Energy Management based on Supertwisting Sliding Mode in the Standalone Photovoltaic Power System with Battery Backup

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Abstract- Electrical energy is an important issue of human being to perform our daily activities like food, transportation, heating, communications, leaving, and so on. Therefore, continues existence of electrical energy is a need of all human being. So that in stand-alone power system applications, energy storage is a very important issue. In these days, batteries are very popular energy storage equipment and controllability of the energy stored in the battery is very hot topic. In this article, the energy management in a stand-alone photovoltaic power system with battery backup is investigated. For this purpose, a simulation model based on Matlab/Simulink is built. Photovoltaic panel is operated to supply the maximum power by using perturb and observe maximum power point tracking (PO-MPPT) algorithm. The battery charging/discharging current is controlled via cascade control structure based on super twisting sliding mode controller. By appropriate control of the battery current, it is aimed to ensure the power balance among the photovoltaic panel, load and battery under different operating conditions as well as keep the DC bus voltage at the desired value. Simulation results show that the super twisting sliding mode controller successfully balances the power between the panel, load and battery and keeps DC bus voltage at reference value.

Keywords: Photovoltaic, Battery, Perturb and Observe Control, Super Twisting Sliding Mode Control.

1. Introduction

Electrical devices need electrical power to continue the operation. In daily life, because of technological developments and devices, electricity become essential. Computers, Cell Phones, Televisions, and other devices need electricity. Some of them use batteries to continue operation without a grid connection (Until the battery is run out). Some of them need grid connection to supply electricity.

In the near future, cars will not use fossil fuel-based sources, and they use electrical power to start and continue their work. For this process, battery technology become more and more important over time.

From reducing the fossil fuel-based system to generating electrical energy to compensate for the increasing electricity energy and also reducing the environmental causes of the fossil fuel-based systems damage the alternative ways to generate electricity are also important. In this process, another important issue is to consistency of the battery charge systems new ways must be examined.

For this purpose, a hybrid stand-alone power network based on PV panel and battery is designed to both generate environmental electrical energy and offer a new way to control the battery charge application.

Renewable-based energy generation is sustainable and environmentally friendly. In 2023, according to the Republic of Türkiye Ministry of Energy and Natural Resources, 36.3 percent is coal-based system, 21,4 percent natural gas, 19.6 percent Hydroelectric, 10.4 percent wind power, 5.7 percent sun, 3.4 percent geothermal energy, 3.2 percent other sources generate the electrical energy in Türkiye [1]. According to this knowledge, 57.7 percent of energy is produced by fossil fuel-based systems, 39.1 percent is renewable energy and 3.2 percent is from other sources. The percentage of the sun and wind-based systems is only 16.1 percent this must be increased. However, the sun and wind sources are temporarily worked sources. If the wind speed or sunlight energy is enough the system generates electricity. If not system does not generate electricity. In light of the above knowledge, battery usage, and efficiency are also important for maintaining the energy flow in the grid system.

The other research examined the wind farm and storage unit. In the article, the battery life and the wind power smoothing were examined [2]. The other renewable energy-based system used a fuel cell device. The device uses a winding electrical machine to remove the DC-DC converter for charging the battery. The system was examined in article [3]. Another research examined the PV-based system and aimed to increase the efficiency of charging and inhibit battery aging [4]. The other article aimed to use photovoltaic (PV) and grid-based systems for charging stations of Electrical vehicles. In the system, the battery systems and charging techniques are also used [5]. There is also a low-cost maximum power point tracking (MPPT) charge controller design for obtaining efficient charge for solar batteries. In the systems, a simple and robust MPPT method was used to protect against overcurrent and voltage [6].

In one research, the PV panel and battery system were used. In the article the proposed control aimed to reduce the PV power fluctuation for the battery charging and discharging condition [7]. Another article searches the EV battery charge condition. In this article, the Battery Swapping System was simulated using PV panels and a grid connection. In the paper, the proposed model reduces the operation cost according to the result [8]. In addition to the above topics, one of the articles examined the Solar charging Zn-air battery system [9]. One article is designed boost type converter that supplied with solar energy and compares the step voltage controller and step duty maximum power point tracking incremental conductance controller [10]. Another study examined off-grid solar-supplied home systems with lithium batteries. In the article aim was to reduce battery capacity and increase the lifetime of the batteries [11]. The other study used a novel capacitor-voltage reduced bidirectional PWM DC-DC buck-boost converter for its advantages in renewable energy battery charge systems [12].

