INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
Bharath K R et al., Vol.8, No.2, June, 2018

Control of Bidirectional DC-DC Converter in Renewable based DC Microgrid with Improved Voltage Stability

Bharath K R*‡, Harsha Choutapalli*, Kanakasabapathy P*

*Department of Electrical and Electronics Engineering, Amrita Vishwa Vidyapeetham, Amritapuri, India

((bharathkr@am.amrita.edu, choutapalliharsha@gmail.com, sabapathy@am.amrita.edu))

‡Corresponding Author; Bharath K R, Assistant Professor, Department of Electrical and Electronics Engineering, Amrita School of Engineering, Amritapuri, Amrita Vishwa Vidyapeetham, Kollam, Kerala, India, 690525. Tel: +919446696584, bharathkr@am.amrita.edu

Received: 24.01.2018 Accepted:03.03.2018

Abstract- Providing a stable voltage at the nominal level according to universally accepted standards is a primary concern of any public electricity network. In a renewable energy fed power electronic based DC microgrid system, renewable sources can have fluctuating power characteristics due to various environmental factors. In such an environment, chances of voltage instability are highly probable due to varying power nature of renewable sources and loads connected. In this paper, a bidirectional converter connected with a battery storage is controlled based on the voltage of the microgrid in order to tackle the aforementioned problem. A selector based control algorithm in conjunction with a proportional-integral controller is used to trigger the bidirectional converter. Proposed control technique is simulated in a 60V DC microgrid and results are provided.

Keywords DC Microgrid; Bidirectional converter; MPPT; Voltage regulation; Microgrid stability.

1. Introduction

AC electric energy systems were proved to be most efficient way of transmitting and distributing power until recent past. The advent of various distributed energy sources, especially renewable energy generation whose output is DC power, demand DC grids for efficient operation. Moreover, user end power requirement in the terminal end for most of the present day devices such as battery chargers, led lights, electronic gadgets, etc. boils down to DC voltage, where conversion elements are added in AC grids to make the voltage level suitable for end equipment connected. This needs further demands use of DC for power distribution.

Use of small-scale isolated DC grids (DC microgrids) in remote areas, with solar PV as the source, was proved to be economically beneficial than extending AC grids to that location [1]. Different economic issues and advantages of DC solar microgrids were summarized in [2]. Detailed structuring of an isolated grid of capacity 200W – 600W are described in [3]. Different challenges involved in the formation of such microgrids is discussed in [4] and [5], which also presents various aspects of the microgrid such as distribution levels, local, central power management units, and their functions. Performance improvement technique of a microgrid is discussed in [6]. The detailed modelling of a control strategy for interconnected microgrids is presented in [7]. A detailed note on present microgrid projects in India, their working models, technical features, problems encountered were discussed in [8].

The DC bus is the crucial component of the DC microgrid. Maintaining constant the voltage on the DC bus is of paramount importance in the microgrid because it is the main factor deciding the performance of the system. The bus voltage varies because of the variations in input power from sources like Solar Photovoltaic (PV) modules. It varies in relation to the amount of power injected into the bus. Similar to this, the voltage on the bus varies with the change in the load power requirement. Strict monitoring and control of bus voltage are required to supply the loads at rated voltage. The reference paper [9] discusses different topologies of bidirectional DC-DC converters such as a bidirectional buck-boost converter, bidirectional full-bridge converter, multi-phase interleaved converter and floating interleaved converter. Different control strategies for the control of these converters like current mode control, power control and non-linear control also have been discussed in the paper [9]. Use of few advanced control techniques such as sliding mode control, self-tuning control, recursive identification method and minimum variance control was presented in [10]. LED's are considered to be an essential load, which is designed to work with AC input. This involves power factor correction and use of electrolytic capacitor [11]. This can be completely eliminated by using an LED using DC supply. The bidirectional converter design and control for this purpose was exclusively presented in [11] and [12]. The design of DC-AC bidirectional converter to facilitate connection with AC grid was given in [13] and [14]. Implementation of transformer-less inverter along with solar PV systems is discussed in [15], [16]. Charging of electrical vehicles with rooftop solar panels were discussed in [17].

