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An Efficient Energy Management System for Standalone DC Microgrid

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ABSTRACT

Standalone microgrid is an effective solution for the electricity needs in remote area. Generally, DC microgrid is a self-management form of grid, integrating Renewable Energy Systems (RES), Energy Management Unit (EMU), Energy Storage Systems (ESS) and Loads. The incorporation of multiple renewable energy resource and proper energy management of the microgrid system to meet the energy demand of the users is a major challenge. Hence, for the proper power flow and energy management of the microgrid, efficient control techniques are required. A Standalone DC Microgrid with an efficient Energy Management System (EMS) is discussed in this paper. Simulation of the proposed system is carried out for several input and load conditions.

Keywords: *Renewable Energy Sources (RES), Energy Management Unit (EMU), Energy Storage System (ESS), Microgrid.*

I. INTRODUCTION

There is a demand for higher generation of power due to the increase in population and the developments in the industrial sector. Currently, conventional resources such as coal, water, natural gas, nuclear power etc. are the major source of electricity. The major drawback of these conventional sources is that they cause high pollution. This paves the way for using renewables such as solar, wind etc. The incorporation of distributed generation (DG) with the existing grid will reduce burden on utility grid and carbon emissions due to the usage of conventional fossil fuel-based systems can also be significantly reduced. [1].

A low voltage power grid, consisting of various loads and DG's is referred to as a Micro-grid. It employs two modes i.e., grid-connected mode and islanded-mode. In grid connected mode, in order to exchange power with the utility grid, the DC microgrid is connected to the utility grid [2]. Hence power fluctuation, faced by the system is high. In islanded mode, no power is exchanged with the utility grid as the microgrid is not connected to the utility grid.

Generally, microgrid is a self-management system that integrates Renewable energy system, Energy storage system, Energy management unit and Loads. Amongst the RES, solar energy is the most abundantly available renewable energy resource. Photovoltaic (PV) cells are used to convert the solar energy into electrical energy. Due to the non-linear characteristics of the PV cell, maximum power which a PV cell can produce may vary. Various techniques called Maximum Power Point Tracking (MPPT) techniques are used to obtain maximum power from PV cells [3].

Energy balance is a major problem caused by the intermittent nature of renewable energy resources in a microgrid, which in turn paved the way for storage devices. Battery is a common storage device used as the Energy Storage Unit [4]. It plays a key role in power sharing and grid stability [5]. By ensuring autonomous operation of the microgrid through managing the distributed sources' power, the performance of the microgrid can be enhanced. This can be attained by incorporating an efficient Energy Management System [6].

In [7], a PV based microgrid with battery storage system incorporating an energy management algorithm is explained. The PV along with buck converter forms the RES unit and it is supported by a battery storage unit. The bidirectional power flow of battery is carried out by a bidirectional converter.

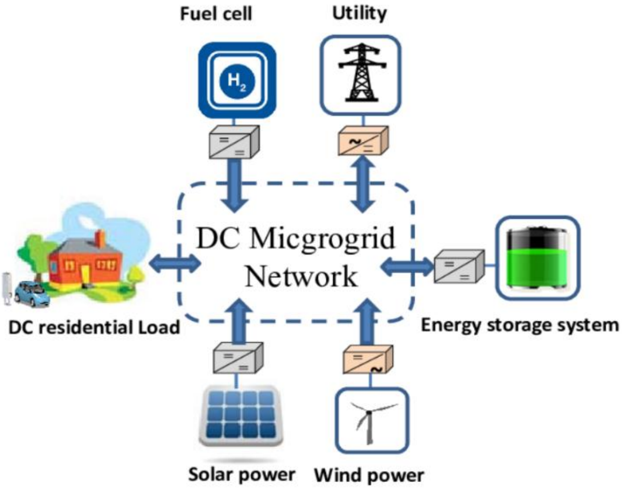

Fig.1 Model of DC microgrid [13]

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The purpose of this paper is to develop and design a DC microgrid consist of distributed energy sources (solar PV), energy storage unit and dc loads with an efficient energy management system so that the power balance in the microgrid is maintained. The rest of the paper is organized as follows; Section II illustrates the complete system design, individual unit details and converter topologies. Following that, the simulation results at various input and load conditions are discussed in section III and the paper ends with conclusions in section IV.

