A Hybrid Controller for Novel Cascaded DC-DC Boost Converters in Residential DC Microgrids

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Abstract*—This paper presents a performance analysis of a new cascaded boost converter for low voltage (LV) residential DC microgrid. Photovoltaic (PV) systems are getting high attention as a renewable energy resource for LV DC microgrid applications. Partial Shading (PS) is a serious issue in PV systems as it leads to a significant reduction in power generation. The conventional boost converter topology is usually employed to mitigate the mismatch issue between the PV arrays or modules caused by the PS problem. In some cases, the PV module is divided into three submodules (SMs) where a bypass diode is integrated with each SM to protect the PV module from the hot spot (HS) effect. The mismatch problem between the SMs inside a single PV module can result in a significant reduction in power generation caused by isolating the shaded SM from the PV system. However, isolating the SM from the PV system can mitigate the HS negative effect at the expense of losing the power of the shaded PV SM. This paper suggests a PV SM DC-DC cascaded boost converter to overcome the mismatch concern between the PV SM of a single PV module in the modern DC microgrid. It employed a Perturb and Observe (P&O) tracing algorithm with each PV SM to individually harvest the maximum available power. The study proposes an optimized operating strategy based on PV power generation, local demand, and battery state of charge (SOC) to enhance the reliability of the DC microgrid system.

Keywords: Microgrid systems, Low Voltage (LV) DC microgrid, Power Electronic converters, DC-DC Boost Converter, Photovoltaic.

I. INTRODUCTION

Global environmental concerns such as global warming and greenhouse gas (GHG) emissions have led to an increased international interest in renewable energy sources (RESs). As a result, the percentage of renewable resources installations including photovoltaic (PV) and wind generators (WGs) has increased rapidly over the last decade. Solar energy gains special attention among renewable energy generators because of its scalability features. Unlike WGs, PV systems can range from small-scale generators with few KWs to large systems at GW-rated power. The low voltage (LV) distributed solar energy market has become a fast-growing market because of its capability to reduce the electricity consumption cost at the end-users. The distributed PV systems can be a safe and noise-free solution, making it a preferable choice for consumers. In terms of power quality and system efficiency, distributed PV systems can minimize the installation cost and reduce the power loss caused by transmission lines, especially in remote areas [1].

The concept of microgrids was introduced a long time ago, however, it has become a focus of research in the last few years due to the growing interest in integrating renewable energy with utility grids. Integrating the different RESs plays an important role in addressing the continuous growth of electricity demand and can increase the electrical system's flexibility. A microgrid is a small-sized electrical network that aims to integrate different RESs and energy storage elements with the utility grid. The microgrid components can be pure DC electrical sources such as solar panels and fuel cells or a combination of DC and AC generators. One unique feature of microgrids is the capability to collaborate with the main grid or work in a self-standing operation mood [7]–[10].

Microgrids can be categorized into DC and AC types according to the common bus voltage. Because the conventional utility grid is based on AC components, the AC microgrid is usually more popular. Typical microgrids usually operate in two different modes, grid-connected and islanded mood. The grid-connected mode is commonly activated when the distributed generation resources (DGRs) in the microgrid, such as solar panels, WGs, and battery energy storage elements (BESEs) cannot meet the local demand [11]. In an islanded mode, the microgrid local demand can be supplied completely by microgrid local generation. In this context, voltage regulation is essential to maintain stability and ensure reliable power generation in time. One practical method to regulate the microgrid's voltage is to control the injected or consumed power according to the voltage level at the common bus. In AC microgrids, voltage synchronization is important to maintain electrical stability, which requires a complicated controlling process. Synchronizing the voltage at the AC bus common voltage is essential regardless of the microgrid operating mood which can increase the complications on the system controllers [12].

In AC microgrids, the double conversion from DC to AC power at the power generation end and from AC to DC power at the DC load can result in unnecessary conversion loss.