This paper describes a method by which DC bus voltage is maintained within allowed tolerance band using a battery as an energy sourcing as well as sinking unit. The battery is interfaced with the DC bus using a bidirectional buck-boost type DC-DC converter. A buck-boost type DC-DC converter is a combination of classical buck type and boost type converters overlapped onto each other. It consists of two controllable switches, which give buck and boost operations when operated individually. The bus voltage is designed to be 60V and a battery voltage at 24V. Two individual PI controllers are provided for both buck and boost operations. The switching between buck and boost operations is selected based on the bus voltage. A logic circuit is provided to switch between buck and boost operations.

The Battery is connected to the low voltage side of converter and DC bus is tied in the high voltage side. If the DC bus voltage becomes greater than the nominal value, the controller enables buck mode of operation, i.e. charging of the battery from DC bus. If the bus voltage falls below the nominal value, boost mode is enabled and the DC bus power requirement is shared from the battery. This scheme makes the bus voltage constant for various changes in the load and source conditions.

Rest of this paper is organized into 5 sections. Section 2 describes the DC microgrid considered for this investigation and its practical significance. Section 2 also presents the details of solar PV system, a battery and a bi-directional converter used in the simulation. Section 3 provides the details of the control of the converter for different modes of operation. Simulation results are discussed in detail in section 4. Finally, conclusions are presented in the 5th section of this paper.

2. DC Microgrid

An islanded DC microgrid system is considered for this investigation as shown in figure 1. Practically, the microgrid consists a DC bus which runs for a length of 1 km to 2 km along with various power sourcing units and loads connected at point of common coupling. The DC bus is sourced from various solar PV sources, wind based sources and other renewable based power supplying unit and the loads are distributed throughout the length of the grid. All the solar PV sources are considered to be operating in MPPT mode and the control of each solar PV source is independent of each other. Practically any number of sources or the loads can be present. The variation in the load and the change in irradiation levels at each solar PV panel is unpredictable. This may result in deviation of DC bus voltage from a nominal value leading to voltage stability issues. This problem must be addressed in real time to prevent mal-operation of the system. This is achieved by controlling a battery storage interfaced to DC bus through a bi-directional power converter.

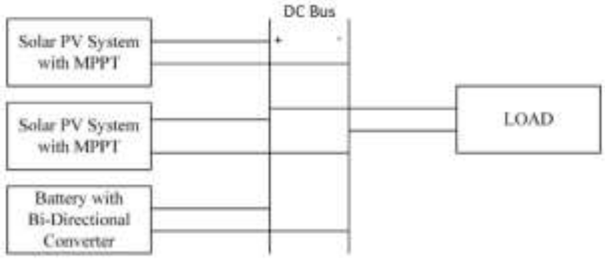

Fig. 1. Block Diagram of considered DC microgrid

Two independent solar PV sources operating at MPPT is considered for the simulation study. Each solar PV module is capable of supplying a peak power of 125W. The DC bus voltage is rated at 60V. A maximum load of 290W is added to the system in steps to study and analyze various modes of operations in the grid and bidirectional converter.

2.1 SPV Source with MPPT

Many methods exist to tap solar energy and convert to electrical energy. Solar PV modules are most convenient for this purpose due to its ease of installation and maintenance, but there can be power output fluctuations due to outdoor environmental conditions [18]. The solar panel is modelled using a single diode model in this analysis is based on single diode model of solar panels as shown in figure 2.

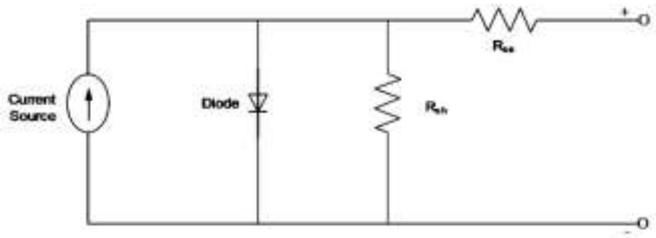

Fig. 2. Single Diode Model of Solar Panel

The forward voltage of the diode is the open circuit voltage (V_{OC}) of the module and the step level to the controlled current source represents the short circuit current, that reflects amount of ambient solar light distributed over the photovoltaic panel.

