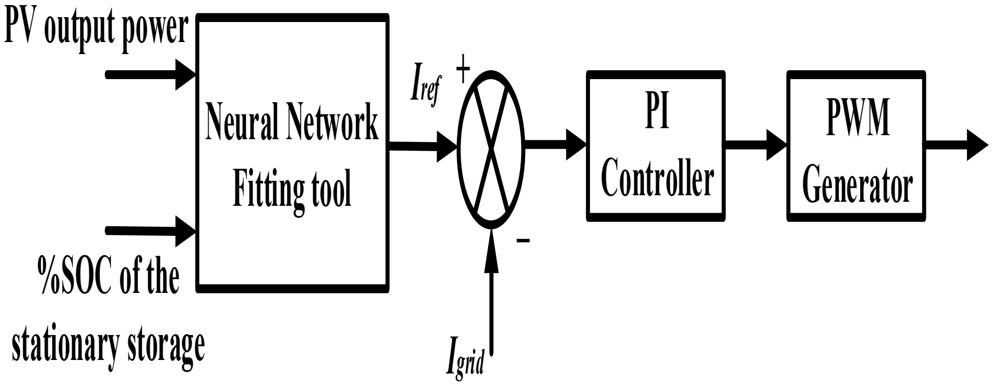

Figure 5. Neural network current controlled structure.

As mentioned earlier, this study uses neural network to control the grid or inverter current flow. Hence, PV output power and SOC of the stationary storage are two input variables of the neural network and an output of reference current. In addition, the reference and inverter currents are compared to be processed by the PI-controller, to produce pulse width modulation (PWM) for the inverter. Figure 5 represents neural network current controlled block.

3.2. ANFIS and PI Controller-based MPPT

This system (ANFIS) is designed to simulate the characteristics of neural−fuzzy inference systems (FIS). In addition, an adaptive neural network lacks synaptic weights, however, it contains both adaptive and non-adaptive nodes. Its name "adaptive network", comes from the fact that it is easily converted into a neural network structure with a typical feedforward topology [22]. Figure 6 indicates five layered ANFIS structures.

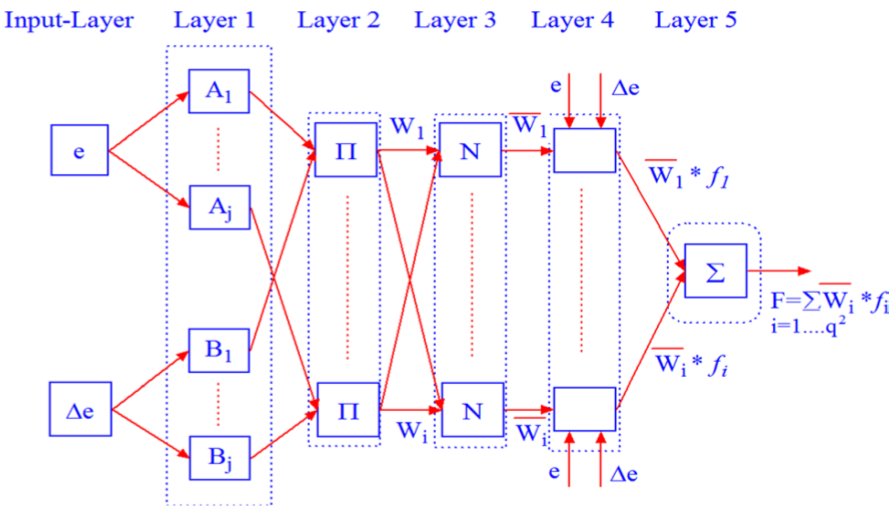

Figure 6. Structure of five-layer ANFIS model.

Layer 1: The parameters of the adaptive node (i) in layer 1 are called non-linear variables of the ANFIS network. The equation of each node can be given as follows:

$$\begin{cases} L_{1,i} = \mu A_i(e) \\ L_{1,i} = \mu B_i(\Delta e) \end{cases} \quad for\ i\ =\ 1,2 \dots .j \tag{9}$$

where A_i and B_i are membership functions (MF) of each node. e and Δe are inputs. Typically, the Gaussian MF is applied to each node to disperse the input elements. Here, the function of the Gaussian MF can be represented as follows:

$$f(x;\sigma,c) = e^{\frac{-(x-c)^2}{2\sigma^2}} \tag{10}$$

where σ and c are width and center of Gaussian MF. Further, σ and c are non-linear variables and can be adjusted during the learning process.

Layer 2: The fixed node (Π) is obtained from the outcome of layer 1 node signal and it's equation can be formulated as follows:

$$L_{2,i} = W_i = \mu A_i(e)\mu B_i(\Delta e) \quad for\ i = 1,2 \dots j^2 \tag{11}$$

Here, the outcome of each node of layer 2 corresponds to the firing power of a rule basis.

