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A Distributed Control Strategy for an Isolated Residential DC Microgrid

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Abstract: A low-voltage unipolar type dc microgrid , which includes photovoltaic (PV) arrays, Fuel Cells (FCs), batteries and power electronic interfaces, is presented in this study. In order to provide the plug-and-play feature, a distributed control strategy based on Dc Bus Signaling (DBS) is studied. According to the proposed control strategy, the operations of the dc microgrid are categorized into three modes: batteries charging/discharging, Constant Voltage (CV) generation and FCs discharging. These three kinds of modes can be automatically switched by using DBS. Control methods of converters for different microsources are also addressed. Simulation results are provided to verify the effectiveness of the proposed control strategy.

Keywords: Dc Bus Signaling (DBS), dc microgrid, distributed control, voltage droop

INTRODUCTION

DC microgrid is suitable for smooth installation of Distributed Generations (DGs) and energy storage devices. Using dc distribution system, some conversion units can be eliminated and dc loads (e.g., electronic load and electric vehicle) can be supplied more effectively, thereby reducing the system losses (Kakigano *et al.*, 2010b). Nowadays, dc microgrid has been received considerable attention from scholars and electric utility industry (Kakigano *et al.*, 2010a; Saeedifard *et al.*, 2010; Balog *et al.*, 2012).

Since Photovoltaic (PV) generation, which has been widely used, is natively dc source, therefore dc microgrid is an effective solution to connect PV system with dc loads. But take the stochastic characteristic of PV generation into account, energy storage elements are indispensable for dc microgrid to smooth the power fluctuations and provide electric power with high quality. It is well known that the most important parameter of dc microgrid is dc voltage. A constant dc voltage indicates balanced active power flow among energy sources, storage devices and loads. Thus, the active power within the dc grid must be balanced under any condition (Fakham *et al.*, 2011; Kai *et al.*, 2011; Li *et al.*, 2011; Lie and Dong, 2011). However, the literatures mentioned above have only one battery, the parallel operation methods of several small rated converters are not considered. Besides, scaled energy storage devices are usually very bulky and therefore paralleling is more advantageous (Klimczak and Munk-Nielsen, 2008). Using lower rated converters in parallel instead of a single, larger rated converter has several advantages, for example higher efficiency, better dynamic response and so on.

In this study, a low-voltage unipolar type dc microgrid is presented. This dc system supplies power for a residential complex, where the grid is difficult and often infeasible to extend lines and feeders to these remote areas. To manage the power among these different converters, a distributed control strategy based on Dc Bus Signaling (DBS) is proposed. Sharing of load among different battery converters are also achieved by using voltage droop characteristic.

METHODOLOGY

System configuration: The structure diagram of the low-voltage unipolar type dc microgrid is shown in Fig. 1. Each house has PV array, Fuel Cell (FC) and battery. All microsources are connected to the dc bus through the power electronic interfaces. Two types of converters are used in this paper, namely boost converter and buck-boost converter. Electric power is shared among different houses using dc distribution line. PV arrays are chosen as primary power sources, which usually operate in Maximum Power Point Tracking (MPPT) mode. Batteries play a role to stabilize dc bus voltage. FCs are used as backup generators, which provide the gap power when batteries have been fully discharged.

The models of PV, FC and battery described in Ceraolo (2000) and Uzunoglu *et al.* (2009) is used in this study, For the details of model development, reader is referred to the aforementioned literatures.

Energy management scheme: An energy management scheme with DBS is proposed to maintain the power balance and stable operation of this system under any conditions, such as variations in solar radiation and loads. The operations of this isolated dc microgrid are