The conversion efficiency of solar PV units are from 12% to 28% and mechanism to harness maximum available energy from such sourcing elements is done using maximum power point tracking algorithms (MPPT Algorithms). There are many existing MPPT methods which are analysed in [19],[20]. Implementation of Fractional Open Circuit Voltage (FOCV) based method is one of the simple and efficient method [21]. FOVC method is adopted for this analysis. The generic equation determining the relation between VOC and VMPP is given by the equation 1.

$$V_{MPP} = K_1 V_{OC} \quad (1)$$

This method is based on the studies which states that the V_{MPP} always lies in the range of 0.7 times V_{OC} to 0.78 times V_{OC} [22]. K_1 in equation 1 takes these values. FOCV is implemented by periodically opening the terminals across solar PV module, determine the open circuit voltage at that instant and fix the V_{MPP} at K_1 times the determined voltage.

2.2 Battery Energy Storage and Bidirectional Converter

A battery-based energy storage element is essential in solar PV based microgrid. Other electric energy storage systems utilized in a microgrid are discussed in [23]. A system involving a battery is incorporated with the bidirectional DC-DC converter (BDDC) is used to interface battery source to the DC bus. The two main objectives of the BDDC are (a) Control of the direction and amount of power from/to the battery and (b) Control the voltage and power requirements of the DC link [10].

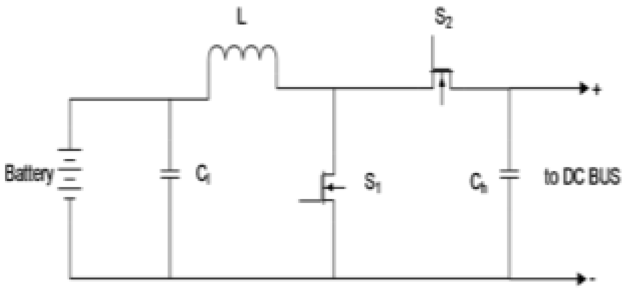

Fig. 3. Circuit diagram of Bidirectional DC-DC Converter

In this study, a battery is used in conjunction with a bidirectional converter to maintain the DC bus voltage constant, using power converter circuit as shown in figure 3. A buck-boost type DC-DC bi-directional converter is employed to inject or absorb power from DC bus. Switch S1 is operated only when switch S2 is OFF giving boost operation and switch S2 is operated only when switch S1 is in OFF condition in order to realise buck mode of operation. The design of inductor and capacitors on high voltage side and low voltage side are crucial for its proper function. The design is based on the detailed studies presented in [24]. The equations 2 and 3 gives the critical value of inductance in buck and boost mode of operations respectively. The higher value of both has to be selected for continuous conduction mode of operation. The capacitance values controls the voltage ripple on high voltage and low voltage sides whose values are given by equations 4 and 5.

$$L_{CR,BOOST} = \frac{V_0 - V_{IN}}{2P} \frac{V_{IN}^2}{V_0} Ts \quad (1)$$

$$L_{CR,BUCK} = \frac{(1-D)V_0 T_S}{2I_0} \quad (2)$$

L = maximum[$L_{CR,BOOST}$, $L_{CR,BUCK}$]

$$C_h = \frac{\Delta I_L}{8\Delta V_{IN}} T_S \quad (3)$$

$$C_1 = \frac{V_0 D}{R_{LOAD} \Delta V_0} Ts \quad (4)$$

A DC bus voltage of 60V and a battery voltage of 24V are selected to perform analysis on the aforementioned algorithm. Operation of one of the two switches gives buck operation and other gives boost operation. The bus voltage is selected as a parameter to select which switch to be operated. When the voltage falls below 60V, boost mode of operation is activated and when goes above 60V, buck mode of operation is selected. The pulse required for the switches are individually generated using a modified discrete PI controller. The bus voltage is taken as reference signal for both buck and boost operations.

3. Control Strategy

Various control strategies are used to achieve constant DC bus voltage and source and the load power balance [25][26]. Widely used control methods include droop control and bus voltage signalling method. Droop control is a mechanism by which power shared by each connected load is controlled by the individual control units tied along with the source converter side based on the terminal voltage of the bus bar [27]. Amount of current injected by individual droop based power source is determined by the droop impedance. This method does not need any communication from participating sources to a central controller. But circulating current issues and poor current sharing accuracy results in poor voltage regulation and slow dynamic response even though this method is relatively cheaper [28].