Layer 3: The output of fixed node (N) is solved by dividing the value of each node by the total value of all nodes which is represented as follows:

$$L_{3,i} = \overline{W}_i = \frac{w_i}{\sum_{i=1}^{j^2} w_i} \tag{12}$$

Layer 4: the function of adaptive node can be given by:

$$L_{4,i} = \overline{W}_i f_i = \overline{W}_i (p_i e + q_i \Delta e + r_i) \tag{13}$$

where $\overline{W}_i$ is the measured firing strength from layer 3. p_i, q_i, r_i are the subsequent variables of ANFIS network, which is modified using least-square technique.

Table 1. System Parameters.

Characteristics	**Value**
Module name	1Soltech 1STH-350-WH
Array data	Parallel strings, 1; series connected cells, 6
Open circuit voltage (V_{oc})	51.5 V
Voltage at maximum power point (V_{mpp})	43 V
Short circuit current (I_{sc})	9.4 A
Current at maximum power point	8.13 A
Maximum power (P_m)	350 W
Stationary storage	Lithium-ion, 240 V, 40 Ah
EV battery	Lithium-ion, 240 V, 10 Ah
Capacitances (C1, C2, C3, C4)	4.07 μF, 8.98μ, 100 μF, 6.01 μF
Inductances (L1, L2, L3, L4)	0.0153 H, 0.0069 H, 0.0072 H, 0.0012 H

Layer 5: The output of this node (Σ) is determined by using weighted average method and is formulated as:

$$L_{5,i} = \sum_{i=1}^{j^2} \overline{W}_i f_i = \frac{\sum_{i=1}^{j^2} w_i f_i}{\sum_{i=1}^{j^2} w_i} \tag{14}$$

In this study, to achieve the maximum output power, ANFIS+PI controller-based MPPT is used. In addition, a five-layer is used to reach maximum power point (MPP), as shown in Figure 7. Temperature (T) and irradiance (G) are two input parameters of the ANFIS+PI controller and single output voltage. Figure 8 shows the developed ANFIS structure. The ANFIS input MF for both irradiance and temperature are given in Figure 9 and Figure 10, respectively.

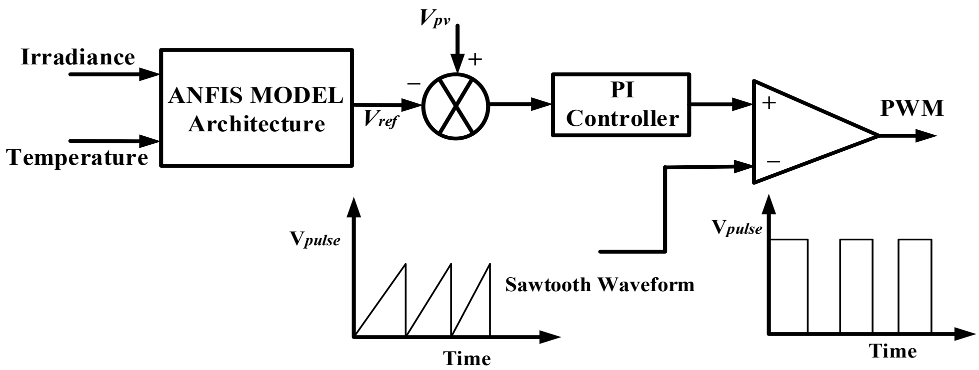

Figure 7. Block diagram of ANFIS and PI controller-based MPPT.

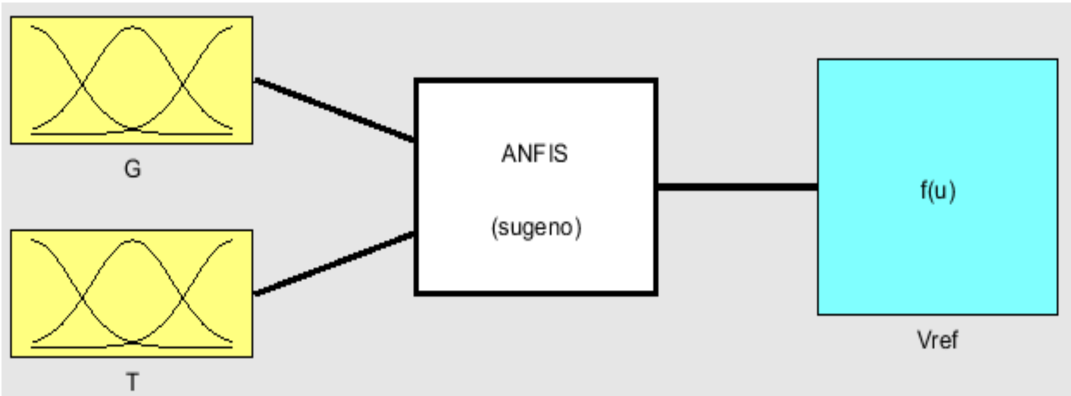

Figure 8. Developed ANFIS system.