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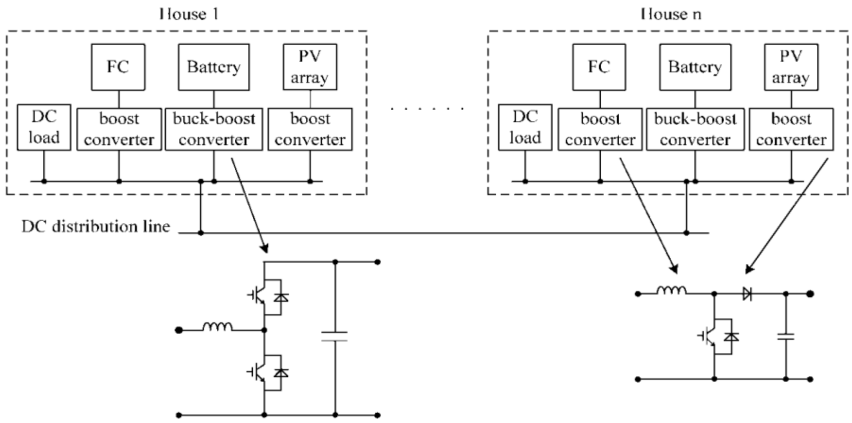

Fig. 1: Configuration of the studied dc microgrid

categorized into three modes: Mode 1, batteries charging/discharging; Mode 2, Constant Voltage (CV) generation; Mode 3, FCs discharging. These three operation modes are identified by different dc bus voltage levels, which means that the dc bus voltage is used as an information carrier. The switching between different operation modes and the changes of corresponding control methods of converters can be realized through dc voltage variations without additional communication links (Schonberger *et al.*, 2006; Li *et al.*, 2011). This benefits cost reduction and reliability enhancement.
Three operation modes are described as follows.

Mode 1: In this mode, the dc bus voltage is regulated at 326V by battery converters and the boost converters of PV arrays work with MPPT. Batteries with bidirectional dc/dc converters are used to balance the power difference between PV power supplies and local loads. If the dc bus voltage (V_{DC}) is lower than 326 V, batteries are discharged. Otherwise, batteries are charged.

Mode 2: In this mode, batteries do not work because they have been fully charged, at this time, dc bus voltage is regulated by PV converters. Since the power generated by PV arrays is greater than dc loads, the dc bus voltage rises, when V_{DC} is equal to 335 V, the control method of PV converters is changed from MPPT to CV, then the dc voltage is kept at 335 V.

Mode 3: In this mode, batteries still do not work as they have been fully discharged. As solar generation is less than user demand, V_{DC} decreases. When the dc voltage is lower than 315 V, FCs come online and provide the gap power. Once the dc voltage exceeds 330 V, FCs will be stopped and return back to standby state.

Table 1: Operation states of different microsources

Mode	PV arrays	Batteries	FCS
1	MPPT	Charge/discharge	Off
2	CV	Off	Off
3	MPPT	Charge	Discharge

Table 2: Control-law implementation

Threshold	Description	Value
V_1	FC discharge threshold	315V
V_2	FC stop working threshold	330V
V_3	CV control threshold	335V

The operation states of different microsources are summarized in Table 1. To implement the control law, three voltage thresholds are defined as shown in Table 2.

Control methods for converters:

Control method for PV converters: Each boost converter for PV array has two operation states: MPPT operation and CV operation. There are many methods to track maximum power from PV array, such as hill climbing, perturb and observe (P&O), incremental conductance and so on. In this paper, the P&O method is used because it is easy and cheap to implement (Khanh *et al.*, 2010). The P&O MPPT algorithm with a power-feedback control is shown in Fig. 2.

Assuming continuous current mode for PV converter, the following expressions are applicable:

$$P_{PV} = I_{PV}V_{PV} \tag{1}$$

$$P_{PV} = I_{PV}V_{DC}(1-D_{PV}) \tag{2}$$

where, V_{PV} and I_{PV} are the output voltage and output current of PV array, respectively. D_{PV} is the duty cycle of the PV converter. MPPT should govern D_{PV}, independent of any other variables. The block diagram of the PV control system is shown in Fig. 3.

