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Design and Power Management of Solar Powered Electric Vehicle Charging Station with Energy Storage System

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***Abstract*—Global warming has led to the large adoption of Electric Vehicles(EVs) which appear to be the best replacement to IC engines. Due to increased number of EVs in the road, charging of the vehicles with conventional fossil fuel based grid is not economical and efficient. Thus, a renewable energy based charging station finds immense potential and control for electric vehicle charging. An electric vehicle charging station integrating solar power and a Battery Energy Storage System (BESS) is designed for the current scenario. For uninterrupted power in the charging station an additional grid support is also considered without becoming an extra burden to the grid. An efficient design of charging station with MPPT, PID and current control strategy is developed for the optimal power management between solar, BESS, grid with the EVs in the charging station. By taking dynamic charging needs of EVs, the design of charging station is formulated and validated in MATLAB/Simulink.**

***Index Terms*—Charging Station, Electric Vehicles, Solar, State of Charge, Battery Energy Storage System**

I. Introduction

Growing concern on climate change due to green house gas emission has raised the need for alternate sources of energy with minimum pollution. It has contributed to the concept of electrification in transportation that has led to the increase in popularity of Electric Vehicles(EVs). But with the deployment of more EVs on the road, charging of the vehicle will be strenuous if electric grid power is used. When more number of EVs are connected to the grid, it will unavoidably bring a huge impact to its fuction and control [1]. Moreover, charging the EVs using the electric grid powered by conventional energy sources gives no benefits. Thus, there is need for an efficient charging system for EVs utilizing the renewable energy sources. Solar energy is green and renewable, but the undependable gathered energy from the Photo-voltaic (PV) system and dynamic charging needs of individual EVs bring new issues to the efficient charging of vehicles from these sources.

Different charging strategy and power management for EV charging station are reviewed in the literature depending on the various energy sources and EV demand. In paper [2], solar powered charging station with battery storage system is explained. The approach introduces forecasted PV system and projection of EV pattern according to collected data. In [3], charging scheduling for EVs by PV and Grid is given by reducing the total cost of the parking lot. With the real-time information about EVs, Model Predictive Control is applied for present time slot and projected information in the coming time slots. Prioritizing the EVs charging from the limited available solar energy is given in [4]. Feasibility of different types of PV and BESS charging for commercial, home and business has been explained in [5]. [6] shows the solar powered e-bike charging station that provides AC, DC and contactless charging of e-bikes. The charging station has an integrated battery storage that gives both grid-connected and off-grid function. In paper [7], it shows the model of a grid connected rapid electric vehicle charging station ensuring power quality with reduced harmonics. The control of each vehicle charging is centralized and individual control is given to transfer energy from AC grid to the DC bus.Thus, for a well grounded charging station for EVs, the concept of utilising both the renewable energy and an energy storage system with additional grid support becomes very prominent in current scenario.

In the proposed work, an optimal approach for design and power management of Electric Vehicle charging station powered by solar PV and a Battery Energy Storage System (BESS) with AC grid is explained. The unreliability of solar and dynamic charging requirements of EVs are considered for the power flow strategy. Solar PV acts as the primary source to charge all the connected EVs in the charging place. Since the power from PV at night is not there, a battery as an energy storage device is provided to charge the EVs connected in the charging station. Whenever there is a deficiency in the power output of solar or BESS to charge the EVs, required amount of power will be taken from the AC grid ensuring continuous operation of charging station throughout the day. The proposed system is formulated, designed and validated using MATLAB/Simulink.

II. Design of Charging Station

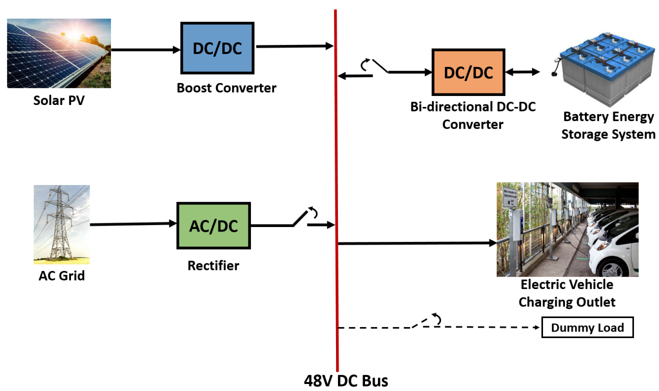

Fig. 1. Layout diagram of proposed charging station.