II. SYSTEM DESIGN AND ARCHITECTURE

A. SYSTEM DESCRIPTION

The proposed system shown in Fig.1. consists of (i). Solar PV system (ii). DC-DC boost converter (iii) Battery Storage System and (iv) Bidirectional buck-boost converter. The system is connected to a DC bus and a resistive load is connected to study the power flow between source, load and energy storage unit. A 100 W photo-voltaic (PV) module is used. The PV system is operated under voltage control method. In order to control the power flow between various units under different conditions, an energy management system is used so as to supply the dc load.

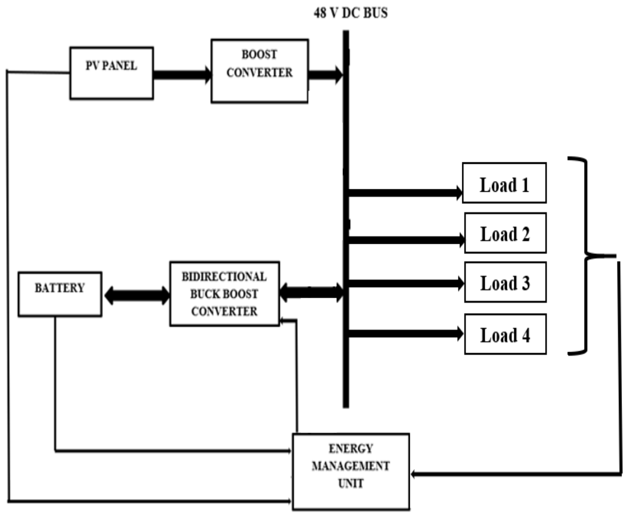

Fig.2 Block diagram of proposed system

(i). SOLAR ENERGY CONVERSION SYSTEM (SECS)

The Solar Energy Conversion System consists of a 100 W PV module which is connected to a boost converter as shown in Fig.3. Depending on the load power and SOC of battery, PV can be operated in either ON mode or in OFF mode. The output of solar PV is dependent on the solar irradiation and temperature. For higher irradiation, power output will be higher. Similarly, for higher temperature, output power will be less than the power generated under Standard Test Condition (STC) i.e., PV current depends on solar irradiation. Current generated by a PV cell can be obtained from the following equations.

$$I = (I_{pv,n} + K_I \Delta T)\frac{G}{G_n} \quad (1)$$

Where $I_{pv,n}$ is the PV current at $25^0 C$ & $1000 W/m^2$ and G_n, G is the Nominal and actual irradiation and T_n, T are Nominal & Actual temperature, $\Delta T = T_n - T$.

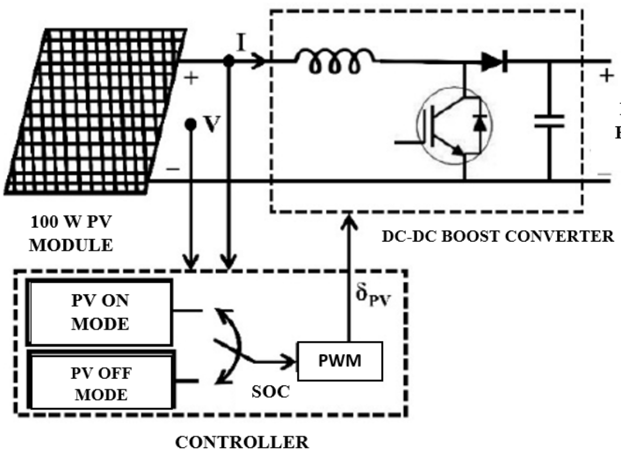

Fig.3 Block diagram of proposed SECS

The P-V characteristics of a 100 W solar panel at various irradiance level [1000 W/m^2, 500W/m^2, 100W/m^2] is shown in fig.4. The parameters of PV module are shown in Table 1.