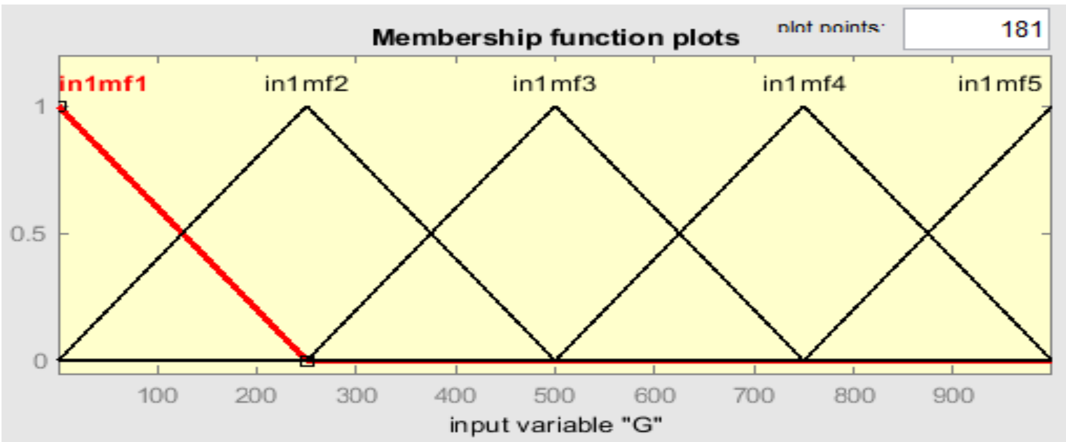

Figure 9. ANFIS input MF for irradiance.

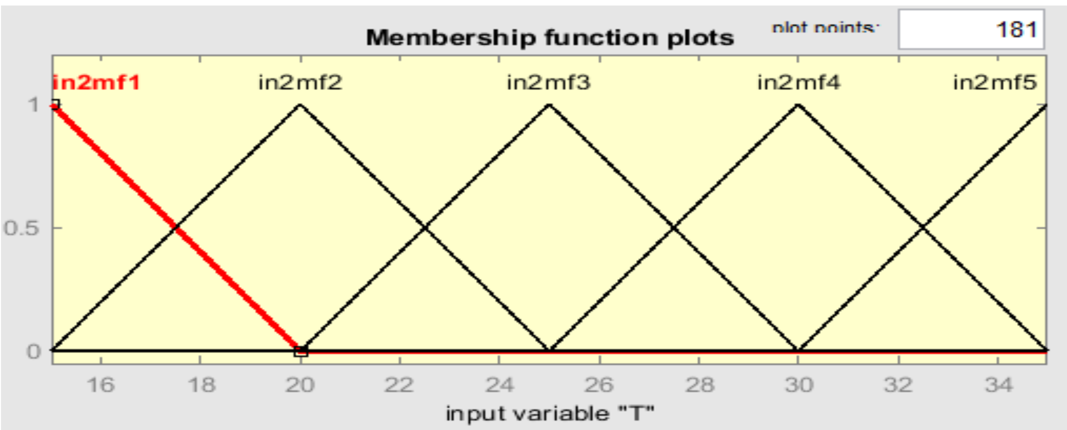

Figure 10. ANFIS input MF for temperature.

4. RESULT AND DISCUSSION

In this paper, a standalone PV system integrated with DC-DC boost converter based on a neural network concept is executed in MATLAB. Additionally, the characteristics of the implemented system, which employs ANFIS+PI controller-based MPPT, are shown in Table 1.

