Design and Control of DC Microgrid based on Solar PV and Storage

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***Abstract*— Microgrids are the solution to accommodate high penetration of renewable energy sources (RES) by achieving good coordination. However, in India, many households do not have access to electricity and some has interrupted and poor quality of electric power supply. The reason for this is large number of houses in remote areas are remaining off grid and which are connected with the grid have long hours of load shedding because shortage of power. Solar PV based DC microgrids with energy storage technologies in low- and medium-income households provides solution to above mentioned challanges. This paper presents a solar PV and BESS based DC microgrid with MPPT and BESS controller and energy management system. The solar PV and the battery energy storage system (BESS) are integrated with the help of dc-dc converters. The load requirements of small society of low demand households can be easily and cost effectively full filled by the proposed PV system and energy storage systems with energy management system.**

Keywords*— DC microgrid; solar PV system; battery energy stogage system (BESS); DC/DC converter; MPPT control

I. Introduction

The idea of microgrid gaining more attention due to increasing penetration of renewable energy sources (RES) and electricity transmission capacity constraints, losses at transmission and distribution level for long distance transmission of electric power [1]. Microgrids allow generation close to the load end increases the power quality and reliability (PQR) of supplied electricity. RES can significantly reduce requirement to expand the existing traditional transmission systems. Coordination and control of large numbers of RES in the system creates numerous difficulties from security and operation point of view.

Microgrid offers attractive solution with effective coordination of RES and reduce RES control burden on the utility grid with acquiring full benefits of RES. RES includes various alternative sources for power generation such as wind, solar, hydro and fuel cell etc. Increasing demand of electricity and environmental concern are the main drivers behind the adoption of RES for electricity production. Energy from sun is being utilized now a days and becoming one of the most prominent and promising form of RES. Since the output power of solar PV is always intermittent in nature an Energy storages system (ESS) is required in order to mitigate the intermittency of the solar PV power generation system.

Multiple power conversion stages are required for integration of dc-inherent system in the traditional AC utility grid. Mostly ESS used with Solar PV systems like batteries, ultra capacitors etc. are dc inherent in nature. There are numerous dc-compatible loads like communication systems, computation devices, LEDs, etc. are gaining more attention now a days. Due to above mentioned reasons DC micro grids are providing attractive solution with high penetration of DC compatible energy sources, storages and loads and need less number of power conversion stages. There are numerous applications of DC microgrids are available such as data center, residential applications, electric vehicle etc. DC microgrid system offers around 10-20% high efficiency as compared to AC systems. In addition, dc systems are more reliable due to minimized power conversion stages. In case of DC systems power transmission cables are utilized more effectively due to absence of reactive power flow.

However, in India, many households do not have access to electricity and some has interrupted and poor quality of electric power supply. A study conducted by the Council for Energy, Environment, and Water (CEEW) with six states (Bihar, Jharkhand, Madhya Pradesh, Uttar Pradesh, West Bengal, and Odisha) and concluded that about 50% of the houses do not have electricity despite having a grid connection [2]. Thousands of villages of different states are being electrified over the past decade under the Government's rural electrification scheme and over 85% of the households in five of the six states are considered as having no electricity or have electricity for less than 8 h with maximum load of 50 W. Other states have better situation than this but people with less income also have poor access to power [3-4].

These challenges need new technology and advance approaches. One approach can be adoption of novel solar and energy storage technologies integrated with DC microgrid in low- and medium-income households. Electricity authorities of many states such as Uttar Pradesh authorities are using 24 V solar powered DC microgrid for lighting loads [4]. Many problems can be mitigate with a DC microgrid having solar PV and battery storage for a household which have access to grid supply but suffers long hours of power cuts. Another advantage is this is highly cost effective for off-grid homes.

One important task in DC microgrids is power management. As the Solar PV is not available in night, ESS is required to operate and proper design of energy management system is necessary. From the stability point of view, the DC bus voltage regulation plays a key role. Researchers carried out various studies on design, operation and control of DC microgrids [5-8]. In this paper, design and control of DC microgrid based on solar PV and energy storage for remote areas is presented with an energy management system. The proposed system consists solar PV array, a battery energy storage system (BESS) with various loads and all are connected to a common DC bus.

This work is organized in following manner: Section 2 presents the system configuration. Section 3 describes the control techniques. Results and discussions are presented in Section 4 followed by the conclusion in section 5.