Another study's topic was selected as battery charge systems from using stand-alone PV systems and MPPT-based solar energy charge controllers [13]. The other topic related to renewable energy and battery charge systems was solar-based charging systems for electrical vehicles. In the article selected battery type is a lithium-ion battery [14]. Another article selected a hybrid storage unit which was based on a battery and supercapacitor for energy storage, in a stand-alone wind power system. In the article, the charge and discharge conditions for the battery and supercapacitor were mentioned [15]. One of the research projects is examined the photovoltaic and battery charge systems. The system was tested under different conditions in the article [16].

There are also battery charging application-related studies in the literature. One of the studies aimed to examine, real-time challenges related to battery packs in on-road conditions such as discharge rate, temperature, depth of discharge, storage condition, and other conditions [17]. The other study aimed to find robust, safe, fast-charging protocols for lithium-ion batteries [18]. Another study topic was selected as Battery charging and swapping stations. In the article, the aim was to minimize unwanted conditions such as transmission losses, voltage deviation, and power cuts of the wind and PV power [19]. Another study was selected topic as for very fast charge systems heat becomes a problem. In the article, a system is established for heat generation and thermal management [20]. Other research designed a Zeta bidirectional DC-DC converter to charge Li-ion batteries at low-frequency ripple current charging [21].

In this study, super twisting sliding mode controller (ST-SMC) for DC bus voltage control and power balancing among PV panel, battery and load in a hybrid stand-alone power network with a PV panel/battery is presented. In this hybrid power network, the PV panel is operated to harvest its maximum power, and the battery is used to ensure power balance between the PV panel and the load. The bidirectional DC-DC converter interfaced with the battery is controlled cascaded control technique based on a ST-SMC. The overall system performance is investigated for two working conditions. These working conditions are considered changes in the irradiation under constant DC bus voltage and changes in the reference DC bus voltage under constant irradiation. It can be seen from the simulation results that the performance of the hybrid stand-alone power network is satisfactory in terms of power balance, battery current, and DC bus voltage.section titles are italic.

2. Design of The Source and Converters

A. PV Panel

In the article, the primary source is PV panel. The modeling of PV is important for obtaining maximum power from the sunlight. It increases the efficiency of electricity generation. PV Panel aims to convert the sunlight using a special design cell circuit and this cell has been made from the P-N junction technique. In the literature, there are design and application studies. In this study, the PV panel related literature is [22-29]. From these sources, the light energy to the electrical energy conversion has three important issues. These issues are:

- If the energy of the light is equal to or greater than the needed energy of the ionization, the electron is released. However, the electron is not stable for this condition. The emitted energy is released by the electron and electron energy is used in the electrical circuit.
- The system could be equalized as one controlled current source, one diode, and two resistances; one is

paralleled to the sources one is a series connected to the converter side.

- The power to voltage or voltage to current graph of the PV panel is not linear so the maximum power point must be found to harvest maximum energy to the light.

Figure 1 shows the equivalent circuit of the single diode model of PV.

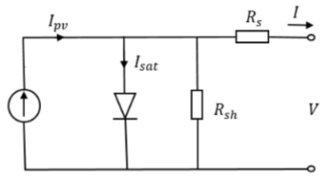

Fig. 1. Single diode model of PV

The following equation explains the connection between the output current and voltage [32].

$$I = I_{pv} - I_d - \frac{V + IR_s}{R_{sh}} \tag{1}$$

Where I_{pv} is the PV current, I_d is the Shockley diode current. The Shockley diode current is given in Eq.2 [32].

$$I_d = I_{sat}\left(e^{\frac{qV}{akT}} - 1\right) \tag{2}$$

In Eq.2, I_{sat} is reverse saturation current, q is electron charge, V is PV output voltage, a is diode ideality factor, k is Boltzmann constant and T is absolute cell temperature. If Eq. 2 is substituted into Eq. 1, then Eq. 3 is obtained.

$$I = I_{pv} - I_{sat}\left(e^{\frac{qV}{akT}} - 1\right) - \frac{V + IR_s}{R_{sh}} \tag{3}$$

The thermal voltage of the cell (V_t) is defined as follows [32]:

$$V_t = \frac{kT}{q} \tag{4}$$

Due to the nonlinear nature of the PV panel, the control of the first converter must be suitable for finding the maximum power point (MPP). For this reason, the control could be adjusted to find the MPP or the MPPT algorithms could be used as the control method. In Part III, it is mentioned in detail.