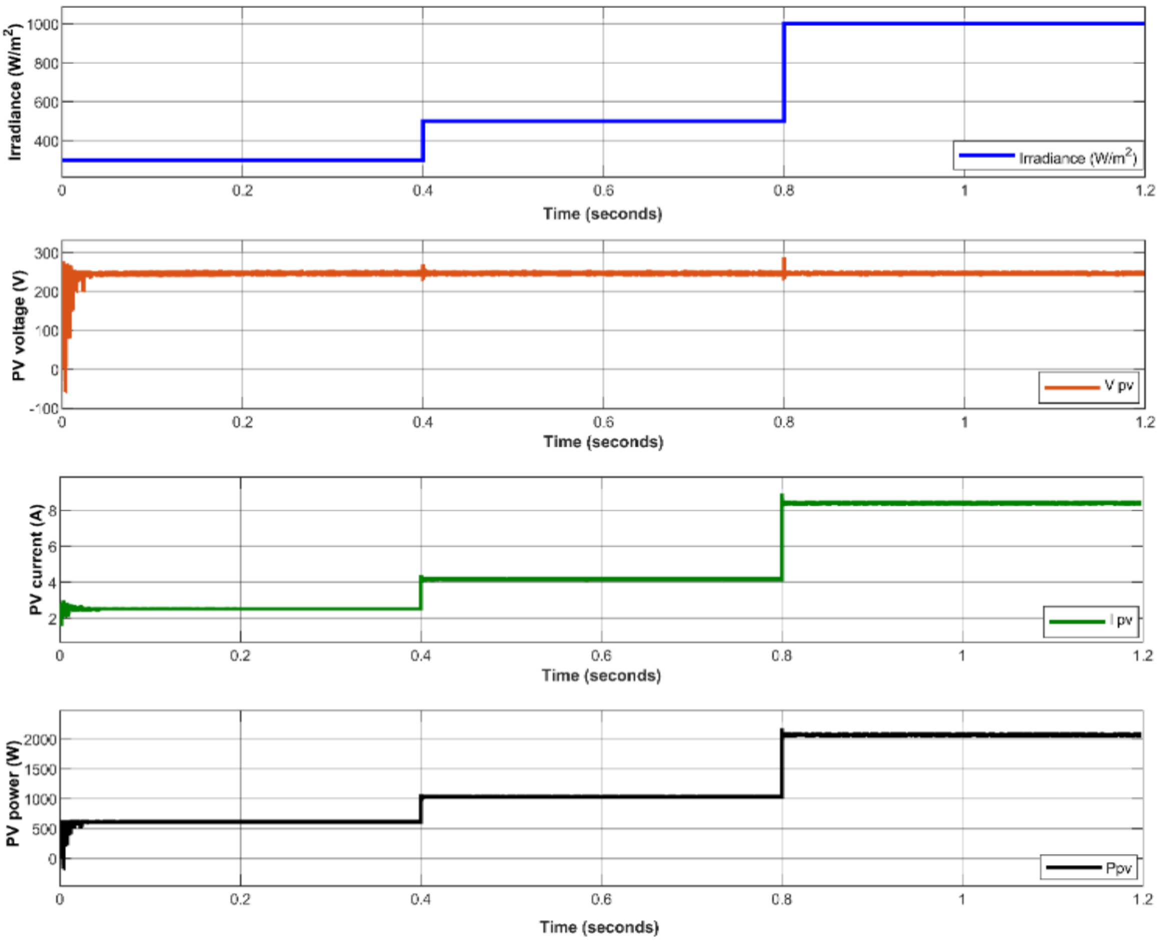

Figure 11. PV voltage, current and power with varying irradiance.

This study simulated the voltage and current of both EV battery and stationary storage, Dc bus voltage, real/reactive grid power and the maximum output power. The overall system has been evaluated under different scenarios of irradiance and temperature. Figure 11 represents the result of PV voltage, current and power with variable irradiance. ANFIS model is first created in MATLAB. The model builds a single output Sugeno-FIS and modifies the system specifications using the input-output training data set. In addition, the ANFIS element is instantly generated using grid partitioning. Afterward, the ANFIS element is trained with 121 Epochs by applying hybrid learning technique. Finally, the ANFIS object is tested with the trained data. The simulation results of the entire system are evaluated under different scenarios such as under standard test condition (STC), under varying irradiance level and charging and discharging modes of EV battery and stationary storage.

First, the simulation starts with constant temperature and varying irradiance. At 1000 W/m^2 irradiance, the PV power improves to 2.1 kW. Further, as the irradiation modifies, the PV power and current also change to a new operating point with constant PV voltage, which allows the PV system to achieve the maximum output power. Moreover, with varying irradiance level and temperature, the PV power also modifies as shown in Figure 12.