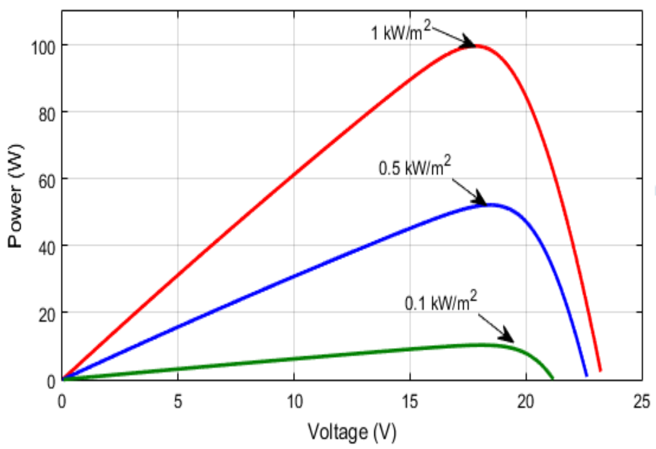

Fig.4 Effect of irradiance on PV module performance at T = $25^0 C$.

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Table 1. Parameters of the PV Module

Parameters	Values
MPP voltage - V_{mpp}	17.8V
MPP current - I_{mpp}	5.6A
Open Circuit Voltage - V_0	23.3 V
Short Circuit Current - I_{sc}	6.4 A
Maximum Power - P_{mpp}	99.68 W

(ii). DC-DC BOOST CONVERTER

DC-DC converters are used either to step up/step down the voltage in a system. In this system, DC-DC boost converter is used to boost the PV voltage to 48V [12]. The input voltage of the boost converter is 24V i.e., the PV output voltage. The duty ratio of the boost converter can be calculated from (2). The value of inductor is given by (3).

$$V_a = \frac{V_s}{1-k} \qquad (2)$$

Where V_a is the grid side voltage and is taken as 48V. V_s is the PV Panel output voltage (24V) From (2), duty ratio k is computed as 50%. The value of inductor is calculated from (3). Here f is the switching frequency. It is taken as 25kHz. ΔI is the current ripple. The ripple value is taken as 1% of output current.

$$L = \frac{V_s k}{f \Delta I} \qquad (3)$$

From (3), value of the inductor is calculated as 2.307mH. Value of capacitor in the boost converter is calculated from (4). ΔV_c is the voltage ripple. It is taken as 1%. I_a is the grid side current.

$$C = \frac{I_a k}{\Delta V_c f} \qquad (4)$$

The value of capacitor is computed as 86.79 μF .

Table 2. Parameters of the DC-DC Boost converter

Parameters	Values
Inductance (L)	2.307 mH
Capacitance (C)	86.790 μF
Switching frequency(f)	25 kHz
Duty cycle	50 %

(iii). BATTERY ENERGY STORAGE SYSTEM

To maintain the grid power, irrespective of the change in solar power output, an energy storage unit is employed in microgrid. A 24 V, 5 Ah battery is used as the ESU and it is connected to a Bidirectional Buck-Boost Converter. It operates in both buck and boost mode allowing power flow between the Microgrid and the battery. The converter is controlled using PI controller as shown in fig.5 and constant voltage is maintained at DC bus. The state of charge of battery (SOC) is calculated using (7).

$$SOC = 100(1 + \int \frac{I_{bat}}{Q} dt) \qquad (7)$$

The battery will operate in two modes; discharging and charging, this depends on two factors, (a) the power generated by the PV system and (b) the energy constraints determined by the battery's SOC limits (8).

$$SOC_{MIN} \leq SOC \leq SOC_{MAX} \qquad (8)$$

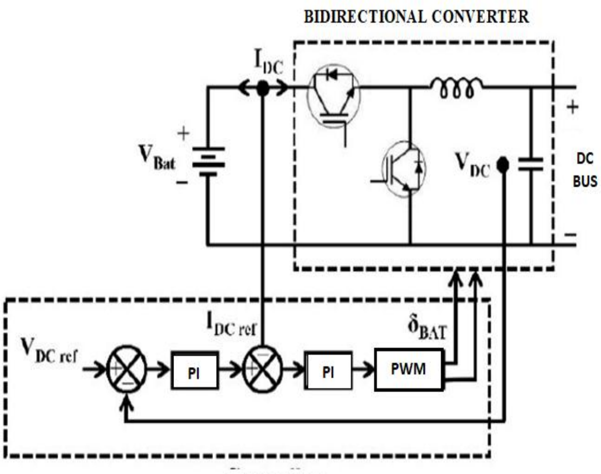

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Fig.5. Battery energy storage system with controller.