Thus, the conversion process can be direct and efficient in a DC microgrid. Figure 1 illustrates a conventional residential DC microgrid where the microgrid components are connected to a 48 DC bus. Controlling the reactive power and frequency synchronization in AC microgrids can be complicated especially with continuous power fluctuation from the DGRs. However, the DC microgrid control process can be less challenging since they do not face these concerns. In terms of end-user safety, the DC microgrid can be comparatively safer for both the systems operators and end users. Consequently, a significant amount of research is currently conducted on DC microgrids [13].

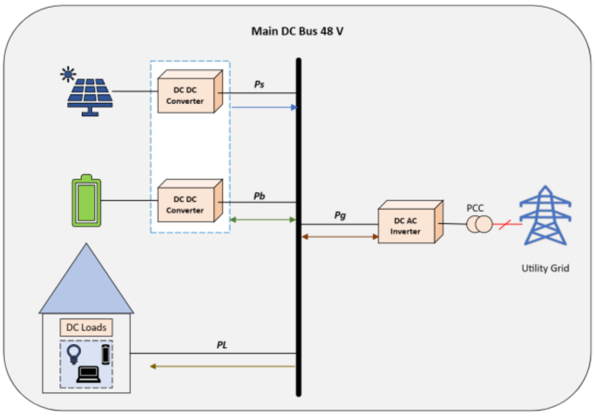

Figure 1. A typical residential DC microgrid.

DC microgrids have been introduced recently to improve the electrical systems' reliability and power quality where most of the components in residential microgrids operate at DC voltage and current including PV modules, fuel cells, supercapacitors, and batteries. Thus, it is practical to integrate these components with a common DC bus. Recently, the loads of residential microgrid systems are DC loads such as laptops, electrical vehicles (EVs), microwaves, and light-emitting diode (LED) lighting, making the DC electrical system preferable [14].

DC microgrids topology proposes excellent features in terms of installation cost, design scalability, and system robustness. Various configurations can be employed to form the DC microgrid according to the chosen application requirements. Radial DC microgrid is a single bus topology where the generators, energy storage elements, and loads are connected to a common DC bus. An optimised energy management system (EMS) is usually employed to improve the system's reliability. Residential applications are commonly connected to radial DC topology because the LV DC bus will be preferable for residential buildings. The multi-bus configuration is an extended version of the radial DC topology which aims to integrate several radial DC topologies and links them with a higher-voltage DC bus. Also, the shipping vessels' electrical system can be an example of a multi-bus DC microgrid. In high voltage (HV) DC systems, the multiterminal topology and ring configurations are the most common topologies [15,16].

The main objective of both AC and DC microgrid control systems is maintaining a constant voltage level at supply points. However, AC microgrid voltage regulation will include frequency and phase synchronization with the utility grid which can significantly maximize the design complexity and reduce the system's efficiency [15]. DC microgrid controller design is relatively simpler and can provide better performance. DC microgrids can have two control systems, local and coordinated controlling systems. The local control system of DC microgrids is responsible for regulating the power of DC microgrids elements such as PV generators, storage systems, or local loads. In residential electrical systems, the local control systems can regulate the voltage or current to meet the set values. The coordinated controller is commonly used as a central controller when the locations of plants, storage systems, and demand differ. In the rooftop residential DC microgrid, the generating units and the local load share the same point thus the coordinated controller is not mandatory [17].

Energy Storage Systems (ESSs) are a critical component in electrical microgrids employed to buffer irregular renewable energy generation. The peak load for most users is usually at night when the PV modules do not generate solar power and hence, storing solar energy during off-peak times is required. Battery ESSs (BESSs) are commonly used in DC microgrids, especially in residential PV systems because of its relatively simpler integration and capability to enhance the DC microgrids' robustness. BESSs can protect DC microgrids against voltage variation at the common DC bus by charging or discharging the battery's stored energy. Thus, obtaining the proper operating mode of the BESS not only maintains the DC microgrid's reliability but can also contribute to providing the system's power-balancing features [18].