II. System Design

The DC microgrid considered in the present work consists of PV array, DC/DC converter, battery energy storage system (BESS), bi directional DC/DC controller for BESSand various loads. The dc microgrid proposed in this work is shown in Fig.l. The battery energy storage system is composed of lead acid battery with high energy density.

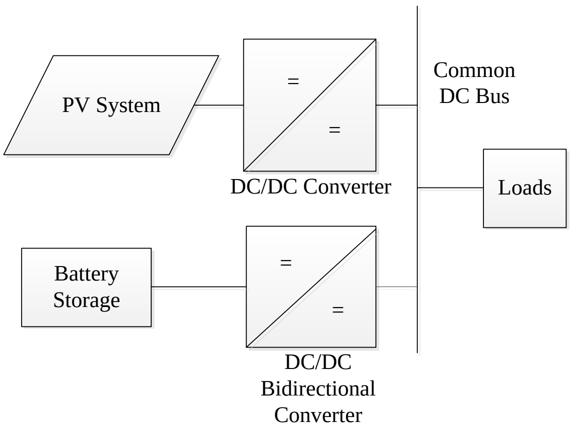

Fig. 1. DC microgrid system

A. *Solar PV array*

A photovoltaic (PV) array consists of several PV modules which are series or parallel interconnection of several PV cells. Power produced by single PV cell is not sufficient to drive any application hence PV cells are connected to obtain PV module. PV modules are further interconnected in array form to achieve more power to fulfill load requirement. To form PV array, modules are first connected in series configuration to produce the high voltages and further, to produce more current, the individual single modules are then connected in parallel configuration. Most widely used single diode model of basic solar PV cell is presented in fig.2 followed by mathematical equations to model a module [9-10].

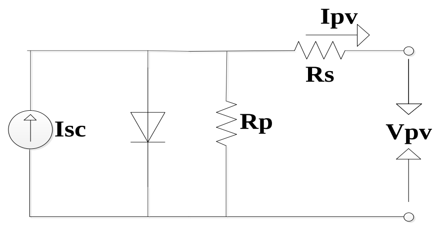

Fig. 2. Single diode model of PV cell

Equations for the output current using fig.2 can be obtained as follows:

$$I_{sc} - I_D - \frac{V_D}{R_p} - I_{PV} = 0 \quad (1)$$

Where

$$I_D = I_{scref}[\exp\left(\frac{qVoc}{kAT}\right) - 1] \quad (2)$$

The incident current measured with respect to some standard conditions depends on irradiance and temperature.

Thus,

$$I_{sc} = [I_{scref} + K_i(T_k - T_{ref})] * S/1000 \quad (3)$$

In above expression I_{sc} denotes the photocurrent in amperes which is generated from solar incident current at the standard condition (25°C and 1000W/m^2), Ki represents the short-circuit current/temperature coefficient at I_{scref} (0.00065A/K), T_k and T_{ref} are the actual and reference temperature in Kelvin, S shows the actual solar irradiance coming at the surface of device and 1000W/m^2 is the irradiation at standard reference conditions.

Reverse saturation current I_{rs} of diode can be written as:

$$I_{rs} = I_{scref} + [\exp\left(\frac{qVoc}{NskAT}\right) - 1] \quad (4)$$

The saturation current of module varies with the cell temperature which is given by;

$$I_o = I_{rs}\left[\frac{\left(\frac{T}{T_{ref}}\right)^3 e^{qEg}}{Ak} * \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \quad (5)$$

The output current equation can be written as:

$$I_{PV} = I_{sc}N_p - N_s I_o\left[\exp\left\{\frac{q(V_{PV} + I_{PV}Rs)}{N_s AkT}\right\} - 1\right] V_{PV} + \frac{I_{PV}Rs}{Rp}$$
(6)

In equation (6) k is the Boltzmann constant (1.38 x 10^{-23} J K^{-1}), q is the electronic charge (1.602 x 10^{-19} C), T is the cell temperature (K); A is the diode ideality factor, R_s the series resistance (Ω) and R_p is the shunt resistance (Ω). N_S is the number of cells connected in series and N_p is the number of cells connected in parallel.