(iv). BIDIRECTIONAL BUCK BOOST CONVERTER

The storage unit 'Battery' is connected to a bidirectional buck boost converter. During charging, the bidirectional buck boost converter operates in buck mode and during discharging it operates in boost mode. The design of the converter is done as in [1].

$$C_h = \frac{I_h D_1}{\Delta V_h f} \tag{9}$$

$$L_m = \frac{D_1 (1 - D_1)^2 R_h}{2 f} \tag{10}$$

$$C_l = \frac{1 - D_2}{8\left(\frac{\Delta V_l}{V_l}\right) L_m f^2} \tag{11}$$

Where I_h, D_1, f, ΔV_h, R_h, ΔV_l and D_2 are the grid side current duty ratio at boost mode, switching frequency, voltage ripple at grid side and resistive load at grid side, voltage ripple at the battery side and duty ratio during boost mode respectively. The voltage ripple is taken as 1%. The switching frequency is set to be 25kHz.The parameters of the Bidirectional Buck-Boost converter is shown in Table 3.

Table 3. Parameters of the Bidirectional Buck- Boost converter

Parameters	**Values**
Inductance (L)	85.33 μH
Capacitance (C_h)	57.2 μF
Capacitance(C_l)	314.07 μF
Switching frequency(f)	25 kHz
Duty cycle	50 %

B. ENERGY MANAGEMENT SYSTEM

The energy management control unit or energy management system controls and coordinates all control action in the dc microgrid. Depending on the power generation, the SECS operates in two modes; PV ON mode and PV OFF mode.

The bidirectional converter of the battery operates in charging or discharging mode and thus, maintains constant DC bus voltage. Power must be balanced in the microgrid under various irradiance and load demand conditions. The power balance equation is as follows.

$$P_{req} = P_{Load} - P_{pv} \tag{4}$$

The various modes of operation of the energy management system is presented in the algorithm and flowchart.

(i). ALGORITHM OF EMS

Step 1: Start

Step 2: Measure voltage and current of PV unit & Load.

Step3: Measure PV power (P_{pv}) and calculate load power (P_{load}) and SOC of battery

Step 4: Calculate $P_{req} = P_{Load} - P_{pv}$

Step 5: Check if P_{req} is greater than zero, goto next step, else goto step 9

Step 6: Check SOC of battery is greater than 30%, and goto next step, else goto step 8

Step 7: Discharge battery to meet load demand. i.e,

$$P_L = P_{PV} + P_{BAT}$$

Step 8: Shut down the load and charge the battery.

Step 9: Check SOC of battery is less than 90% and goto next step, else goto step 11

Step 10: Charge the battery and Load is met by solar power.

Step 11: Supply Load

Step 12: Return

The Energy Management System is operated based on two conditions; state of charge of battery and the net power difference between the PV power output and the load power. When the PV power output is deficient compared to load power, then the battery's SOC is checked and if it is greater than 30%, both PV and battery supplies the load otherwise shut down the load and charge the battery. When there is excess of PV power compared to load power, again SOC of

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battery is checked and if it is less than 90%, charge the battery and supply the load otherwise supply the load only.