Unlike droop control, DC bus signalling method uses DC bus voltage as the parameter to control the output of each source. A controller has to be present at each source to monitor the voltage and power delivered from each source. In this method, adding a source result in adding a controller and a change in the program at each source.The proposed control method utilizes a battery to maintain the bus voltage constant. At any location, a battery is interfaced to the DC bus through a bi-directional converter. The battery is discharged when DC bus voltage is lower than the rated value, and battery unit is charged when in the DC bus voltage is higher than the rated value.

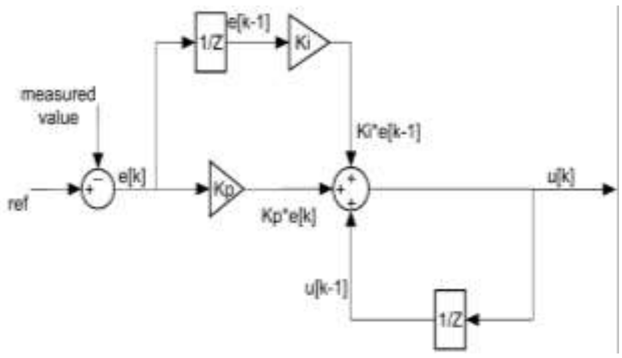

Fig. 4. Modified PI controller unit for transient minimization

The controller used for tuning the buck and boost modes is a modified PI controller to reduce transient and steady state voltage oscillations and voltage ripples. The controller signal is generated based on the signal flow diagram shown in the figure 4. The output of the controller is a function of the voltage error, delayed by the sample of the voltage error and delayed sample of the output of the controller. The integral part of the controller gives the stable steady state output and proportional part minimises the settling time.

The overall response of controller is given by equation 6.

$$u[k] = k_p * e[k] + k_i * e[k-1] + u[k-1] \quad (5)$$

Equation 6 can be rearranged to obtain equation 7.

$$u[k] - u[k-1] = k_p * e[k] + k_i * e[k-1] \quad (6)$$

The above equation represents the relation between the change in controller gain which is proportional to the change in voltage error. This gives an advanced control over the control variable, which takes sudden changes of output (parameter to be controlled) into consideration. Two such controllers are used for the two switches of the bi-directional converter. The operation of the two switches solely depends on the bus voltage. Selection of one switch gives the buck or boost operation. The selection is based on the logic in Figure 5. The system floats (power is neither sinked, nor sourced) if the voltage measured is exactly 60V.

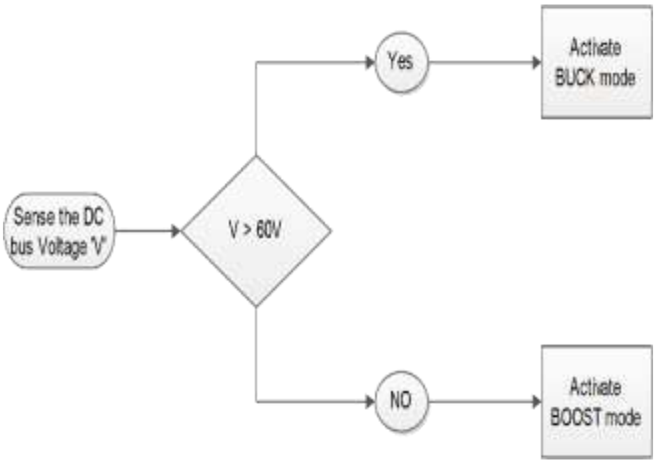

Fig. 4. Mode selection logic

4. Simulation Results and Analysis

4.1 System under Consideration

Two solar PV sources each rated at 125W are considered as power source for the simulation study. They are interfaced to boost converters, which operates independently in MPPT mode. FOCV method of MPPT is used to tap maximum available energy from the solar based power source. A variable load of maximum 300W is attached to the DC bus. The nominal value of DC bus voltage is fixed at 60V. A battery energy source is interfaced to DC bus with a bi-directional converter.