B. Boost Converter Design

In the topic of the Power Electronic, there are lots of subtopics. One of the subtopics is energy conversion topic. In this topic, the aim is to change the voltage type to AC or DC and change the voltage level without changing the voltage type. The boost converter changes the voltage level without changing the voltage type. The boost converter increases the average value of the input side voltage and transfers it to the output side. In this process the average power value is not changing, so the average value of the current value must be decreased.

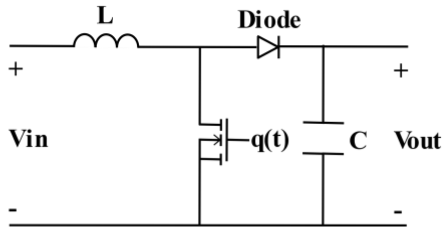

Fig. 2. Boost Converter Circuit

In the Boost Converter, there are two different working conditions. If the control signal is 1, The MOSFET is short-circuit and the load side and source side are disconnected due to the short circuit part. If the control signal is 0 the MOSFET is an open circuit, and the load side and source side is connected again.

If the Voltage of Capacitance and Inductor current formulas are obtained and using this information the Voltage equation is found, and they are given in Eq.5-6. From these important formulas, the unwanted ripples of these components are under control. This means that a lower ripple increases the operating stability and efficiency. The detailed analysis of this converter was done in [26], [30].

$$\Delta I_L = \frac{V_{in} D}{Lf} \tag{5}$$

$$\Delta V_{out} = \frac{I_{out} D}{Cf} \tag{6}$$

$$V_{out} = \frac{V_{in}}{1 - D} \tag{7}$$

Where ΔI_L is ripple of the inductance current, V_{in} is input voltage of the converter, D is duty ratio, L is inductance, ΔV_{out} is ripple of the converter output voltage, C is capacitor, V_{out} is converter output voltage and f is switching frequency.

C. Bidirectional Converter

To provide desired DC voltage to the load, the charge-discharge of the battery needs to be controlled according to the power demand on the load side and the power produced by the PV panel. So, both DC bus voltage and charging/discharging current of the battery must be controlled by using a converter allowing bidirectional power flow. In this study, charging/discharging current of the battery is controlled by a bidirectional converter shown in Fig. 3. The bidirectional converter has two MOSFET switches, two capacitors, and one inductor. This converter has two working conditions. In this converter, the switch q2 and diode D1 function in this case as a boost converter, supplying power to the load in the discharging mode, and the switch q1 and diode D2 function as a buck converter, injecting power into the battery in the charging mode. Fig. 4

and 5 show equivalent circuits for the case where switches q1 and q2 are on, respectively [31].