The power electronic converter is a basic element in the different electrical microgrid systems that aim to interface the RESs to the common DC bus or the local load. The RESs usually operate at a low voltage level and hence, boosting the low voltage of the renewable resources is required. In DC microgrids, the boost converters are commonly used to step up the PV system voltage to meet the voltage set point at the common DC bus. The DC-DC boost converters were introduced many years ago to overcome the low voltage nature of different RESs. The microgrid system requirements are different according to the size of the DC microgrid and different power electronic topologies can be used. In rooftop PV systems, the mismatch between PV modules and PV SM is a serious issue leading to reducing the PV system power generation. Therefore, proposing an efficient power electronic configuration is important in mitigating the mismatch problem [19].

This paper proposes a new topology to overcome the mismatch issue between the PV SMs and effectively operate the BESS in the residential DC microgrid systems. It targets the mismatch problem between the PV SMs inside an individual PV module. The typical PV module commonly has three PV cell groups where the output voltage of these groups of PV cells is relatively low. Thus, stepping up the output voltage of each group of PV cells is necessary to meet the output voltage requirements at the common 48 DC bus. The introduced topology integrates a DC-DC boost converter with each PV cell group and cascades the output of the three DC-DC boost converters to enhance the stepping-up capability of the PV system. Freewheeling diodes are used between the PV module and BESS to protect the PV modules from reverse currents when the system becomes faulty. A bidirectional power electronic converter is employed at the BESS to charge and discharge the battery.

II. The Operation Modes of The Proposed Topology

The proposed topology aims to reduce the mismatch concern between PV SM in residential DC microgrid. The Partial Shading (PS) in PV module leads to massive losses in PV power generation because the behavior of the PV SM becomes different. Extracting the power from PV SM individually can mitigate mismatch issues between PV SM and maximize overall PV power generation.

The proposed structure for operating the PV system and the BESS of the residential DC microgrid is shown in Figure 2. The system is assumed to work in an islanding mood where the DC microgrid is disconnected from the utility grid.

The output voltage of a single PV SM is relatively low; thus, a boost DC-DC converter has been used with each PV SM to step up the voltage at the common DC bus. The suggested system's boosting capability has been improved by cascading the three outputs of the PV SMs. A separate MPPT harvests the maximum available power from each PV SM to increase the output power of a single PV module. The PV module should be protected from the reverse current when the residential PV system suffers from external issues. Therefore, a forward diode is connected at the PV module site to enhance the protection capacity of the system. A bidirectional DC-DC converter is used at the battery to examine the charging and discharging scenarios for the residential PV system.

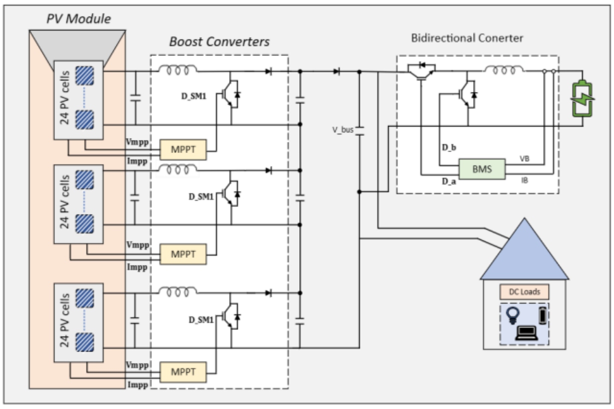

Figure 2. The proposed topology of modern residential DC microgrid.

Mathematical Formulation.

$$P_L(T) - P_V\ (T) - P_B\ (T) - \ P_G(T) = 0 \qquad (1)$$
$$P_L(T) = P_V\ (T) + P_B\ (T) + \ P_G(T) \qquad (2)$$

Where P_L (T) is the load, P_V (T) is PV power generation, P_B(T) is battery power and P_G(T) is the grid power. The proposed operation of the residential electrical system relies on PV power generation to meet the local demand and charge the BES. The excessive PV power generation fed to the utility grid. However, when the PV power generation can only meet the residential local demand then the battery is isolated from the system. Once the PV power generation becomes below the local demand, both the PV modules and battery supplied DC local demand. At nighttime the PV modules are not generating electrical power thus the systems rely on battery to meet the local demand. The system is connected to utility grid only when the local generation of the rooftop PV system cannot meet the local DC demand.