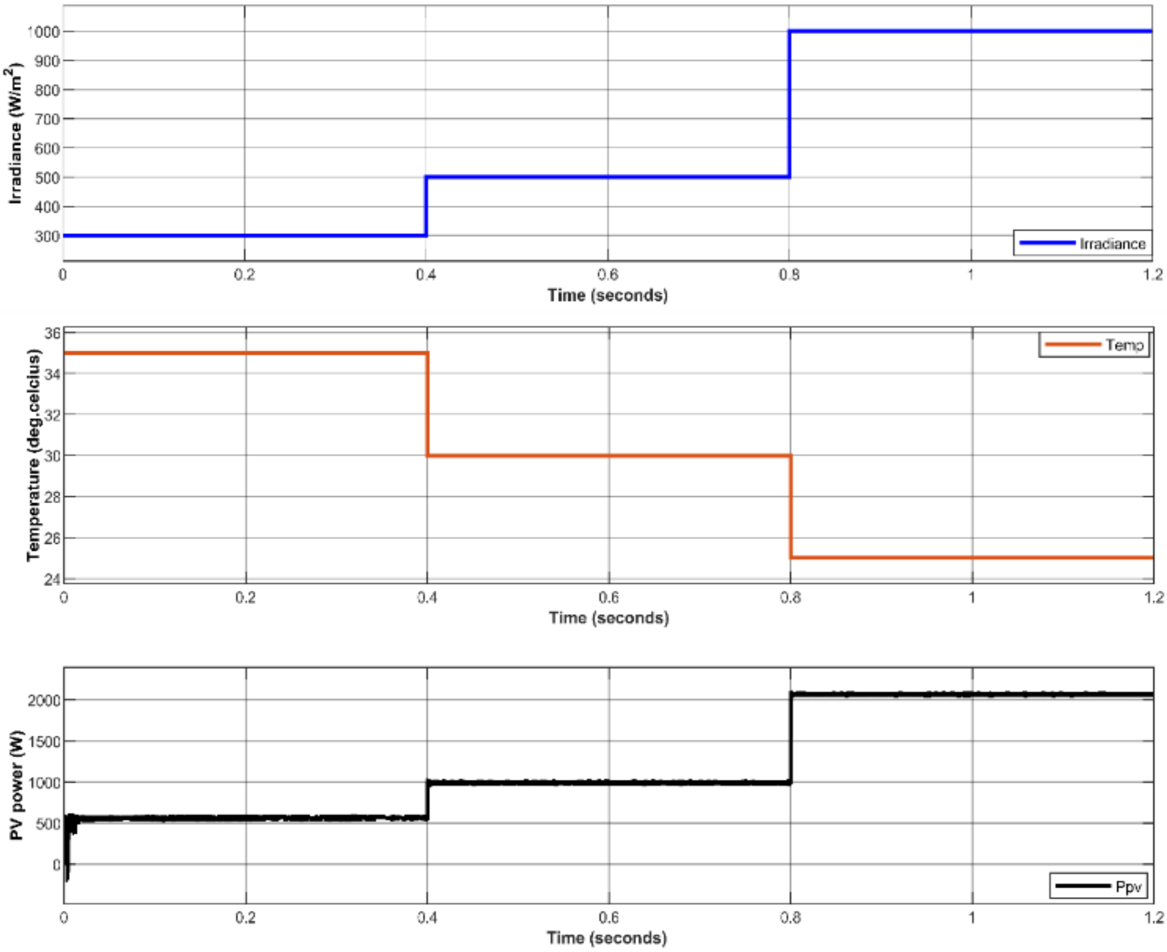

Figure 12. PV power with variable irradiance and temperature.

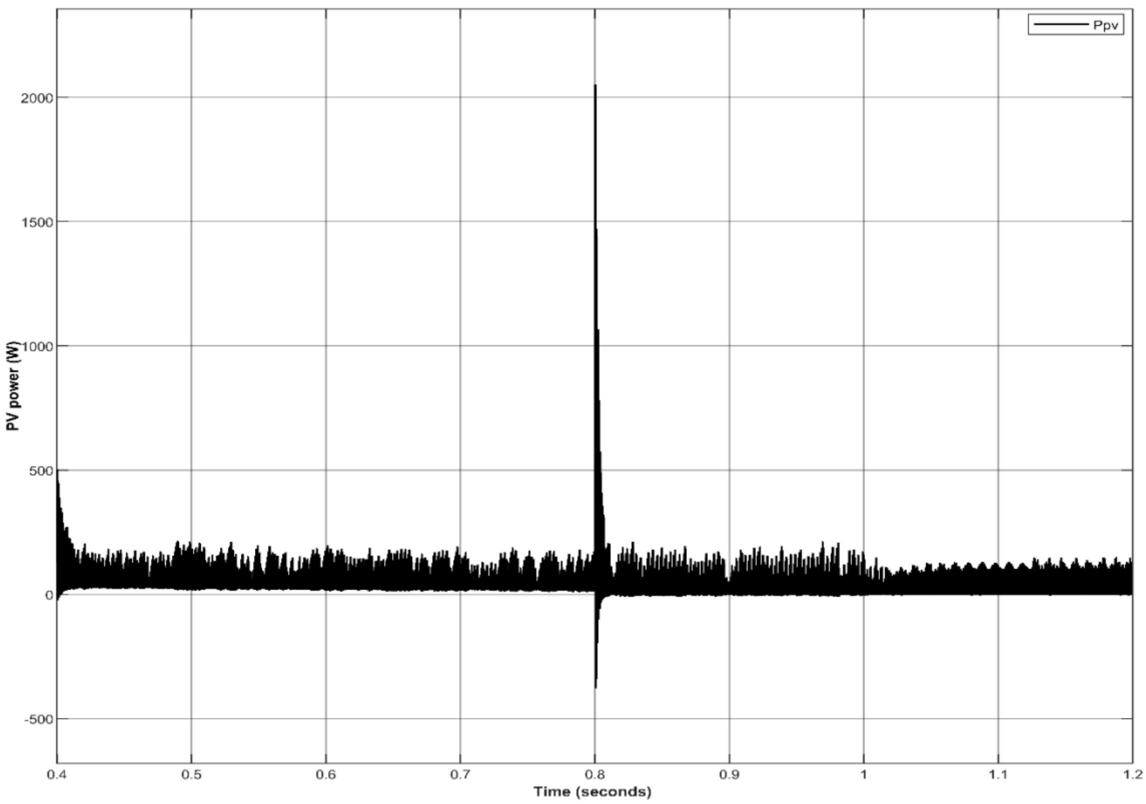

Figure 13. PV power during the night.