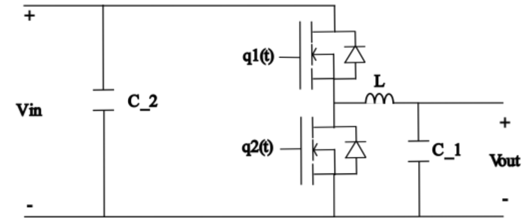

Fig. 3. Bidirectional converter circuit

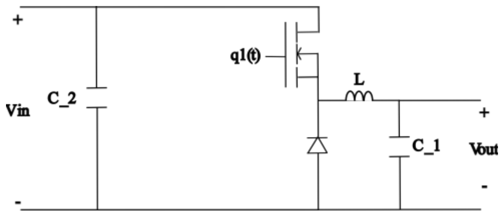

Fig. 4. The first equivalent circuit $q2(t) = 0$

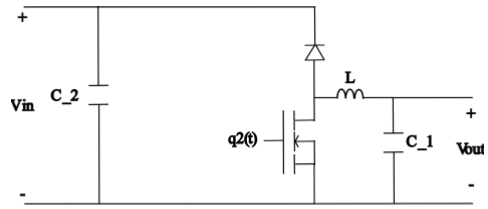

Fig. 5. The second equivalent circuit $q1(t) = 0$

3. Control Algorithms

A. Perturb and Observe Algorithm

In the literature, The Perturb and Observe Control has been commonly preferred as the MPPT algorithm. In perturb and observe MPPT algorithm, the control systems output changes, after this step the output changes are detected. From the changes, the next step is decided. It continues such as this and the MPP is found at the end of the steps. The decision table is given in Table 1.

Table 1. P&O Decision Table [23-26]

ΔV Sign	ΔP Sign	Next ΔV
+	+	+
+	-	-
-	+	-
-	-	+

B. Super Twisting Sliding Mode Control

In this study, Sliding Mode Control is combined with Super Twisting Algorithm to increase the efficiency of the system [26]. The structure of Super Twisting Control is given in Fig. 6. There are two nested closed loop controls are used. Voltage control was performed in the outer loop and current control was carried out in the inner loop. As a controller, the ST-SMC algorithm is preferred due to its robust structure. In a previous study, SMC, STSMC and STSMC-T2Fuzzy based MPPT methods are compared [33].

e is error and equals to difference between reference and actual signal value.

$$e = \text{Reference Signal} - \text{Signal Value} \tag{8}$$

$$x = \frac{d(e)}{dt} + Gain * e \tag{9}$$

$$Duty = sign(x) * Gain * \sqrt{|x|} - Gain * \int sign(|x|)dx \tag{10}$$

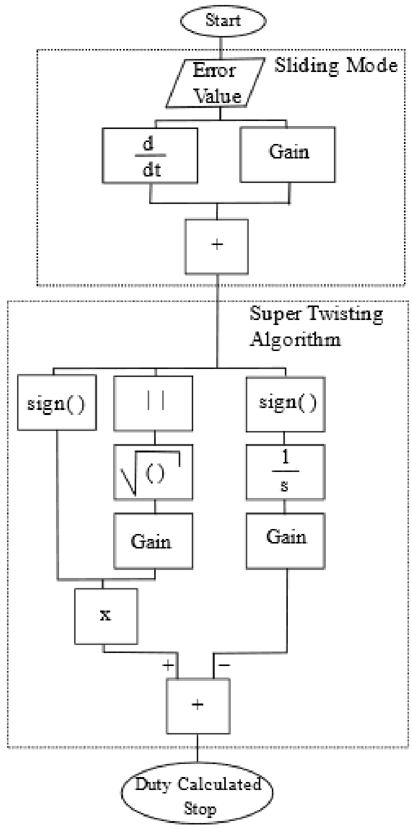

Fig. 6. The structure of the ST-SMC

4. Simulation Studies

In this study, the DC voltage of a stand-alone photovoltaic power network with battery backup is controlled using a cascade control structure based on ST-SMC. The Matlab/Simulink model of the power system is depicted in Fig. 7. The model consists of a PV panel, battery, DC-DC converters, load, MPPT control algorithm, DC voltage regulator, and battery current regulator. The simulation parameters are given in Table 2 and Table 3.

Table 2. Parameters of PV panel

Parameter	Value
V_{oc}	39.7 V
V_{mppt}	33V
$V_{oc\ temp\ coeff}$	−0.284
N_{cell}	60
I_{sc}	9.37 A
I_{mppt}	8.84A
$I_{sc\ temp\ coeff}$	0.042999
I_{Sat}	1.5979×10^{-11}