The battery is rated to supply or absorb a power of 150W at any source and the load condition. The system is simulated for different source and the load conditions as shown in table 1. Different conditions are considered to show the capability of a battery to absorb or give the required amount of power and investigate the voltage stability of the DC microgrid. The variation in power at different sources for different modes of operation is discussed in the coming sections.

4.2 Modes of Operation

Entire conditions that can be occurred are grouped under four different mode of operation. Analysis of power flows during each mode is detailed below.

Table 1. Load and source switching periods

Time(s)	SPV-1 Power (W)	SPV-2 Power (W)	Load Connected (W)	Battery Power (W)
0 – 0.015	24.58	36.18	71.91	11.36
0.015–.03	124.5	84.12	71.91	-136.5
0.03 – 0.06	124.5	84.12	143.2	-65
0.06 – 0.1	124.5	85	283	77.5

4.2.1 Mode 1, Discharge mode 1

In the initial state, when the system is being turned ON, the power from the solar PV modules is not sufficient to meet the load. At this point, the battery operates in discharging mode to supply the required power. The initial transient in the waveforms of power from solar modules is due to the action of the MPPT tracker implemented. The fixed load absorbs the power as generated by the solar PV modules. After the tracking settles, a fixed power is drawn by the load. The battery initially tries to supply the power by maximum current discharge and supplies constant power according to the variation in power from solar PV modules. The power supplied by each source is as shown in figure 6. The load on the system is 71.91W. The two solar PV sources are together supplied 60.76W. As shown in figure 6, the remaining 11.36W is supplied by a battery during all the variation from solar PV sources and maintained a smooth load voltage profile.

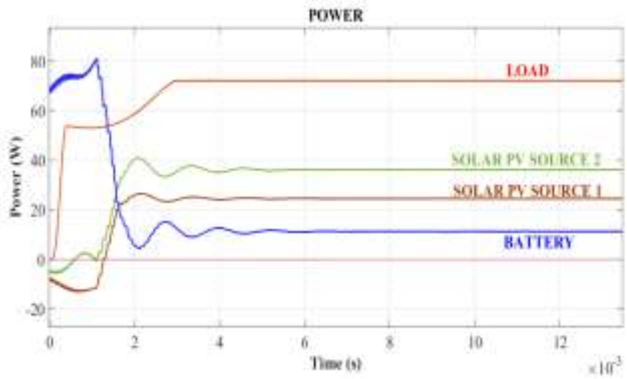

Fig. 6. Power flows in various nodes during Discharge Mode 1

4.2.2 Mode 2, Charging Mode 1

System operates in charging mode 1 when the power generated from solar PV modules is more than that the load demand. In this case, the excess power is utilized to charge the battery. The power from one of the module increases with increase in insolation level. This result in increase in power is absorbed by a battery. Power flows in various source and the load nodes are shown in figure 7.

4.2.3 Mode 3, Charging Mode 2

This mode of operation gets activated when the load is increased from range of load demand present in mode 2. Both the solar PV modules supply same power as in mode 2 but due to the increase in the load power, the battery charging current comes down considerably thereby reducing the battery charging rate. A disturbance in the insolation level of one of the module will get reflected as a disturbance in the voltage level, which is shown in the figure 8. The battery responds to this change in the system and sinks power accordingly to maintain the voltage at the load.

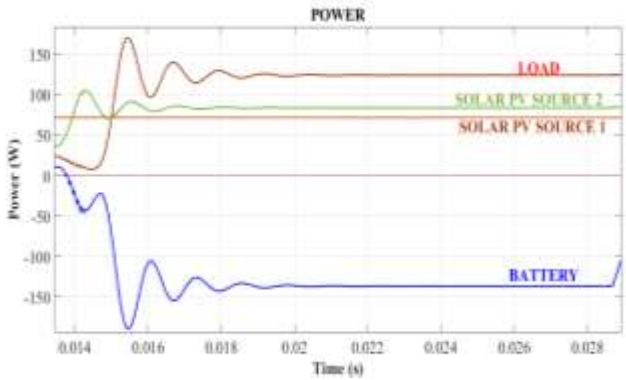

Fig. 7. Power flows in various nodes during Charging Mode 1

4.2.4 Mode 4, Discharge mode 2

This mode of operation occurs when power given from solar PV sources becomes insufficient to meet the load demand. In this case, the battery discharges more power than that of initial condition to maintain the system voltage. The power levels of different devices are as shown in figure 9. The power flows at each source and the load is shown in the figure 10 and the bus voltage after connection of a battery is provided in the figure 11.