Fig. 1 gives the block diagram of the proposed EV charging station. As per Bharat EV specifications [8], a 48V DC bus with 3kW power outlet for each EV is considered for the charging station. In this paper, a charging station with 5 power outlets for charging 5 EVs at a time is adopted for the design of proposed work.

A. Electric Vehicle as load

A load of five electric vehicles, 48V, 28Ah with 0.5 hours to maximum 2 hours as charging time [9], is studied for the charging station. Charging requirements of incoming EVs varies time to time. The user can specify the State of Charge (SOC) limit, SOC_{lt} and the time required h hours for charging the EVs. The power requirement for charging all the EVs are calculated in terms of its SOC according to [10].The remaining SOC, SOC_r required to charge the vehicle is calculated from time to time with the difference between SOC_{lt} and current SOC, SOC_c.

$$SOC_r = SOC_{lt} - SOC_c \tag{1}$$

If EV battery voltage V_{EV} and its Ampere-hour rating Ah_{rating} is known, required energy E_{EV} for each electric vehicle to be charged is given as

$$E_{EV} = \frac{SOC_r V_{EV} Ah_{rating}}{100} \tag{2}$$

The dynamic power required by the individual vehicle for charging in h hours is

$$P_{EV} = \frac{E_{EV}}{h - t} \tag{3}$$

where t is the time already covered by the EV for charging. Thus, the total power needed for charging all the 5 EVs can be obtained by summation of (3).

$$P_{tot} = \sum P_{EV} \tag{4}$$

For simulation study, it is assumed that the incoming EV has a minimum of 20% SOC in its battery.

B. Solar PV with Boost Converter

PV array of 250W at 37.3V as open circuit voltage is considered for the charging station design in MATLAB/Simulink. To step-up the PV array voltage, a boost converter is used to get the required DC bus voltage as 48V. With boost converter efficiency as 90%, the solar PV is designed for a load of 5 EVs to charge from 20% to 100% SOC for 2 hours. Thus, a total of 24 panels are required for the specified charging station.

C. BESS with Bidirectional DC-DC Converter

A battery energy storage system is used to store the excess power from the solar for charging the EVs at night. A bi-directional DC-DC converter controls the charging and discharging operation of the BESS. Considering charge-discharge efficiency and bi-directional converter efficiency as 90%, for supplying maximum energy to the connected EVs for 2 hours, a 24V 350Ah BESS is used for the charging station. It is assumed that BESS maintains/ discharges to a minimum of 20%SOC and charges to a maximum of 95% SOC.

D. Grid with Rectifier

For additional power requirement for the charging station 230V AC grid is considered. In MATLAB/Simulink, a 230V AC source with a linear transformer is considered as grid to step down the voltage to 48V AC. A controlled rectifier is provided to convert the AC voltage to constant 48V DC bus voltage.

III. Operation and Control of Charging Station

A. Modes of Operation

- Mode 1: $P_{PV} > P_{tot}$ and $SOC_{BESS} < maxSOC_{BESS}$
  If the delivered power from the solar PV is more than the required power of all the connected EVs, then the EVs will be charged to its SOC_{lt} using the solar power only. If the current SOC of BESS is lower than its maximum SOC, then the surplus power from the solar is used to charge the BESS by connecting it to the bus.
- Mode 2: $P_{PV} > P_{tot}$ and $SOC_{BESS} \geq \text{maxSOC}_{BESS}$
  With the power from the solar, EVs are charged but if the SOC of BESS reaches its maximum, then it is disconnected from the grid and dummy loads are connected for the power balance.
- Mode 3: $P_{PV} < P_{Tot}$
  Due to rain or cloudy condition, if the power harvested from the solar PV is lower than the power required by the EVs for charging, then the deficient power will be taken from the AC grid by connecting it to the DC bus.
- Mode 4: $P_{PV} = 0$ and $SOC_{BESS} > minSOC_{BESS}$
  At night conditions, when there is no solar output, BESS provides energy for charging the EVS in the station by maintaining the minimum SOC in the battery.
- Mode 5: $P_{PV} = 0$ and $SOC_{BESS} < minSOC_{BESS}$
  When the current SOC of BESS is less than its minimum SOC, then the required power for charging the vehicles will be taken from the AC grid by connecting it to the DC bus.