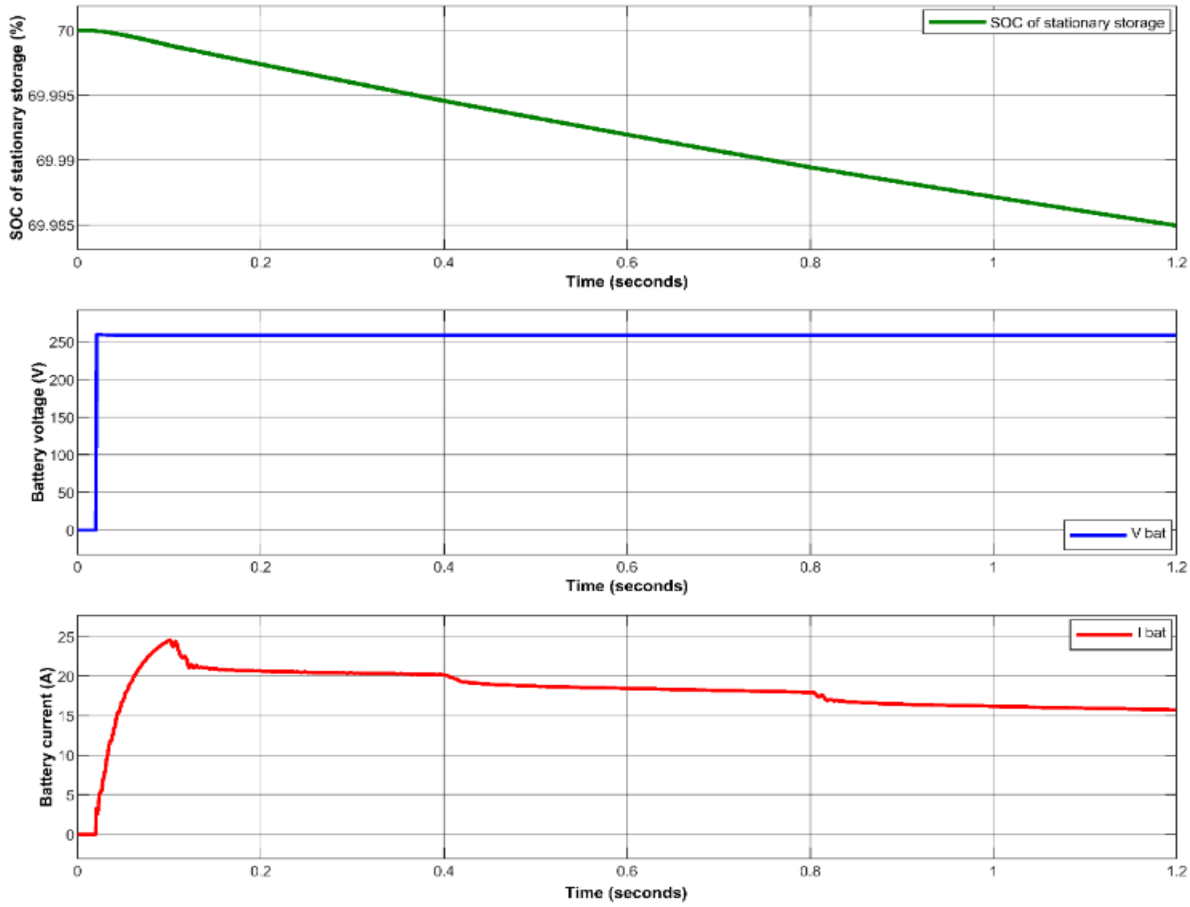

Figure 8. SOC, voltage and current of the stationary storage.