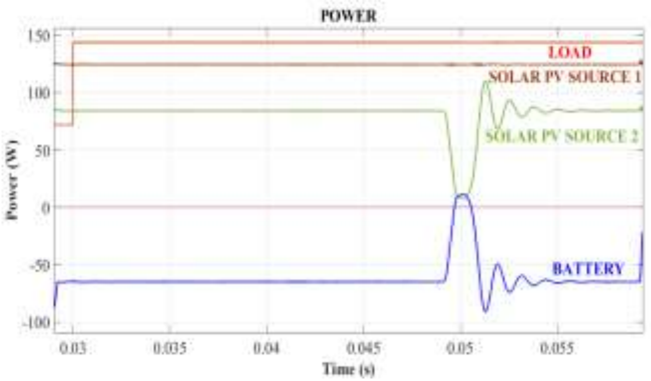

Fig. 8. Power flows in various nodes during Charging Mode 2

4.3 DC Bus Voltage Details during various Modes of Operation

Voltage level maintenance is the primary aim of the power converter control logic. In the following sections, voltage levels of the DC bus are discussed during both the conditions, i.e., using the battery based system with bidirectional converter unit and without the battery support unit.

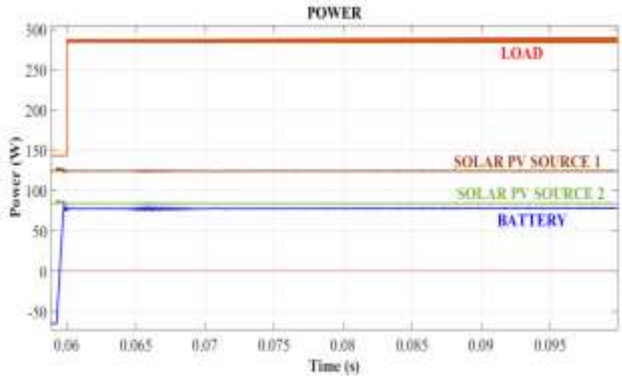

Fig. 9. Power flows in various nodes during Discharge Mode 2

4.3.1 DC Bus Unit without the Battery support unit

The bus voltage levels during the absence of a battery based control unit are shown in figure 11. As discussed in table 1, at 0.015s, SPV module 1 increases it's generation and the bus voltage boosts than 90V. At the instant 0.03s, the load is increased and the bus voltage comes down to 72V. At 0.05s, solar PV module 2 increases its power production, which makes a rise the voltage level after the dip incurred. At 0.06s, the load demand increases resulting in voltage to fall down to 50V. It is clear from the figure 11 that, the system voltage swing is beyond the rated microgrid standards resulting the DC Bus totally unreliable for safe operation.

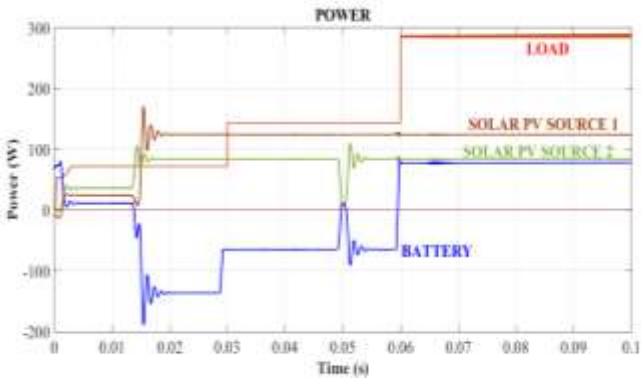

Fig.10. Power absorbed and delivered by different sources and loads.