B. DC/DC Converter

Numerous meteorological parameters such solar irradiance, temperature, wind speed, wind direction, humidity, incident angle etc. significantly makes impact on solar PV output, that is the reason of intermittency of the PV output power. A DC/DC converter is needed in order to implement the algorithm which keeps on tracking the maximum power point of the PV array and to match the load with the source. In the present system a DC/DC boost converter is used to step up the voltage level. Basic DC/DC boost converter configuration is presented in fig. 3.The design of input inductor of DC/DC boost converter is depend on the input ripple current (ΔI_1) and switching frequency (f_{sw}). ΔI_1 is considered as 6% of input current to the DC/DC boost converter and switching frequency (f_{sw}) is chosen as 10 kHz. The value of input inductor (L_b) can be calculated as:

$$L_b = \frac{V_{PV}\,D}{\Delta i f_{sw}} \tag{7}$$

Where, $D = 1 - \frac{V_{PV}}{V_{DC}}$

DC link Capacitors (C)

$$C = \frac{I_{in} D}{\Delta v f_{sw}} \tag{8}$$

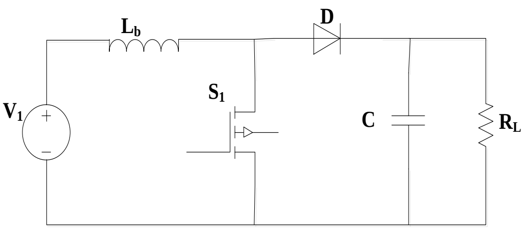

Fig. 3. DC/DC boost converter

C. Battery Energy Storage System (BESS)

The BESS can be modeled as a controlled voltage source in series with constant resistance. Output voltage of which depends on the current and state of charge (SOC) of battery which is nonlinear function of the current and time. State of a battery can be modeled as a function of two parameters; terminal voltage and state of charge [11-12].

$$V_b = V_o + R_b i_b - K\frac{Q}{Q-\int i_b dt} + A * \exp\left(B \int i_b dt\right) \tag{9}$$

$$SOC = 100\left(1 + \frac{\int i_b dt}{Q}\right) \tag{10}$$

In above mentioned expressions V_b denotes battery voltage, V_o is no load voltage, R_b represent constant series resistance, i_b is battery current, K is polarization constant, is capacity of battery, A and B are exponential voltage and capacity respectively. A lead acid battery is being considered in present work using a DC source and internal resistance.

D. DC/DC Bidirectional Buck-Boost Converter

In case of excessive generation from solar PV system during day time battery storage gets charged and this power may be used during night time or when the generation from solar PV is not sufficient to feed the load. A DC/DC bi-directional converter performs the regulation of dc link voltage at a constant level.

During charging mode of BESS converter works in buck mode by using duty cycle provided by the BESS controller. Boost mode comes in picture during discharge operation required. Two IGBT switches operates complementary with single Pulse Width Modulation (PWM) signal. Input and output voltage relationship during buck and boost mode are presented in equation (11) and (12) respectively. D denotes the duty cycle in below given expressions.

$$\frac{V_{bat}}{V_{dc}} = D \tag{11}$$

$$\frac{V_{bat}}{V_{dc}} = \frac{1}{1-D} \tag{12}$$

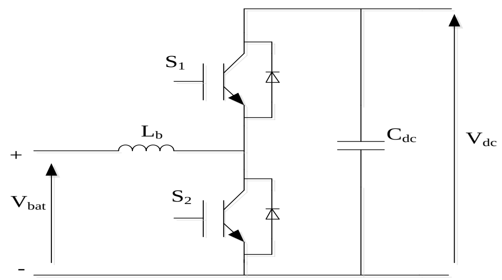

Fig. 4. DC/DC bidirectional buck boost converter

III. Control Design

A. DC/DC Converter control

A MPPT algorithm is used to extract the maximum power from PV array. PV array output voltage/current is varied by MPPT controller according to the P-V or I-V characteristic curves of PV array. A large number of MPPT techniques are reported in the literature to track the maximum power point [13]. MPPT techniques like perturb and observe, incremental conductance, constant voltage, open circuit voltage, short circuit current, extremum seeking control and hybrid etc are widely being used in systems. MPPT techniques based on artificial intelligence like artificial neural networks, fuzzy logic, genetic algorithms are also provided in the literature.

An Incremental conductance (INC) based method is being considered in the present work. This method is based on the concept that the slope of the solar PV array curve is zero at maximum power point. The slope of PV curve will be positive for values of output power smaller then maximum power point (MPP) and negative for output power greater then maximum power point.