B. Control Methodology

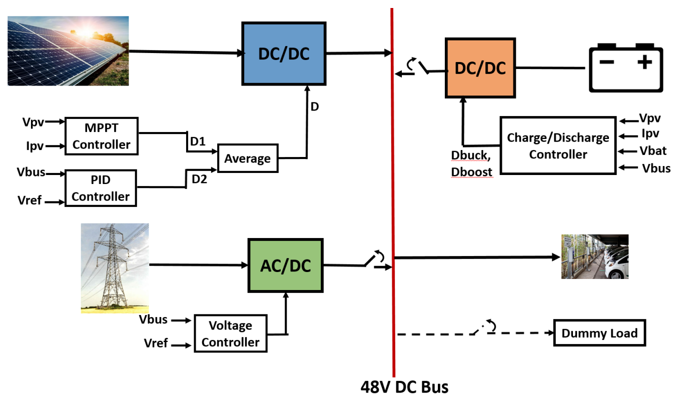

Fig. 2. EV charging station model with controllers.

Here, two types of control such as for power management and for making the DC bus voltage constant are demanded for the presented work. Fig. 2 shows the model with adopted control topology for the charging station.

- MPPT and PID Control for Boost Converter
  For obtaining the maximum power from the solar, Maximum Power Point Tracking (MPPT) using Perturb and Observe (P&O) method [11] is adopted in this system. Using P&O method, if the power is more, the voltage is adjusted in that direction until power no longer increases. The duty ratio for the converter obtained by P&O method is noted as D_1. Here a PID controller is used for making the DC bus voltage constant at 48V. DC bus voltage V_{bus}, is measured and considered with the desired voltage and the obtained error is given to the PID controller. D_2 gives the desired duty ratio from the PID controller.The average of the 2 duty ratios, D_1 and D_2, is fed to the boost converter for getting the utmost power from the solar by keeping the DC bus voltage constant.
- Current Control for Bi-directional Converter
  Whenever there is excess power in the solar, the battery storage system is to be charged and at night this is to be discharged to supply power for the EVs. Here, current control strategy is adapted for the charging/discharging of the BESS [12]. When the battery is charging, the duty ratio of the the converter in Buck mode is given in (7).

$$I_b = \frac{P_{PV} - P_{tot}}{V_{bat}} \tag{5}$$

$$I_{charging} = \frac{P_{PV} - P_{tot}}{V_{bus}} \tag{6}$$

$$D_{buck} = \frac{I_{charging}}{I_b} \tag{7}$$

  When in boost mode, BESS discharges to supply power for charging for all the EVs in the charging station. For boost mode of operation in bidirectional converter D_{boost} is given as the duty ratio.

$$I_b = \frac{P_{tot} - P_{PV}}{V_{bat}} \tag{8}$$

$$I_{discharging} = \frac{P_{tot} - P_{PV}}{V_{bus}} \tag{9}$$

$$D_{boost} = 1 - \frac{I_{discharging}}{I_b} \tag{10}$$

- Voltage Control for Rectifier
  Using a PWM rectifier, voltage at DC bus is made constant at 48V by comparing it with V_{bus} and reference voltage 48V.

IV. Simulation Results

For simulation study, 2 cases of EV requirements are investigated. In case 1, five EVs are connected to charge from 20% to 95% SOC for 2 hours. Case 2 explains the requirement of 2 EVs to charge from 50% SOC to 95% SOC, 1 EV to charge from 80% to 95% SOC and 2 EVs to charge from 30% to 95% SOC are used.

A. Mode 1

A lookup table of irradiance and temperature for a day is given as the data to the PV panel block in MATLAB/Simulink. Fig. 3 shows the extreme power obtained from the PV array by MPPT for the corresponding data. A maximum of 4500W at peak time is obtained from 24 parallel connected solar panels of the selected PV array.

In this work, for considered 2 hours of operation, solar output increases from 3050W to 4000W. In simulation study, the power needed for charging all the five EVs at a time is obtained as 2688W to 980W for case 1 and 1780W to 600W case 2 respectively is shown in Fig. 4 and Fig. 5. The battery of EV charging from 20%, 30%, 50% and 80% to 95% SOC is shown in Fig. 6 for case 1 and case 2 respectively. The EVs are charged from their current SOC, SOC_c to 95% SOC in 2 hours.