4.3.2 DC Bus Unit with the Battery support unit connected

In figure 11, DC bus voltage after connecting the battery support unit is also depicted. From the DC bus voltage shown in figure 11, it can be inferred that the bidirectional power converter was able to restore the bus voltage to 60V at all operating conditions. But voltage ripples are present in the DC bus, which varies depending on the amount of power drawn from the load. From 0s to 0.015s, the ripple of output voltage is 0.6V, i.e. 1%. From 0.015s to 0.06s, the ripple is 0.3V, i.e. 0.5%. This is because initially the converter had to bridge a large gap of voltage, which reduced in later stage.

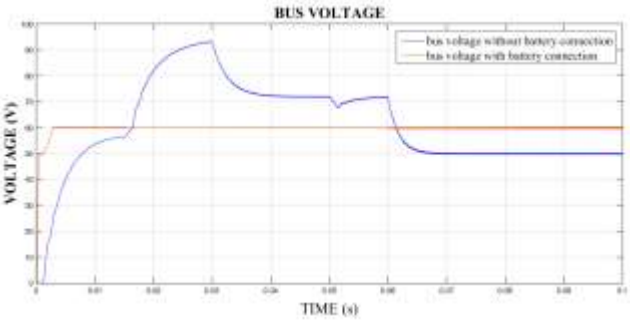

Fig.11. DC Bus voltage without a battery support unit connection

Table 2 describes levels of voltage ripple during various modes of operation. Based on the data tabulated in table 2, it is clear that the voltage ripple at any instant of time does not exceed 0.83% which is under the defined limit of 1%.

Table 2 Voltage ripples in various modes of operation

Mode of Operation	Voltage Range (V)	Voltage Ripple (%)
Mode 1	60.35 - 59.85	0.83%
Mode 2	60.15 - 59.85	0.5%
Mode 3	60.1 - 59.75	0.58%
Mode 4	60.1 - 59.6	0.83%

4.4 Battery Charging Current Analysis

Battery charge current control circuit is provided to avoid high magnitudes of current entering the battery during any of charging modes. In mode 2, the battery has to take around 140W of power at 24V resulting in high current of 5.5A, which is more than the accepted charging current level of the selected a battery.

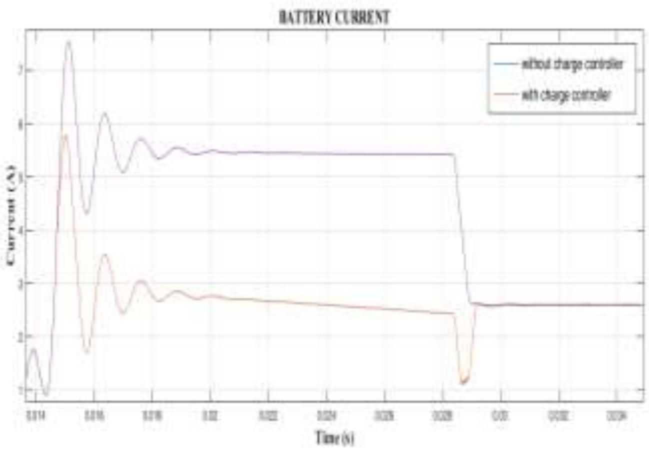

Fig. 12. Battery current graph

From figure 12, it is visible that after using the dump load mechanism, a battery is not fed with excess energy. Current flowing through a battery is maintained within allowable limit. To avoid batter over current injection, an additional dump resistance of small value is connected at the terminals of a battery through a buck converter. The converter operates when the current exceeds rated value to divert the additional current into the dump resistance. The current going into a battery with and without charge controller is shown in figure 12.

5. Conclusion

In this paper, a new power management strategy is proposed, tested on a DC microgrid system and results are analyzed. The changes in voltage with changes in the irradiation of solar PV modules in a DC microgrid with and without proposed units are observed. The proposed PMS unit is successful in maintaining constant voltage on the DC bus with the use of single controller. This arrangement facilitates user to add a solar PV source at any location in a microgrid with corresponding changes in the single controller. This flexibility also depends on the rating of the battery, which decides the amount of power it can handle. In addition, this PMS reduces the expense of implementation, as it does not require a controller at each source or a separate communication channel. This gives all the customers in the grid, the freedom to operating independently based on their own capacity without having to worry about the grid stability.

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