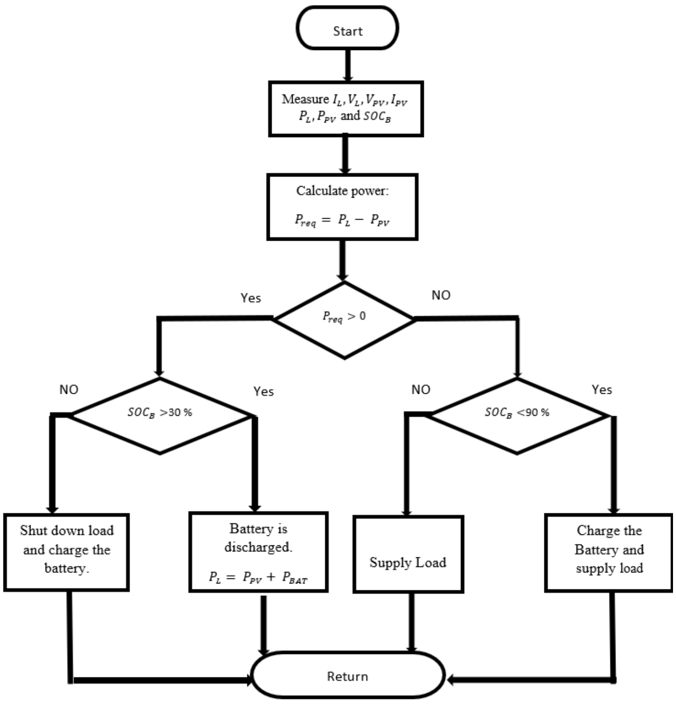

Fig.6 Flow chart of the Energy Management Unit.

I. SIMULATION RESULTS

The complete simulation model of the DC microgrid is shown in Fig. 7. The system integrates PV module, an energy storage unit (battery) and converters along with an energy management unit.

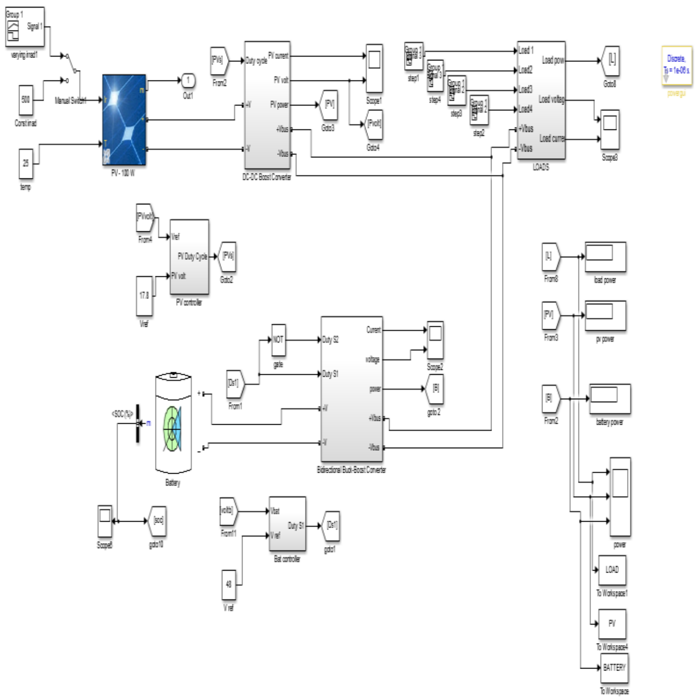

Fig.7 MATLAB Simulink Model of proposed system

The DC microgrid model is built in MATLAB / Simulink. Simulation is carried out for different cases in order to analyze the performance of the Controllers and EMU. The first case is carried out for variations in load demand with constant PV output power by maintaining constant irradiance. The second case is performed at a constant load and varying irradiation conditions and the results are plotted. At 1000 W/m^2 and $25^0 C$, the power reaches a maximum of 99.68 Watts power at 17.8 V. The voltage control method in PV unit keeps the output power near to its maximum power.

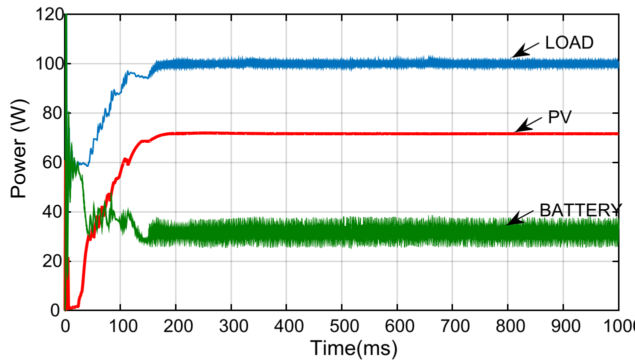

Fig.8 Power sharing at a load of 100W and irradiance of 700 W/m^2

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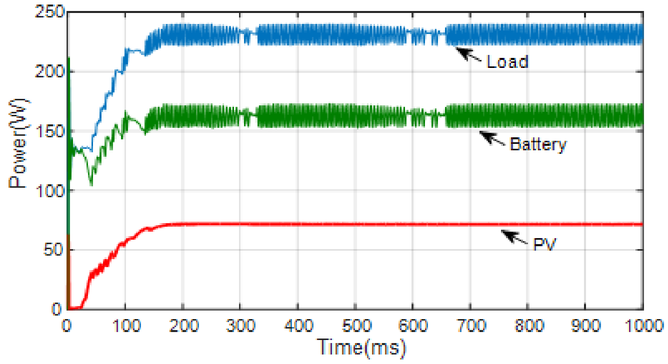