ideality factor	0.95098
R_{sh}	218.2149Ω
R_{ser}	0.24303 Ω

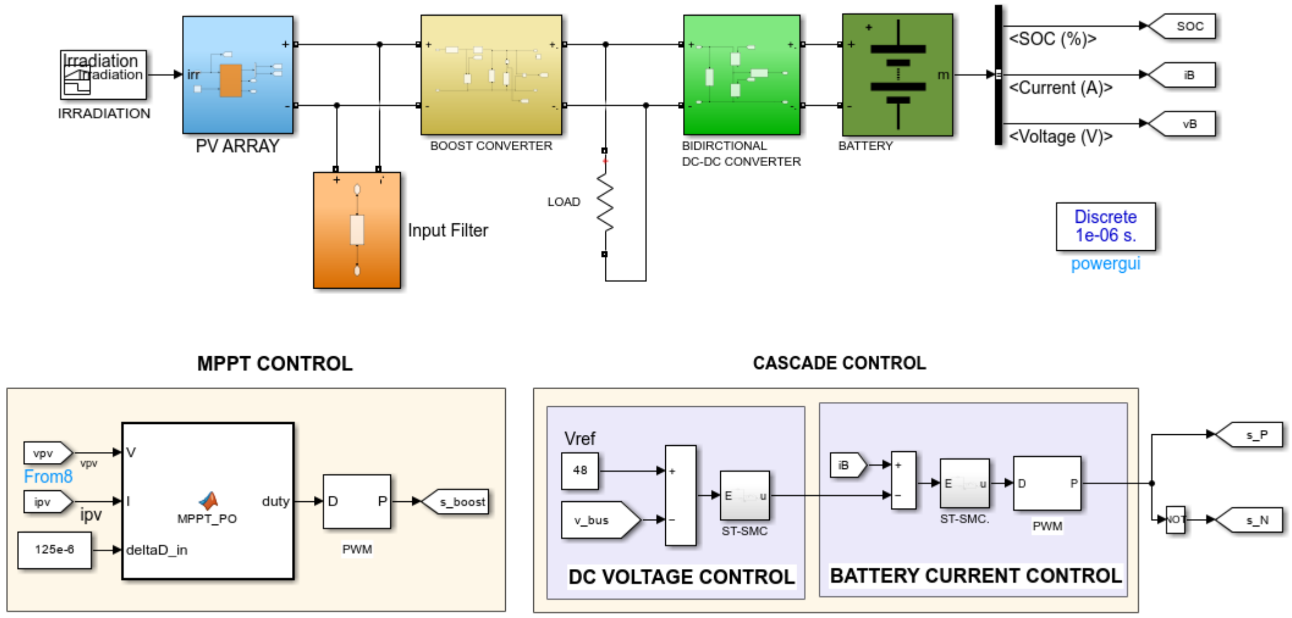

Fig. 7. MATLAB/Simulink model of the power system

Table 3. Parameters of Boost Converter

Parameter	Value
L	5 mH
C_o	3300 µF
R	6 Ω
f	5 kHz

The power balancing and DC bus voltage performance of the ST-SMC are examined for two different operating cases. The first operating case is considered the irradiation change under constant DC bus voltage whereas the second operating case is considered the reference DC voltage change under constant irradiation. The simulation results for the first operating condition are given in Fig. 8. As seen in Fig. 8(a), the irradiation is increased step by step until the fourth second of the simulation. Then, the irradiation is decreased step by step after the fourth second of the simulation. At 1000 W/m^2 irradiation, the PV panel produces 1458 W maximum power. Fig. 8(b) shows the powers of the PV panel, battery, and load.

The irradiation is zero from the beginning of the simulation to the first second, and in this case, since no power is produced by the PV panel, the power of the load and the power losses in the system are provided by the battery. In 1-2 seconds, when the irradiation was 300 W, the power of the load and the losses in the system were provided by the PV panel. At irradiation values above 300 W (between 1-7 seconds), the power produced by the PV panel is more than the power of the load, so the excess power is stored in the battery. Also, it can be seen from the Fig. 8(b) that the power produced by the panel changes proportionally to the irradiation. Fig. 8(b) shows that the power balance between the PV panel, load and battery is successfully achieved by the ST-SMC. Further, the controller manages to keep the DC voltage and battery current at their reference value (Fig. 8(c) and (d)). From Fig. 8(e), the state of charge (SoC) of the battery increases in the charge mode and vice versa.