A. Mode I

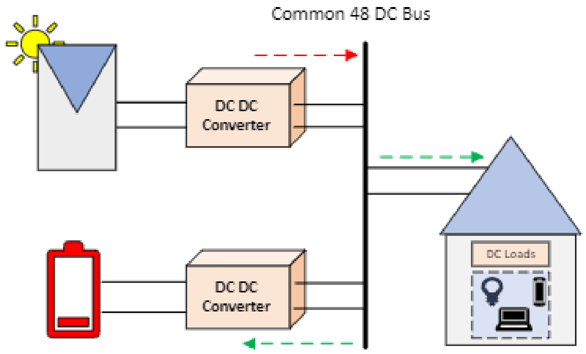

Figure 3. The PV system meets local demand and charging the battery.

This mode is activated when the PV power generation can meet the local DC demand, charge the battery, and inject the extra power to the grid.

$$P_V\ (T) > P_L(T) + P_B\ (T) \qquad (3)$$
$$P_V(T) = P_L\ (T) + P_B\ (T) + \ P_G(T) \qquad (4)$$

The PV system can meet the local demand of the residential house and charging the BESS when the output power of the rooftop PV system exceeds the local demand of the end users, and BESS power below minimum charging limit.

B. Mode II

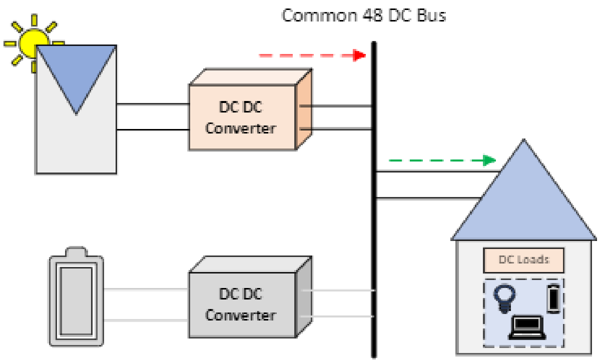

Figure 4. The PV system meet local demand only.

The secund mode is applied if the PV power generation can only meet the local DC demand and charge the battery and no extra power to feed to the utility grid.

$$P_V\ (T) > P_L(T) + P_B\ (T) \qquad (5)$$
$$P_V(T) = P_L\ (T) + P_B\ (T) \qquad (6)$$

During daytime, when the PV panel generates DC power, the DC load of the rooftop PV system is supplied by the PV power generation apart from the BESS. The BESS is isolated from the residential PV system once it is fully charged. This mode is activated when the PV power exceeds the local demand of the end user.

C. Mode III

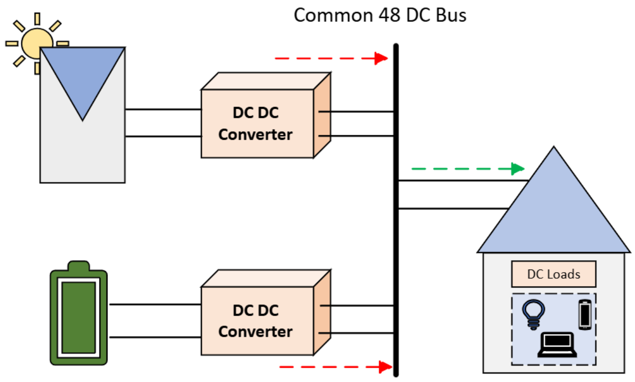

Figure 5. The PV system and the battery supply local demand.

The third mode is operated once the local DC demand exceeds the PV power generation. Both the PV modules and the battery supply the local demand of the residential load.

$$P_V\ (T) + P_B\ (T) > P_L(T) \quad (7)$$
$$P_V(T) + P_B\ (T) = P_L\ (T) \quad (8)$$

The proposed EMS aims to efficiently utilize the local energy of the rooftop PV system. Thus, the DC demand of the rooftop PV system is supplied by both the PV generation and stored Energy in BESS once the local DC demand of the end users exceeds the PV system power generation.