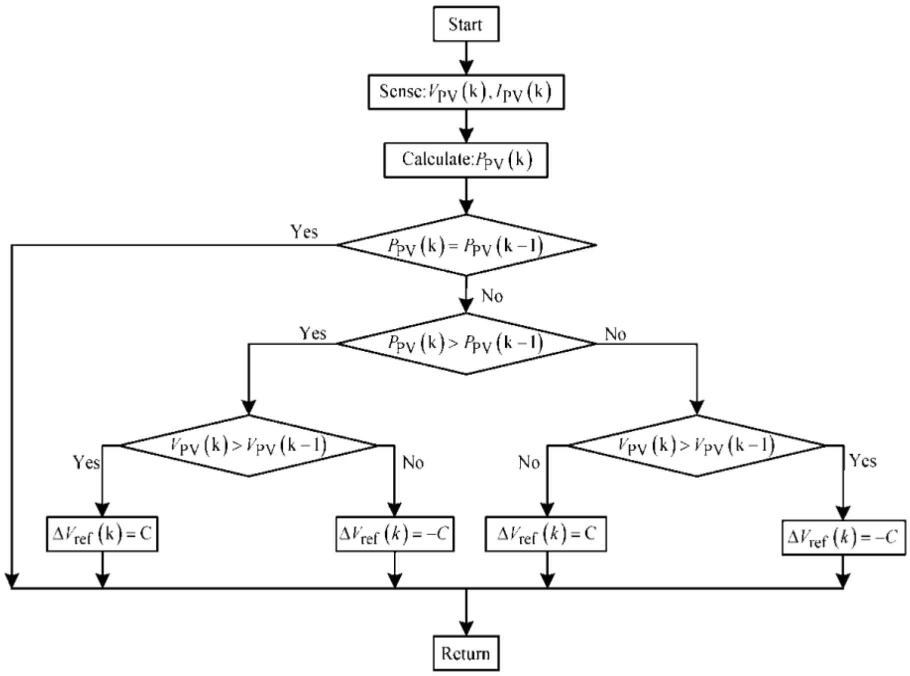

Fig. 2: P&O MPPT algorithm

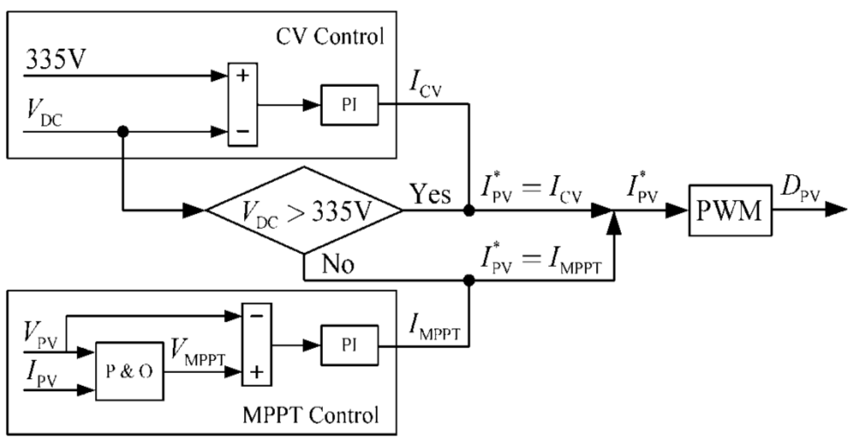

Fig. 3: Control diagram of each boost converter for a PV array

Control method for battery converters: Each buck-boost converter for battery has three operation states: off, discharge and charge. The nominal dc bus voltage (V_{DCRef}) is 326V. When V_{DC} is higher than 326V, battery is charged by surplus power. On the contrary, when V_{DC} is lower than 326V, battery starts to discharge. Taking the overcharging and over discharging protection for battery into account, V_{BH} and V_{BL} are introduced. where, V_{BH} is the maximum allowable voltage and V_{BL} is the minimum allowable voltage. If the terminal voltage of battery (V_B) is within the range of (V_{BL},V_{BH}), battery has the ability to smooth the power fluctuation of PV arrays, otherwise, it has to be outage.

Additionally, to permit the load current sharing between other battery converters, a voltage droop characteristic is adopted. The set point for the output voltage is given by:

$$V_i^* = V_{DCRef} - k_i \times I_{io} \tag{3}$$

where, I_{io} and k_i are the output current and droop coefficient of the i-th battery converter, respectively.