Maximum output power is obtained by using the derivative of PV output power with respect to voltage and equating this to zero.

$$\frac{dP}{dV} = I + V\frac{dI}{dV} = 0 \tag{13}$$

Equation (13) can be further used to obtain below given expression:

$$\frac{dI}{dV} \cong \frac{\Delta I}{\Delta V} = -\frac{I_{MPP}}{V_{MPP}} \tag{14}$$

$$\frac{dP}{dV} = 0 \qquad \frac{\Delta I}{\Delta V} = -\frac{I}{V} \qquad \text{at MPP}$$

$$\frac{dP}{dV} > 0 \qquad \frac{\Delta I}{\Delta V} > -\frac{I}{V} \qquad \text{left side of MPP}$$

$$\frac{dP}{dV} < 0 \qquad \frac{\Delta I}{\Delta V} < -\frac{I}{V} \qquad \text{right side of MPP}$$

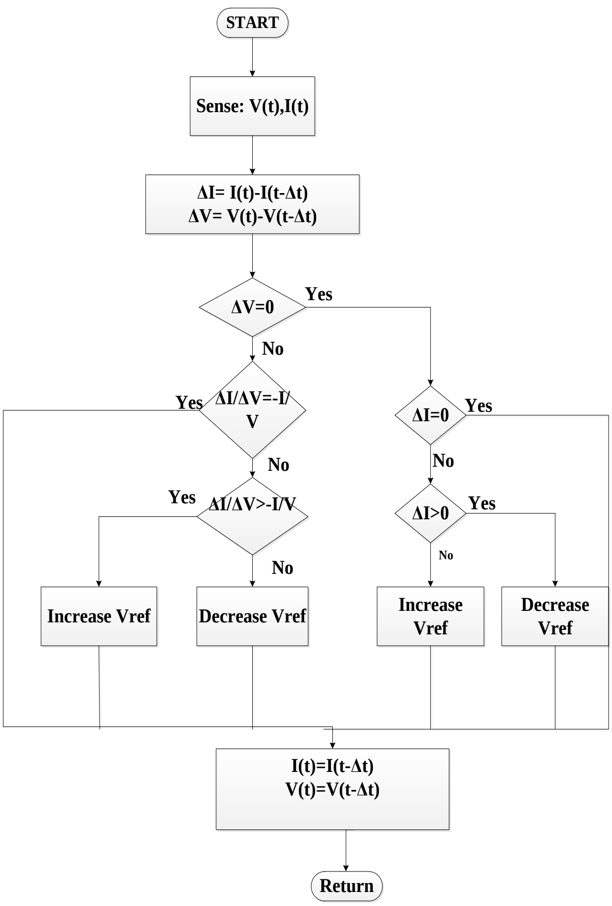

Fig. 5. Flowchart of MPPT algorithm

In INC algorithm compares instantaneous conductance with the incremental conductance to achieve the maximum power point operation of solar PV array. After reaching at MPP, the operation of PV array system is forced to remain at this point unless a change in current occurs due to varying meteorological parameters which further leads to the variation in MPP. The flowchart for this technique is presented in Fig. 5.

B. BESS control

Battery energy storage systems (BESS) are most widely adopted ESS especially for low power residential applications. BESS are the storage devices that cannot be overcharged or depleted entirely. For a long life, charging and discharging has to be properly controlled. State of the charge (SOC) of the BESS is a key parameter to develop control methodology [14-15]. The BESS is integrated with the Solar PV system is used to supply or consume real power to support the SPV generator in form of charging and discharging.

In case of surplus power production by solar PV, the battery bank will be get charged. If there is no sufficient power from SPV available then the battery will supply the remaining power in order to fulfill load requirements in night time or unavailability of solar power. Controller for bidirectional DC/DC converter of BESS is presented in fig. 6. The proposed controller consists of a PI controller, which receives the error signal of actual battery power (P_b) and battery reference power (P_{bref}). The output of PI controller further compared with a triangular carrier waveform of unity magnitude to generate the PWM signal G. K_p and K_I are the proportional and integral gains of PI controller, respectively. The controller action equation is given in equation 15.