D. Mode IV

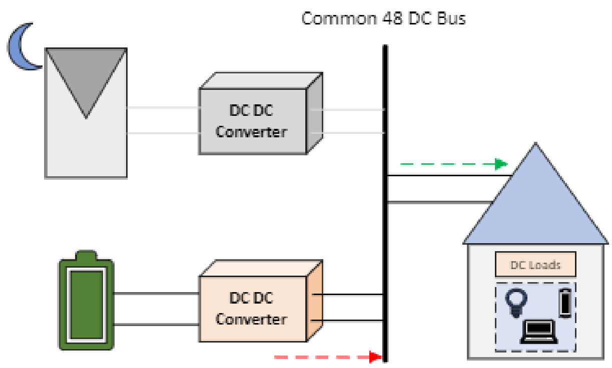

Figure 6. The battery storage unit system meets local demand.

This mode is activated at nighttime when PV modules do not generate electrical power. The system is connected to the battery only to meet the local demand of the residential DC microgrid.

$$P_B(T) > P_L\ (T) \quad (9)$$
$$P_L(T) = P_B\ (T) \quad (10)$$

The PV modules stop working at nighttime and the stored energy in BESS is used to meet the DC local demand. Sizing the BESS is crucial to maintain the reliability of the residential PV system especially for isolated rooftop PV systems. Once the local generation of the rooftop PV system drops, the system automatically will be connected to the grid to meet the end user demand and charge the BESS.

III. EMS Operation

The rooftop PV system is assumed to operate according to Figure 7. The presented strategy starts by calculating the initial values of the system variables. The variables of the system are PV power P(PV), battery power P(Battery), The load power P(load), the maximum charging power of the battery P (Charging Max), and the minimum discharging power of the battery P (Discharging Min). The EMS compares the local DC load with the generated power from the PV system. When the PV power generation exceeds the local DC demand, the systems start calculating the battery power. The system supplied the local DC load and charged the battery when the battery power was below the maximum charging power limit. The system meets the local demand only once the battery is fully charged and it relies on the battery once the PV power generation cannot meet the local DC demand of the residential PV system. The PV system and the battery or the battery can supply the local demand once the PV power generation becomes below the local load of the end user. The system is connected to the utility grid when both the power generation from the PV system and battery power cannot fulfil the local demand of the rooftop PV system.

IV. Simulation Results

Figure 7 illustrates the circuit of the conventional DC-DC boost converter. In this study, a Bipolar Junction Transistor (BJT) is used as an active switch to operate the step-up converter. The current flows throw the inductor when the switch is turned on resulting in increased the inductor voltage. After switching off the BJT switch the polarity of the voltage across the inductor will change and the output voltage becomes the summation of source voltage and inductor voltage. Therefore, the output voltage of the boost converter has to be greater than the input voltage. In the proposed topology the outputs of the three boost converters are connected in series to further increase the output voltage of the PV module.

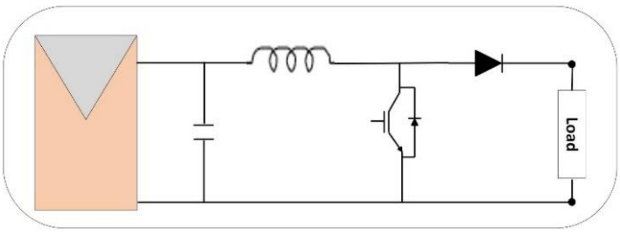

Figure 7: A typical DC-DC PV boost converter.

During the daytime, the output power of the rooftop PV system can meet local demand requirements and charge the storage element. At nighttime, the PV system is directly relying on a storage unit to operate the PV system. Thus, these two scenarios have been considered in the simulation results.

The two different scenarios have been simulated under the assumption that the system is isolated from the utility grid. The MATLAB/Simulink has been used to examine the validity of the proposed residential DC microgrid. The first scenario is to study the system during the standard situation when the PV modules are supplying the local demand and charging the battery. Figure 8 shows the performance of the proposed residential DC microgrid when the PV modules can meet the local demand and charge the BES unit. The current of the battery is positive which illustrates that charging mode is activated and the PV modules start charging the battery.