Suppose that each battery (Fig. 1) has the same capacity and shares the load equally, we can get the following formula:

$$k_1 = k_2 = ... = k_i = k \tag{4}$$

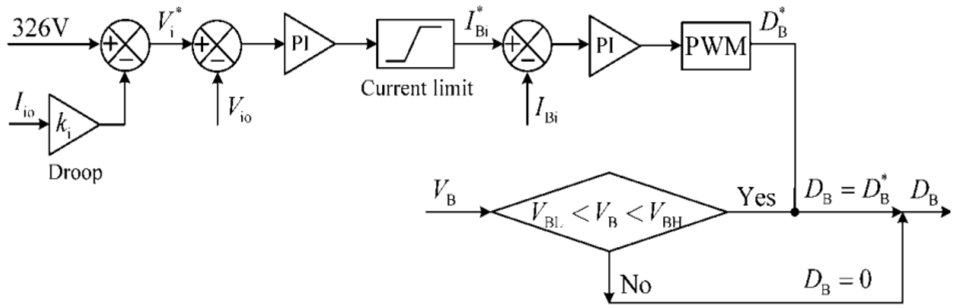

Fig. 4: Control diagram of each buck-boost converter for a battery

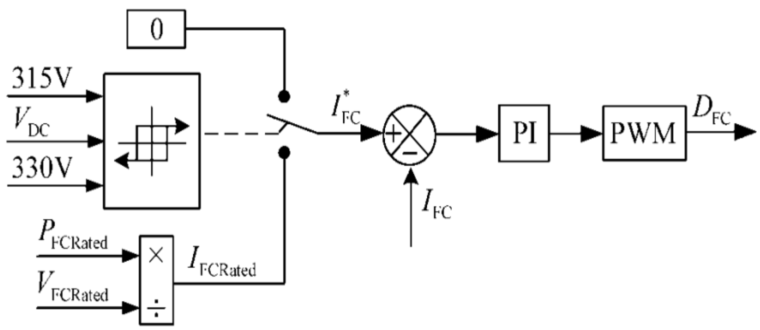

Fig. 5: Control diagram of each boost converter for a FC

The circulating currents can be avoided because each battery converter has the same droop coefficient, that means the power provided or absorbed by each battery is equal.

The control method for a battery converter is shown in Fig. 4. The control structure is two tiered, comprising a fast inner current control loop and a slower outer PI voltage control loop (Schonberger *et al.*, 2006). A current limit is included between the voltage and current loops to make the battery current within an interval [$-I_{BRated}$, I_{BRated}]. The PI controller regulates the output voltage of the converter to nominal dc voltage by providing a current reference to the inner loop.

In Fig. 4, I^*_{Bi} is the current reference for the i-th battery converter, I_{Bi} is the detected current and D_B is the duty ratio of the i-th buck-boost converter. As shown in Fig. 4, the charging/discharging of a battery converter is determined by I^*_{Bi}. When $I^*_{Bi} > 0$, the battery converter is used for discharging. When $I^*_{Bi} < 0$, the battery converter is used for charging.

Control method for FC converters: Each FC converter has two operation states: standby and discharge. Usually, FCs operate in standby unless the dc bus voltage decreases below their discharge threshold. At this point, FCs come online, acting as constant power sources. In order to keep high efficiency, FCs should not be operated by a partial load condition, but operated by a start/stop control. Fig. 5. shows the control scheme for a FC converter. where, $P_{FCRated}$ and $V_{FCRated}$ are the rated power and the rated voltage of FC, respectively. $I_{FCRated}$ is the FC rated current.

From Fig. 5, it can be seen that FC state depends only on dc bus voltage: FC current reference I^*_{FC} will be equal to $I_{FCRated}$ if V_{DC} < 315V. When V_{DC} > 330V, it will be zero.