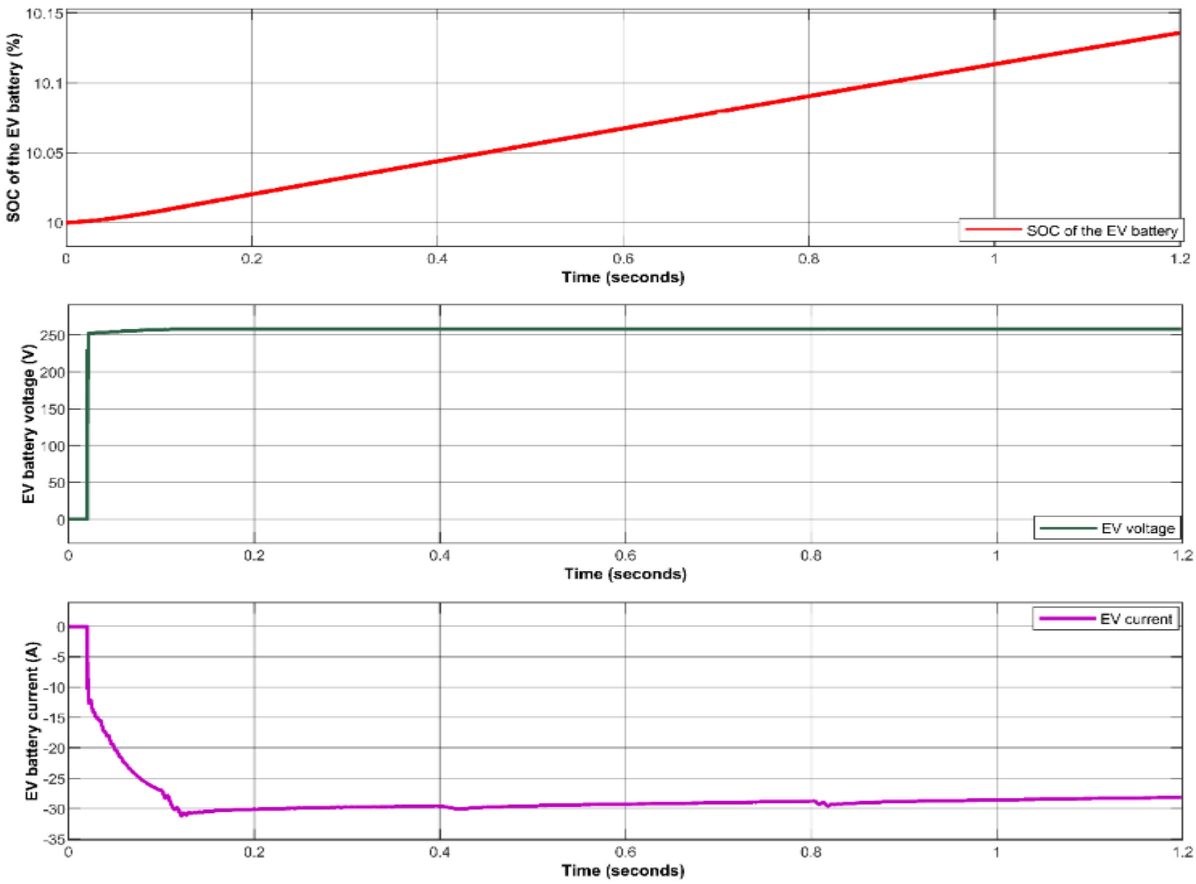

Figure 9. SOC, current and voltage of the EV battery.

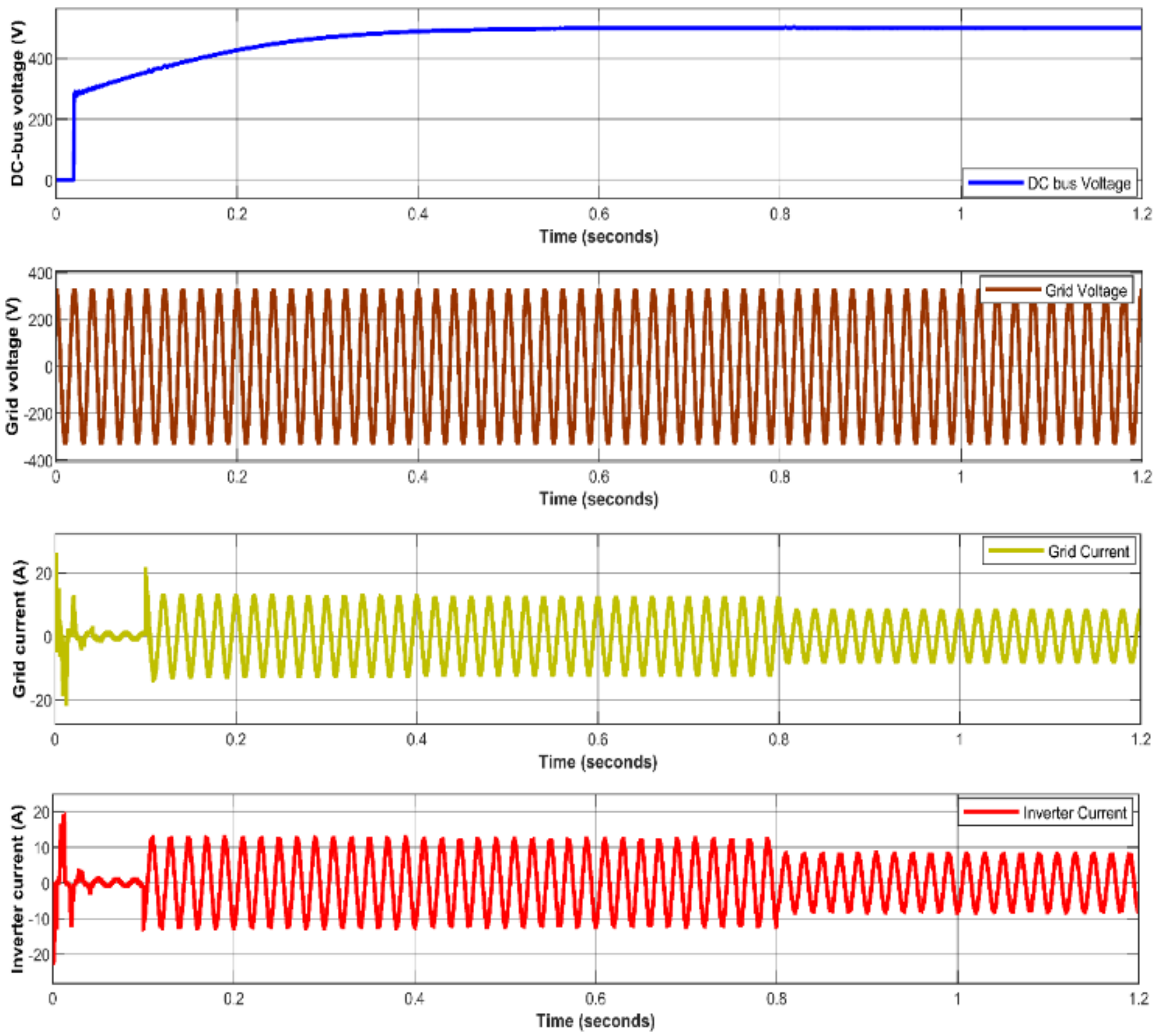

Figure 10. Performances of the dc bus voltage, grid voltage and current.