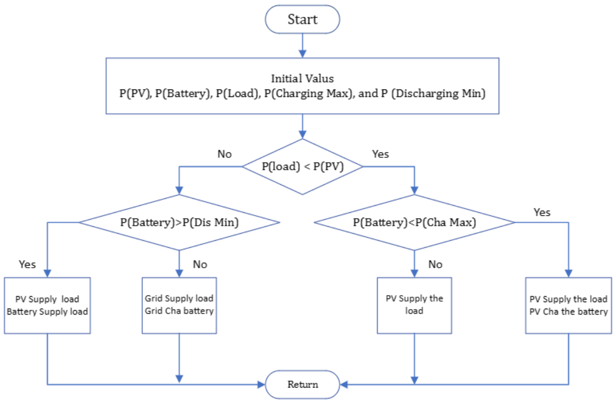

Figure 8. The proposed EMS operation for the residential DC microgrid topology.

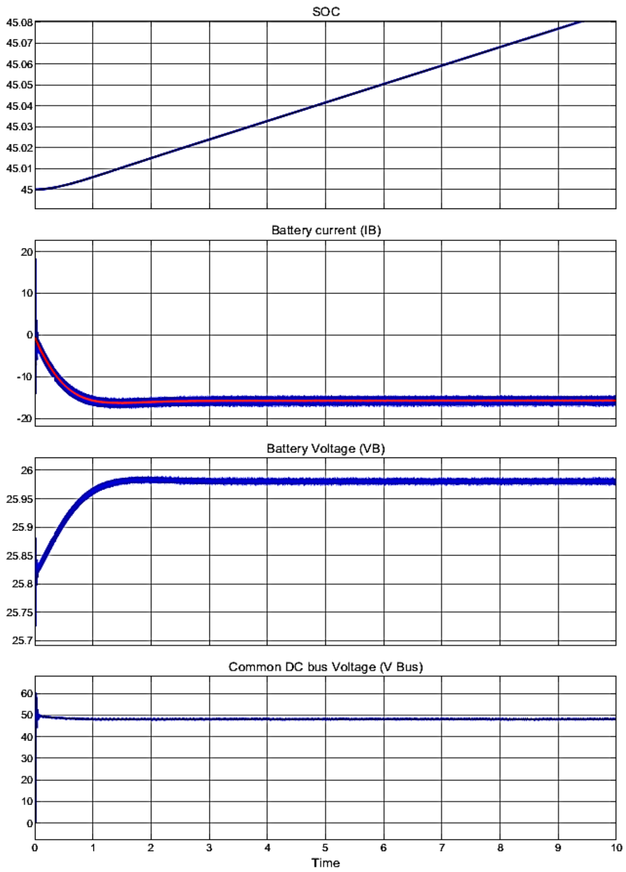

Figure 9. The PV generator supplied the local demand and charged the battery storage unit.

The second scenario examines the performance of the suggested residential DC microgrid system when the PV modules do not generate electrical power and the DC microgrid relies on the BES units to meet the local residential demand as shown in Figure 9. In this case, the battery current sign is negative which means the battery discharging mode is applied and the battery starts supplying the local load of the residential DC microgrid.