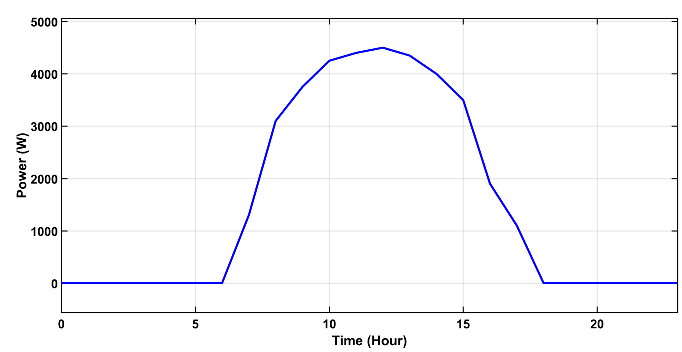

Fig. 3. Maximum power harvested from the PV array.

The current taken from the bus for charging the EVs is given in Fig. 7. At 40 minutes, for case 1, SOC of EV is charged from 20% to 70% with 6.5A at a power of 1500W thus validating the equation (3). The total current required for charging all the EVs at an instant of 40 minutes in case 2

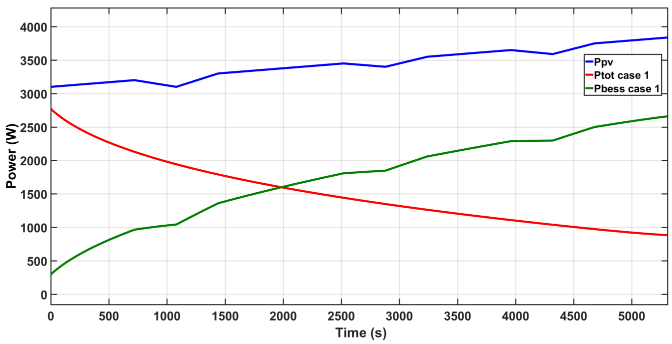

Fig. 4. Power from solar and total power required for EVs and BESS power for case 1.

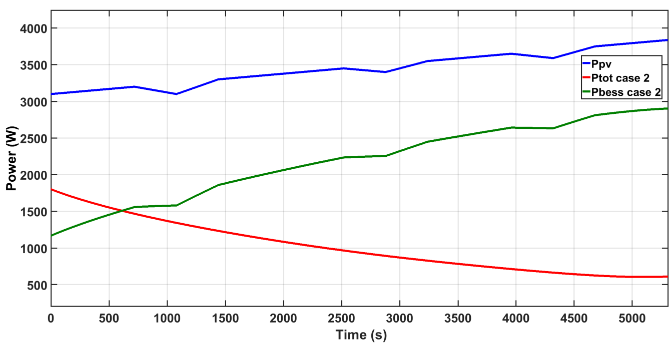

Fig. 5. Power from solar and total power required for EVs and power BESS for case 2.

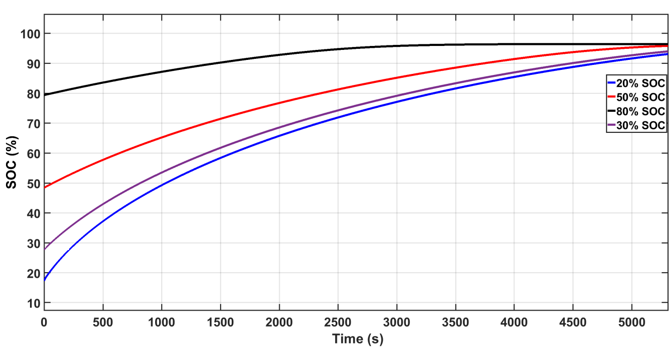

Fig. 6. Electric Vehicle charging for case 1 and case 2.

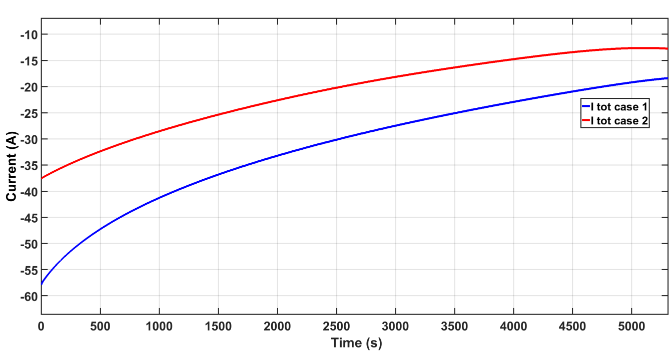

Fig. 7. Total current drawn by EVs for case 1 and for case 2.