SIMULATION RESULTS

To validate the proposed control methods, simulation model has been developed in Matlab/Simulink software environment. It is assumed that there are two households in the system. Fig. 6 shows the simulation circuit. In this simulation, we assume that the average load is 1 kW, the peak load is 5 kW, the rated capacity of PV array is 5 kW, the rated capacity of FC is 10 kW and the battery capacity is 15 A h. The minimum and maximum acceptable voltage values of battery are equal to 240 V and 260 V, respectively and the initial voltage is set to be 250 V. Battery maximum charging/discharging current is 50 A. The switching frequencies of all converters are 20kHz.

The source and load power is varied to force a transition between the operating modes of the system. Fig. 7 shows the output power of PV arrays. Fig. 8 shows the variations in load power. Fig. 9 shows the terminal voltage of battery 1 and battery 2. The changes of dc bus voltage and output power of FCs are shown in Fig. 10 and Fig. 11, respectively.

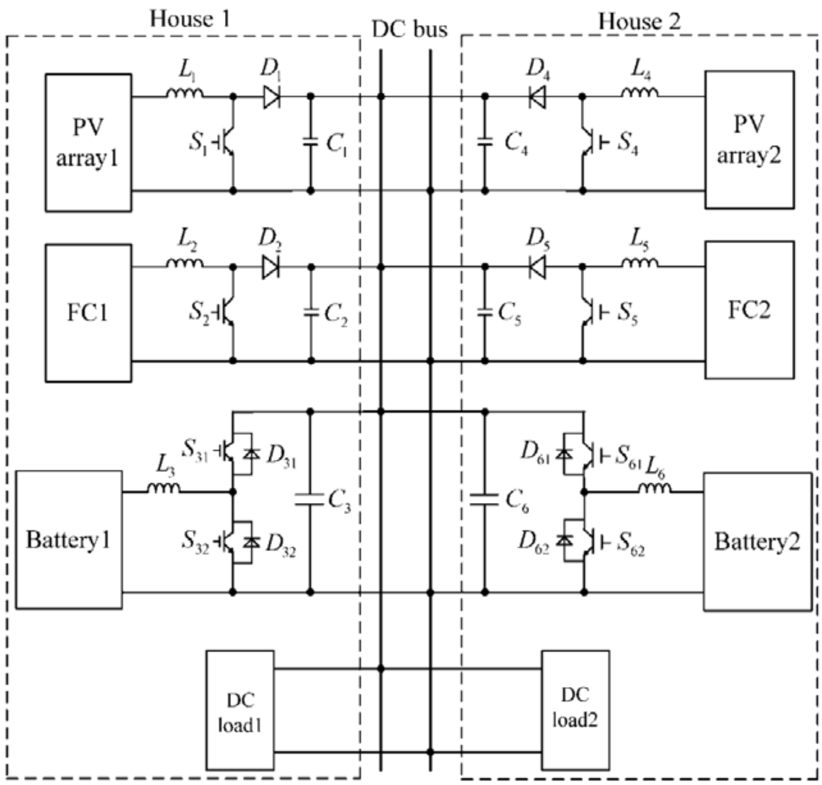

Fig. 6: Simulation circuit

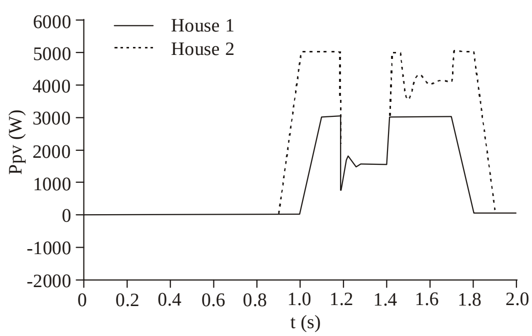

Fig. 7: The output power of PV array 1 and PV array 2

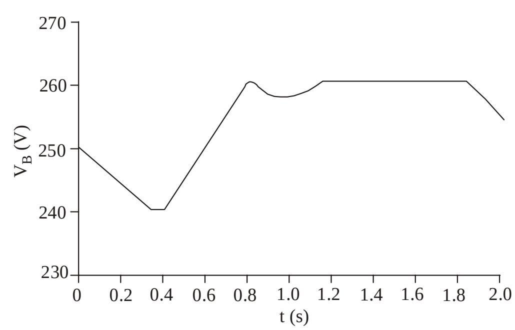

Fig. 9: Terminal voltage of battery 1 and battery 2

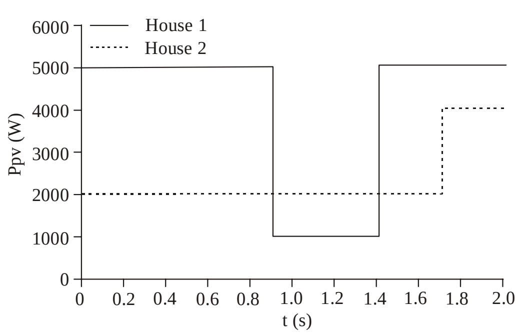

Fig. 8: Load curves of dc load 1 and dc load 2

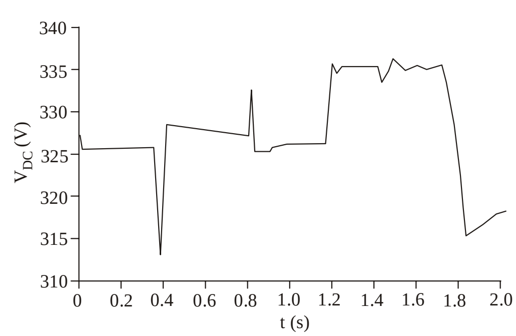

Fig.10: The changes of dc bus voltage

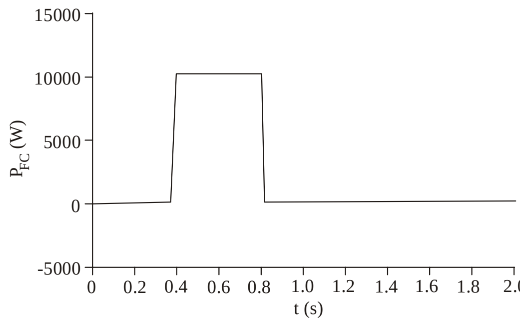

Fig. 11: The output power of Fcs