Fig.9 Power sharing at a load of 230W and irradiance of 700 W/m^2

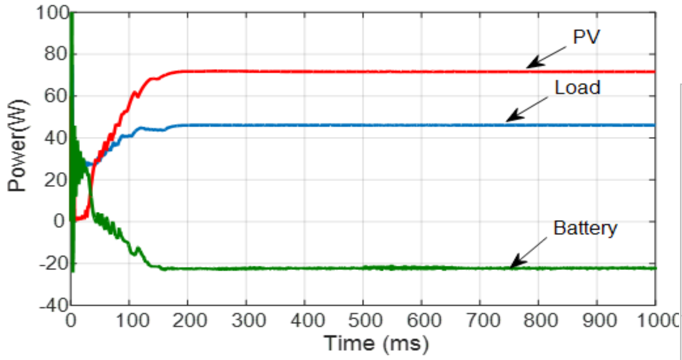

Fig.10 Power sharing at a load of 48W and irradiance of 700 W/m^2

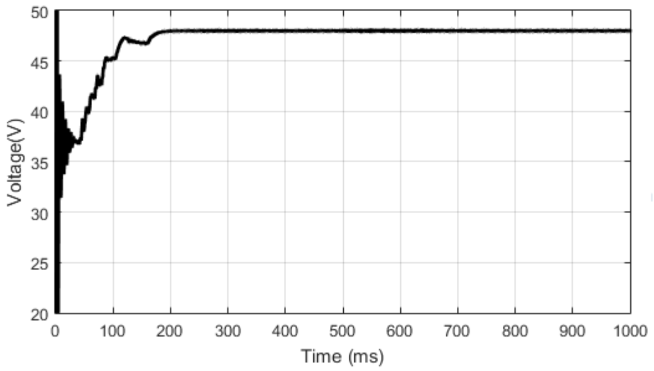

Fig.11 Output voltage (bus voltage) at all cases

Table 4. Power sharing between load, PV and battery at irradiance of 700 W/m^2

Irradiations (W/m^2)	**V_{out} (v)**	**Load power (W)**	**PV power (W)**	**Battery power (W)**
700	48.2	100.8	71.6	31.1
	47.8	228.2	71.6	156.6
	48.01	48.07	71.63	-21.5

Fig.8, Fig.9, Fig.10 illustrates the power flow between PV and battery at various load conditions. The DC microgrid is tested at the irradiance level of 700 W/m^2 and the initial load is about 100W.At these conditions the PV is able to produce a power of 71.6W. Since the load demand cannot met by PV alone, the battery starts discharging a power of 31.1W Second condition is that the load power is set above 100W i.e.; 228 W. At this condition also the battery is in discharging mode and supplies a power of 156W as shown in fig 9. Third case is that the load is set below 100W i.e.; 48W as shown in fig 10. In this condition there is excess of PV power and it is stored in battery, so the battery is in charging mode. In all these conditions the system voltage remains constant as 48 V as shown in Fig 11

Table.4 summarizes the results of power flow between PV, battery and load at constant irradiance level [700 W/m^2]. Hence the PV power output is also constant (71.63W). In all three cases the system voltage remains constant (48V). In first two cases, the load demand is met by both PV and battery. In last case the load is met by PV alone and its excess power is stored in battery.