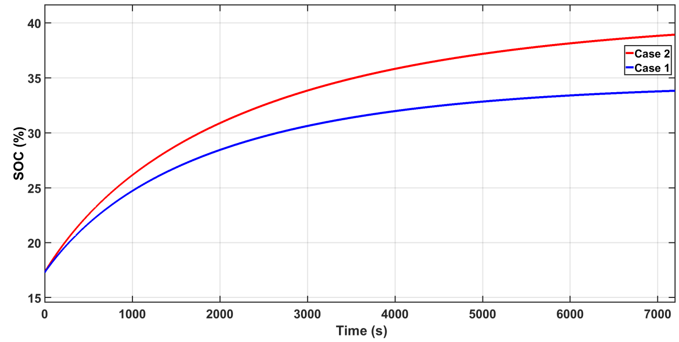

Fig. 8. SOC of BESS in case 1 and in case 2.

is given by 1000W/48V = 20A denoting the power balance. Since the EV battery is charging, the current is denoted as negative.

As in mode 1, the power from the solar is more compared with power needed for all EVs, BESS is connected to the DC bus for charging. BESS can be charged till it reaches the maximum SOC using the excess power. In case 1, with excess power 400W to 2400W, the BESS charges from 20% to 33% SOC and in case 2, the excess power 3100W-1800W = 1200W charges the BESS from 20% to 40% SOC as shown in Fig. 8.

B. Mode 2

In mode 2, BESS is disconnected and dummy loads are connected to the system for maintaining power balance. In simulation study, it is obtained that, P_{PV} ≈P_{Tot} + P_{dummy} as shown in Fig. 9. The dummy loads are connected to the system for maintaining power balance in the design of charging station. In practice, this excess power from the solar can be utilised for any residential or commercial purpose.

C. Mode 3

Since the PV power is less, switch closes and AC grid is cascaded to the system. Non-peak hours of solar output is taken for simulation purpose. Considering the rectifier efficiency, P_{grid} ≈P_{Tot} - P_{PV}, i.e. 2688W-1700W = 1000W as in Fig. 10 for case 1. Fig. 11 represents for case 2. The current drawn from the grid for both the cases is shown in Fig. 12. Current taken from the grid varies from 25A to 10A in case 1 and nearly 5A in case 2.

D. Mode 4

BESS discharges from its maximum SOC 95% to nearly 89% drawing 55A and 35A for case 1 and case 2 as in Fig. 13. Current drawn from the BESS for charging the EVs is shown in Fig. 14. The duty ratio is obtained for boost operation of the bi-directional converter as per [10].

E. Mode 5

With BESS state of charge 35% to discharging nearly 20%, the power in the storage system is lower than the power needed to charge all the EVs. Grid is connected to the system and deficient power is drawn. Fig. 15 shows the discharged BESS and Fig. 16 depicts the power drawn from the grid.

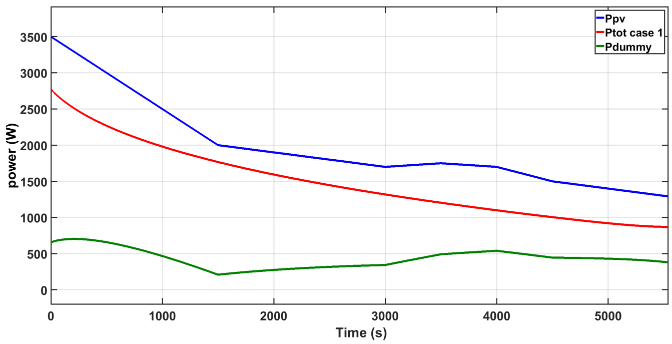

Fig. 9. Power from PV and excess power drawn by dummy loads.