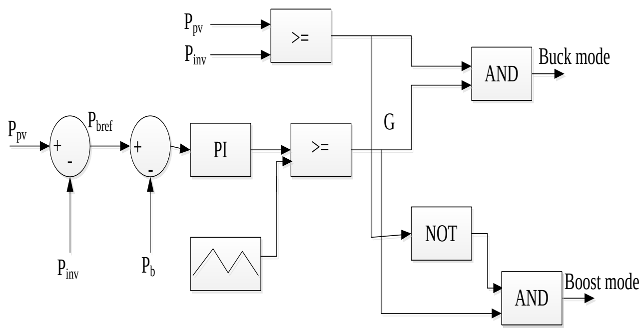

Fig. 6. Bi-directional DC/DC converter controller

$$G = K_p\left(P_{bref} - P_b\right) + K_I \int \left(P_{bref} - P_b\right)dt \tag{15}$$

Energy management system (EMS) control algorithm for the proposed system is presented in Fig. 7. SOC indication is used to maintain the charging and discharging of BESS within prescribed limits which are considered as 25% and 85% respectively here. The actions taken by the controller according to state of charge condition of BESS are presented in table I.

TABLE I. OPERATION OF ENERGY MANAGEMENT SYSTEM

Condition	Battery SOC	P_{pv} and P_{load}	Action
I	SOC<85%	$P_{pv}>P_{load}$	Charge battery
II	SOC<25%	$P_{pv}>P_{load}$	Charge battery
III	SOC>85%	$P_{pv}<P_{load}$	Discharge battery
IV	SOC>25%	$P_{pv}<P_{load}$	Discharge battery
V	SOC<25%	$P_{pv}<P_{load}$	Load Shedding
VI	SOC>85%	$P_{pv}>P_{load}$	Idle (If no additional available)

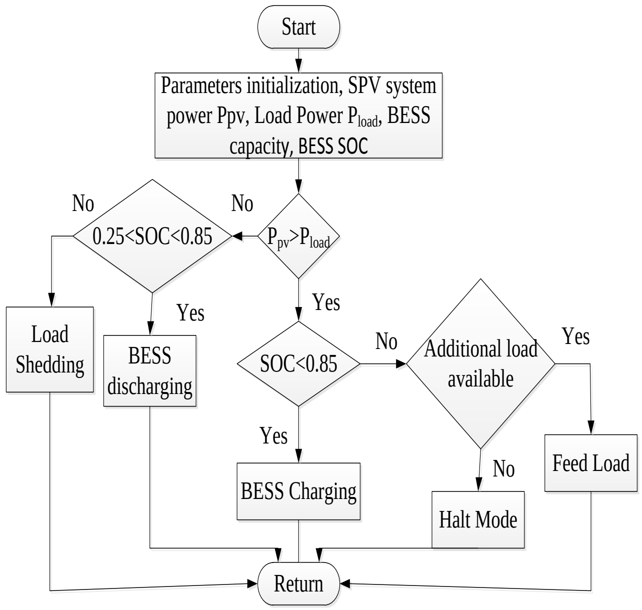

Fig. 7. Flowchart for BESS control

IV. RESULTS

The simulations studies of the proposed system is presented in this section with controllers and energy management system of DC microgrid based on solar PV and battery. Typical loads for a household application powered by DC microgrid are presented in table II. For a practical application, a 2 kW PV array has been considered here to power a small locality of such type of houses. A typical solar irradiance profile for a day is presented in fig. 8.

TABLE II. TYPICAL LOADS FOR RESIDENTIAL APPLICTIONS

DC Load Type	Power Rating (W)	Numbers	No. of operational hours
Fan	24	3	8
Tubelight	18	2	10
Bulb	5	3	10
TV	30	1	4
Phone	5	2	10