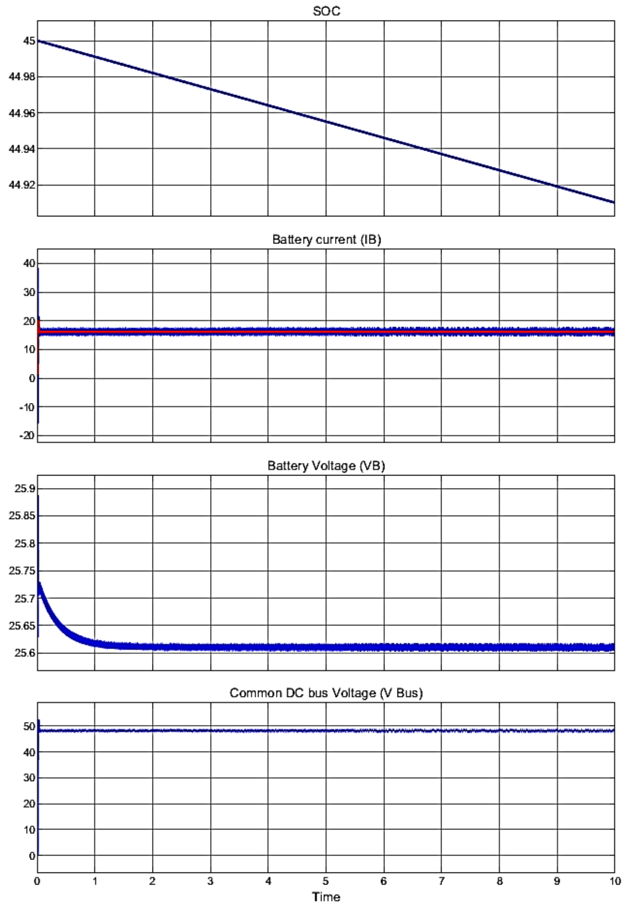

Figure 10. The battery storage is used as the main supply unit.

The stability analysis of the suggested residential DC microgrid is examined by suddenly changing the mode of operation from one scenario to another. Figure 10 illustrates the performance of the proposed DC microgrid system when the battery storage unit mode suddenly changes from chagrining to discharging mode. The system is assumed to rely on the PV system to supply local load and charge the battery unit. Then, the PV modules stop generating power and the battery starts meeting the local demand.

V. Conclusion

The paper presented a DC-DC cascaded boost converter for obtaining the maximum available power from the three series PV SMs in a residential DC microgrid. The DC-DC boost converter has been chosen because it can obtain the maximum available power and increase the low voltage at higher PV SM output voltage. The step-up capability of the DC-DC boost converters is limited especially at low input voltage. Thus, cascading the three SM boost converters has been proposed to boost the voltage further to meet the voltage at the common DC bus of the DC microgrid. An optimized operating strategy for residential DC microgrid systems with different operating moods has been conducted. The conventional P&O MPPT tracking algorithm has been employed to maintain a pure DC input current of each PV SM at different operation conditions. The proposed operating strategy of the residential DC microgrid aims to effectively buffer the PV power in the BESS during off-peak time and utilize the storage energy the local demand peaked.

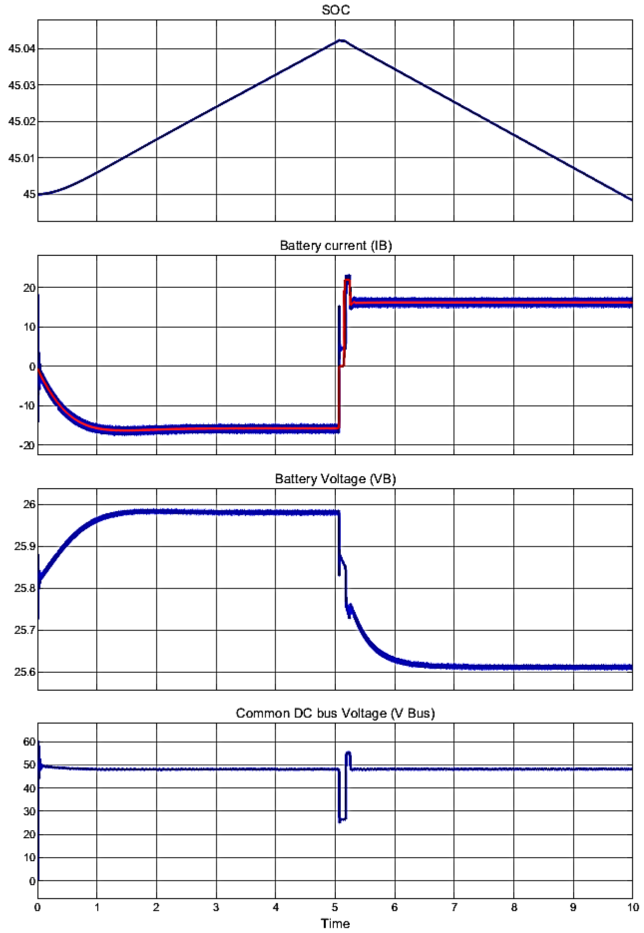

Figure 11. The DC grid system responds to sudden changes in the battery unit mode.

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