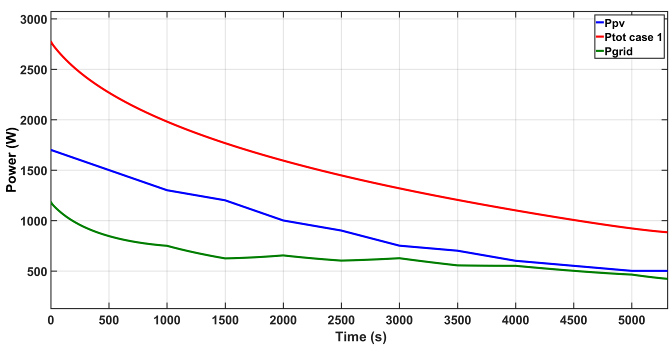

Fig. 10. Power from solar and total power required for EVs and power drawn from grid for case 1.

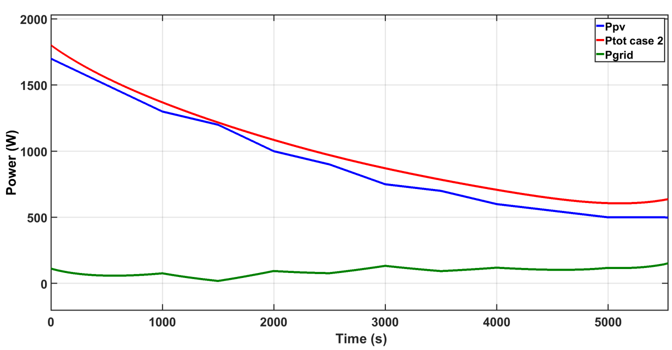

Fig. 11. Power from solar and total power required for EVs and power drawn from grid for case 2.

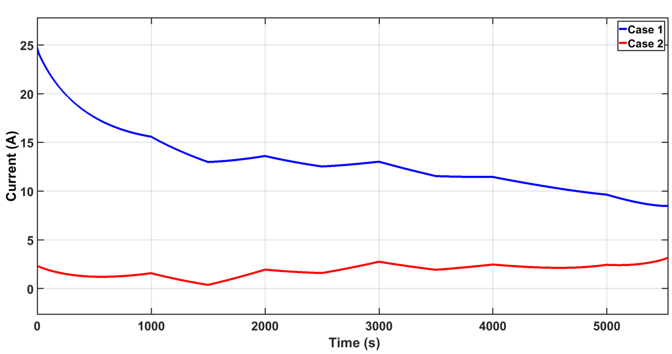

Fig. 12. Current drawn from grid for case 1 and case 2.

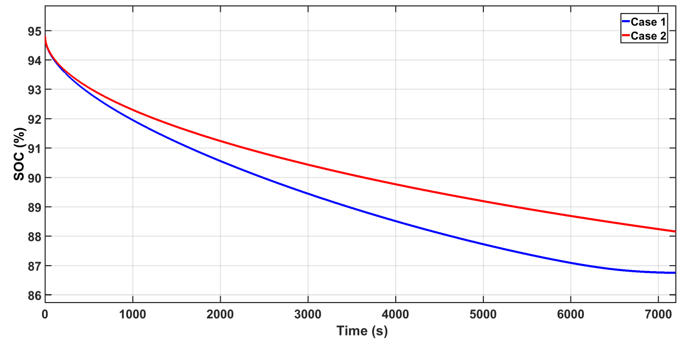

Fig. 13. BESS discharging for case 1 and case 2.

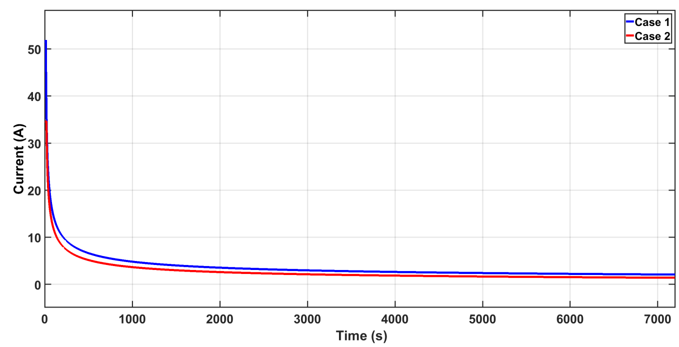

Fig. 14. Current drawn from BESS by EVs for case 1 and case 2.