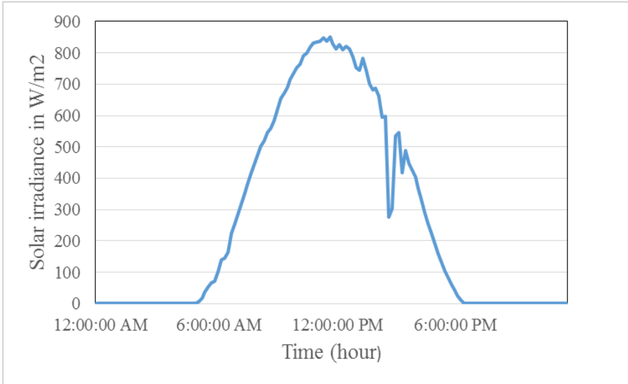

Fig. 8. Typical solar irradiance profile for a day

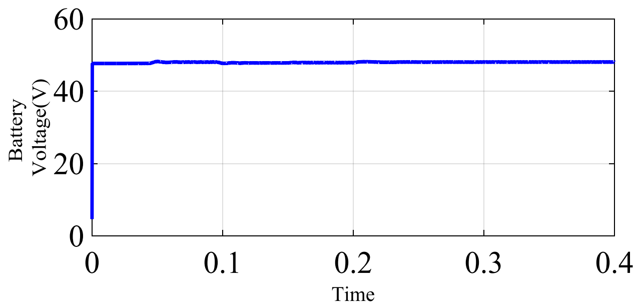

Fig. 9. Battery voltage in volts

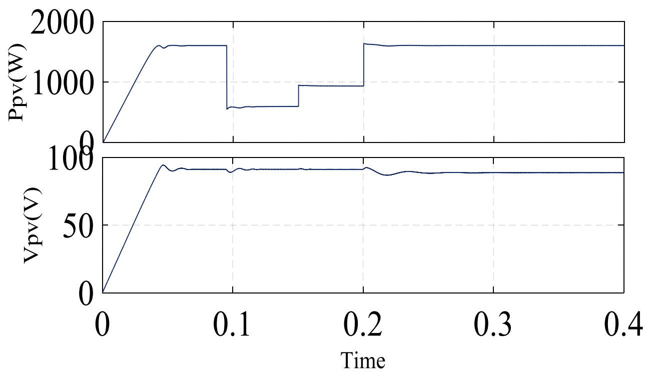

Fig. 10. Solar PV power (W) and voltage (V)

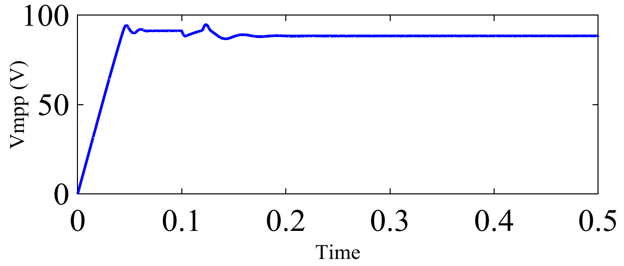

Fig. 11. Solar PV voltage at maximum power point maintained by INC MPPT Technique

By using BESS controller a constant voltage of 48 V maintained across the BESS and shown in fig. 9. Fig. 10 shows the output PV power at varying solar irradiance level and depicting practical case. INC MPPT technique regulates the PV voltage at constant MPP level and shown in fig. 11. When excess PV power is generated battery is getting charged otherwise feeding to the load. Power of PV, load and battery is given in fig. 12. If solar irradiance comes down battery follows a rapid discharging rate. While during large amount of solar irradiance BESS get charged until the maximum SOC level.

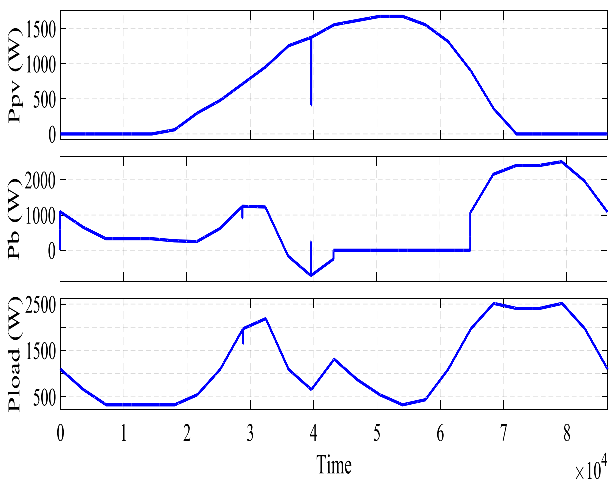

Fig. 12. Solar PV power, BESS power and load power

V. Conclusion

A solar PV system and battery energy storage based DC microgrid has been developed in this paper with MPPT and BESS controllers. The performance of proposed system in terms of PV output power, PV voltage, BESS voltage, BESS power and SOC is presented. Disruptive technology is the demand of the present time in order to get uninterruptable power supply. A DC microgrid based on solar PV and BESS for households seems attractive solution. As a result of which the overall cost of power can be reduced and become affordable in the presence of a utility grid also by reducing load shedding significantly.

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