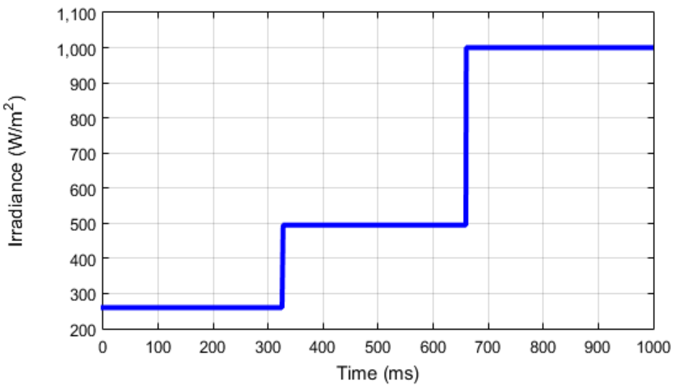

Fig.12 Varying irradiance level.

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To study the operation of the system under varying input conditions, the irradiance is varied as shown in fig.12. The load is constant throughout the operation.

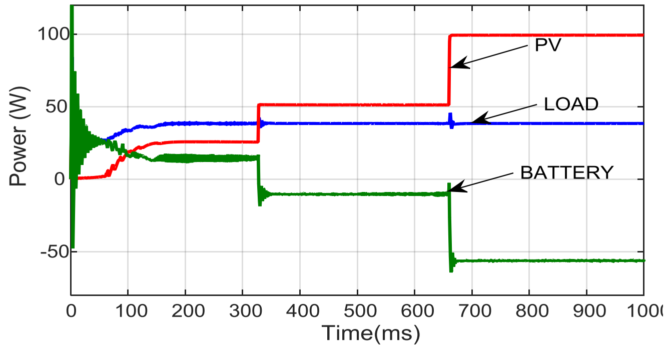

Fig.13 Power sharing between PV, load and battery at varying irradiance

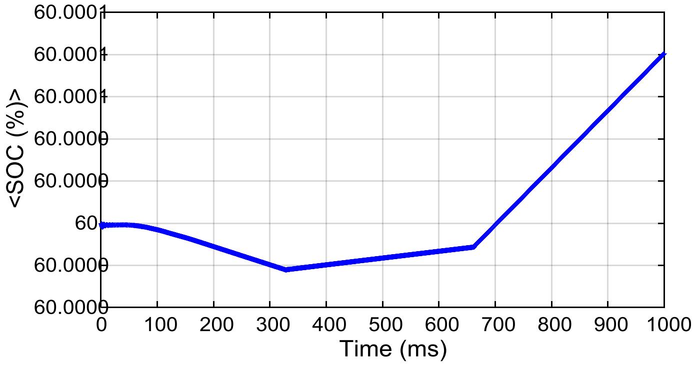

Fig.14 SOC of battery at varying irradiance

The fig13 illustrates the power flow between PV, battery and load at varying irradiance level. The DC microgrid is tested under varying irradiance level of 250 W/m^2, 500 W/m^2, 1000 W/m^2 at a load of 40W.

At above conditions the PV is able to produce varying power of 25.67W, 51.7W, 99.7W. In the first condition, the load power is higher than the PV power, then the battery starts discharging a power of 17.2W upto 333ms. Second condition is that the load power remains the same as 40W and PV power is about 51.7 W upto 666 ms at this condition battery is in charging mode and the excess PV power is stored in battery. After 666 ms the PV power increases to 99.7W at this condition battery is in charging mode as shown in fig.14 and the battery stores power about 55.6W.

Table 5. Power sharing between load, PV and battery at varying irradiance

IRRADIATIONS (W/m^2)	V_{out} (V)	LOAD POWER (W)	PV POWER (W)	BATTERY POWER (W)
250	48.033	40	25.67	17.2
500	48.03	40	51.7	-10.4
1000	48.01	40	99.7	-55.6

The summarized results of power flow between PV, battery and load at varying irradiance level [250 W/m^2, 500 W/m^2, 1000 W/m^2] are presented in Table.5. The PV power output is varying at every 333 milliseconds. In first case, the load demand

is met by both PV and battery. In the last two cases the load is met by PV alone and its excess power is stored in battery. In all these conditions the system voltage is kept constant (48V).

II. Conclusion

A simple DC microgrid system with an energy management system is discussed in this paper. The model is built and simulation is carried out for several input and load conditions. The simulation results show that the system accommodates the different variations in the renewable energy sources as well as the load and is flexible. The entire simulation is performed using MATLAB /Simulink.

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