By the adopted voltage control algorithm, the voltage of the DC bus was found as varying from 47.86V to 48.13V maintaining the 48V DC bus voltage limits. Fig. 17 depicts the DC bus voltage for the 2 hours of operation. With the proposed design, in Fig. 18, it shows the uninterrupted continuous operation of the presented charging station working throughout the day. By keeping the maximum power needed for all EV as constant at 2688W, the power management between solar, BESS and grid with the EV is shown describing all the modes of operation. Power from the PV, power drawn from the grid, dummy loads power with power demanded by all the EVs are plotted with state of charge of BESS. This shows the validation of the system for which it can be adopted for more EV demand and parking capacity.

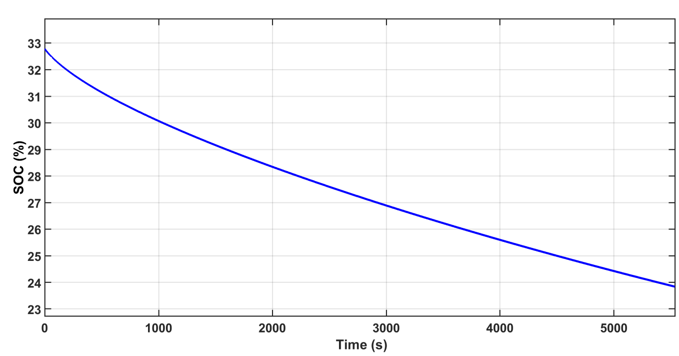

Fig. 15. BESS discharging for case 1.

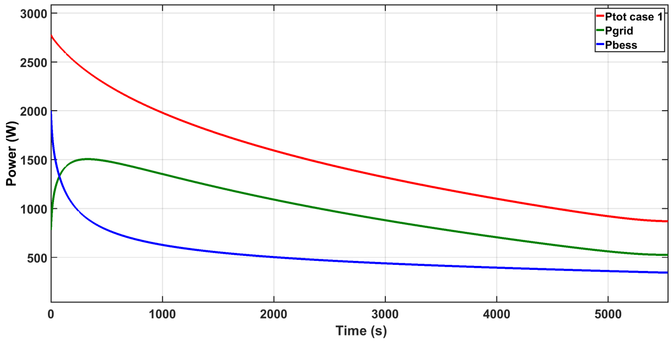

Fig. 16. Power taken from grid in case 1.

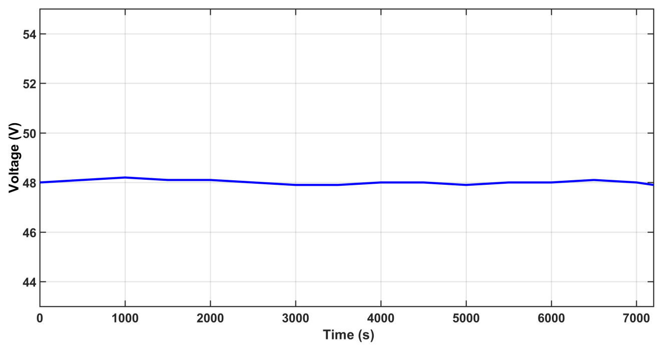

Fig. 17. DC bus voltage.

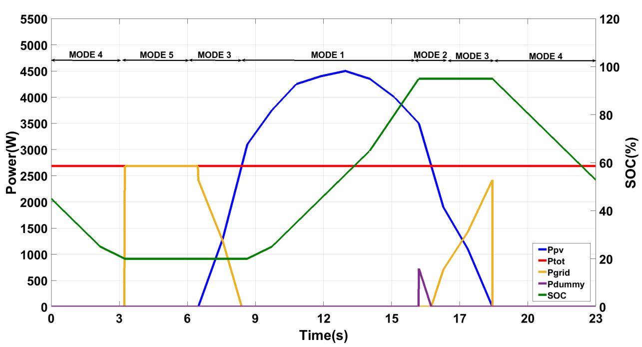

Fig. 18. Power management showing all modes of operation.

V. Conclusion

With increase of EVs on the road,charging of EVs possess as a critical issue. A charging station with solar, battery storage system with additional grid support gives a promising solution for satisfying charging requirements of all EVs connected throughout the day. Using PID, current control and voltage control desired power is obtained by maintaining the DC bus voltage constant for the station. The design and its power management of the proposed station is explained and validated in MATLAB/Simulink considering 5 different modes of operation and studying 2 cases of EV requirement thus making the design and algorithm robust. This can be adopted in large power rating and capacity for providing as the power outlet for EVs at workplace or parking lot.

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