The power balancing and DC bus voltage performance of the ST-SMC are examined for second operating cases (changes in the reference DC bus voltage under constant irradiance of 600 W/m^2). The simulation results for the second operating case are given in Fig. 9. The changes in the reference DC bus voltage are depicted in Fig. 9(c). The reference DC bus voltage is set to 48 V between the simulation initial and 1 s, 55 V between 1 s and 2 s, 42 V between 2 s and 3 s, and again 48 V between 3 s and 4 s. From Fig. 9(c), it is seen that the DC bus voltage tracks its command. Fig. 9(b) shows the power of the PV panel, battery, and load. PV panel generates 875 W power at approximately 600 W/m^2 irradiation. The load demands 382 W at 48 V, 504 W at 55 V, and 294 W at 42 V. Since the PV panel produces more power than the load demands, the excess power is stored in the battery and some of the PV panel power compensates for power losses in the system. From the simulation studies shown in Figure 9b, it can be seen that the power balance between the PV panel, load and battery is successfully achieved by the controller in the second operating case. Fig. 9(d) shows simulation results related to battery current. This figure shows that the battery current tracks its command. In addition, the SoC of the battery increases as the battery charges.

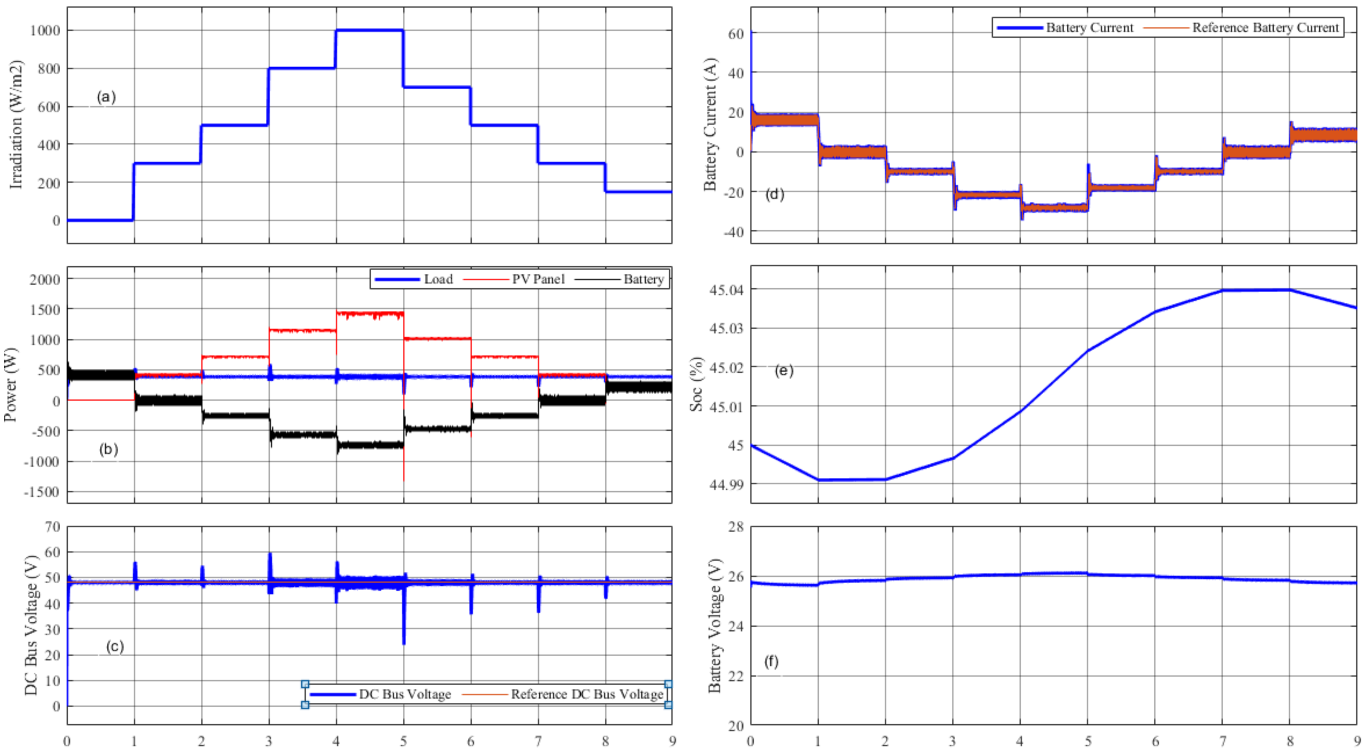

Fig. 8. Simulation results for first operating case

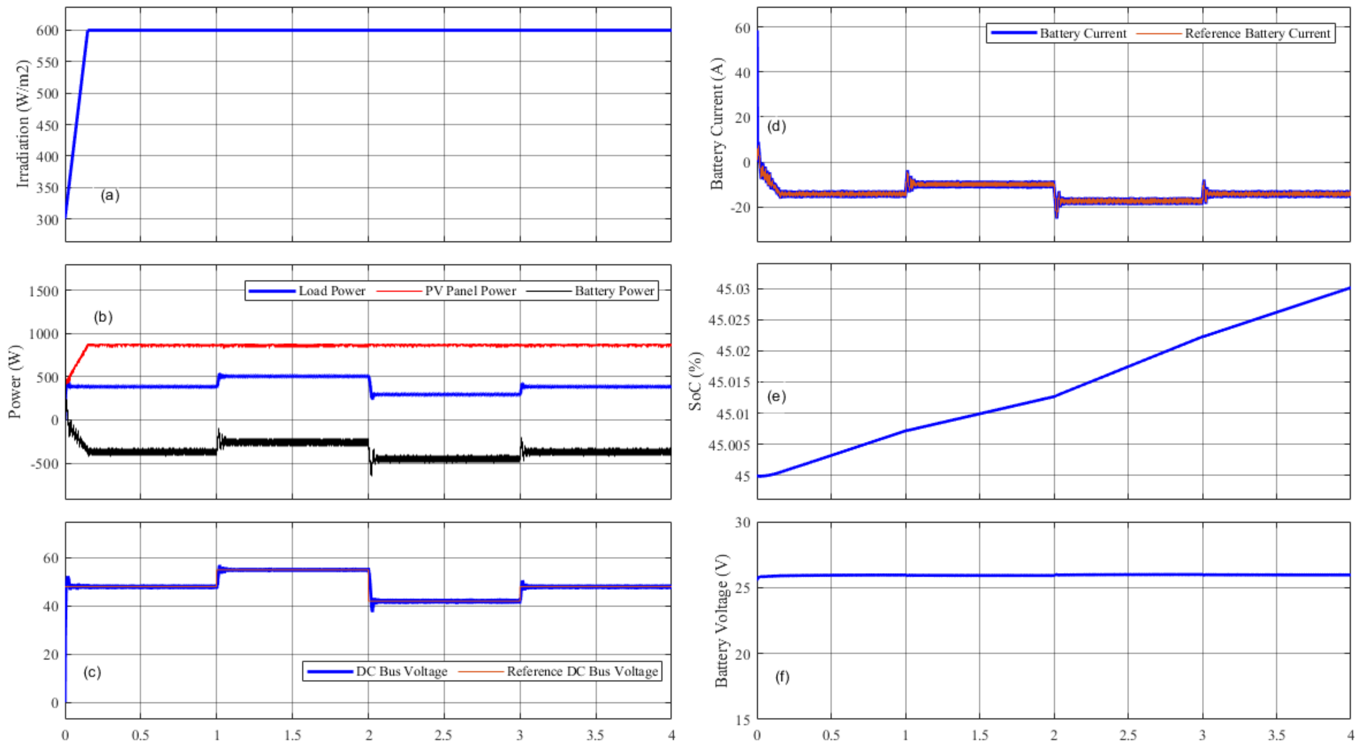

Fig. 9. Simulation results for second operating case

5. Conclusion

This study presents ST-SMC for DC bus voltage control and power balance in a hybrid stand-alone power network with a PV panel/battery. In this power network, the PV panel is operated to harvest its maximum power, and the battery is used to ensure power balance between the PV panel and the load. The bidirectional DC-DC converter interfaced with the battery is controlled cascaded control structure based on a ST-SMC. The overall system performance is investigated for two working conditions. These working conditions are considered changes in the irradiation under constant DC bus voltage and changes in the reference DC bus voltage under constant irradiation. It can be seen from the simulation results that the performance of the hybrid stand-alone power network is satisfactory in terms of power balance, battery current, and DC bus voltage.

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