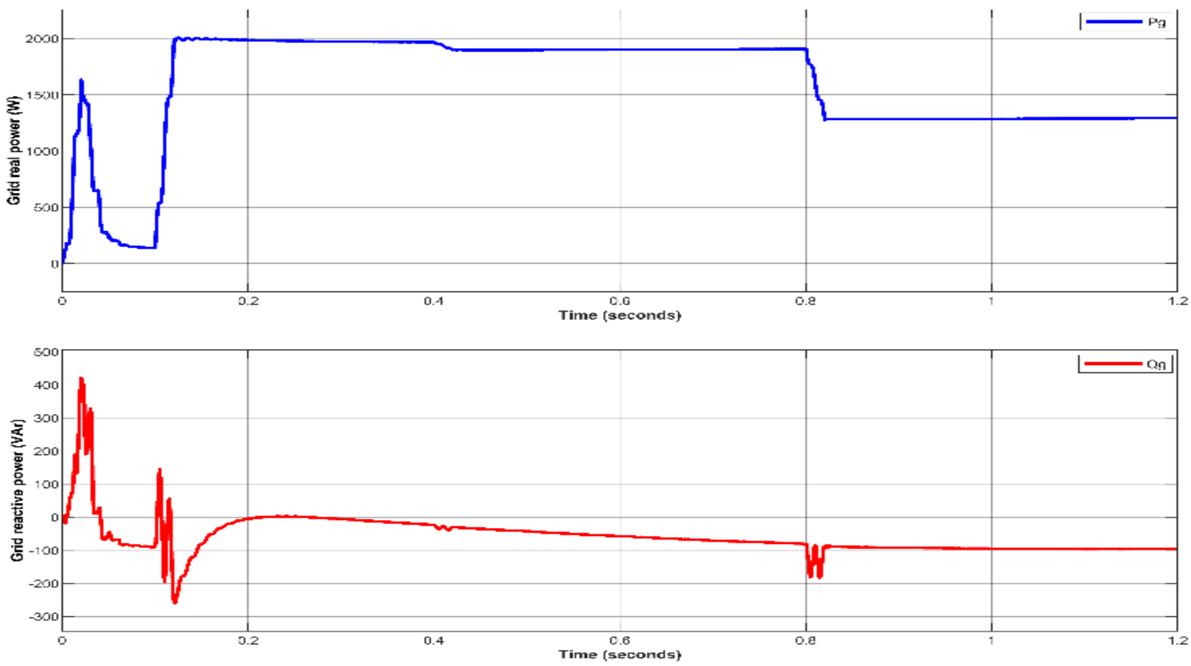

Figure 11. Performances of real and reactive grid powers.

In addition, Figure 14 represents the SOC of the stationary storage, its voltage and current. Since the SOC of the stationary storage decreases from 70 %, thus, the battery current operates in discharging mode. On the other hand, the SOC of the EV battery is increasing from 10 % as considered, accordingly, the EV battery current is around -30 A, which shows that it's in charging mode as indicated in Figure 15. A capacitor element attaches between the solar PV−EV battery and stationary storage as given in Figure 1. Additionally, the purpose of the capacitor is to keep the dc-bus voltage constant and it's maintaining 500 V as illustrated in Figure 16. Further, the grid voltage, current and inverter are working properly. Figure 17 represents the performances of real and reactive grid powers.

In this work, the grid voltage and current, real/reactive grid power and maximum output power were mainly discussed. In the literature, the design features and application of a modern PV-based level-2 EV charging station regulated by a type-1 vehicle connecter was developed [9]. A charging station strategy for fast DC charging has been presented in [10]. Moreover, a dc-bus was developed by connecting to the power grid through converter. Then the converter was developed to such a degree that the power factor was close to unity and the line current harmonics were maintained to a minimum. In Ref [11], an off-grid charging station for EV and HV has been proposed. In addition, both EV and HV are charged simultaneously. Ref [12] investigates an ideal PV-based EV charging station design from a technical and economical perspective under various irradiance level. However, most of this literatures focused on the limitation of charging stations architectures and its dependency on the electrical grid. When compared the above literatures with this study, a novel ANFIS+PI controller was developed, to achieve the maximum output power from the PV system. Furthermore, a five-layered ANFIS model was used to reach at MPP. Then the PV power provides power to the EV battery and stationary storage. During night-hour, the power from the PV source is less (see Figure 13), as a result, a NN begins to regulate the grid power. Afterward, the grid power supplies power to the stationary storage and EV battery.

5. CONCLUSION

In this work, a novel ANFIS+PI controller-based MPPT strategy for solar PV-battery based on EV charging stations connected to an AC grid was designed. The entire system has been simulated under different scenarios of irradiance level and temperature. Thereafter, an appropriate controller (NN concept and ANFIS-PI controller) was chosen and integrated into the system. During the day, the PV power goes to charge the stationary storage and EV battery. Similarly, stationary storage discharges to fulfill EV demand when the PV power is low, especially during the night. Moreover, during this time, a NN concept starts to regulate the grid power, to supply power to the stationary storage.

The simulation results will be compared with the experimental results in the future work, to enhance the reliability of the system.

Conflict of Interest

No conflict of interest was declared by the authors.

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