Initially, the maximum power of PV array 1 and PV array 2 is 0 kW, dc load 1 is 5 kW and dc load 2 is 2 kW. Since PV arrays do not generate any power, dc load is supplied by batteries, with the terminal voltage of batteries decreasing. The system operates in mode 1 and dc bus voltage is kept at 326 V. When V_B is decreased to 240 V, the batteries are disabled due to over discharging protection. As a result, the dc bus voltage begin to drop. When V_{DC} is equal to 315 V, FCs begin discharging to provide the dc loads, maintaining the power balance. The system now operates in mode 3. Because the output of FCs is capable of supplying the loads, batteries are charged by the excess power, with V_B rising. At this moment, the dc voltage is regulated by battery converters. When V_B reaches 260 V, batteries are stopped due to overcharging protection. Then V_{DC} starts to rise, once V_{DC} exceeds 330 V, FCs will be stopped. Subsequently, batteries are discharged to supply dc loads and the system returns back to mode 1.

At 0.9s, the Maximum Power Point (MPP) of the PV array 2 is increased from 0 kW to 5 kW and dc load 1 is decreased from 5 kW to 1 kW. Since the PV arrays are able to meet the load demands, the system still operates in mode 1.

At 1s, the MPP of the PV array 1 is increased to 3 kW, dc load 1 is 1 kW and dc load 2 is 2 kW. Since the power generated by PV arrays is higher than dc load, the batteries are charged by the surplus power, with V_B rising. When V_B reaches 260V, the batteries have to be stopped. Then V_{DC} begin rising, when the dc bus voltage reaches 335V, the control mode of PV converters is switched from MPPT control to CV control. The dc voltage is now kept at 335V and the output power of each PV array is limited to 1.5kW. The system now operates in mode 2.

At 1.4s, dc load 1 is increased to 5 kW while dc load 2 remains at 2 kW. The load demands are now higher than the limited solar power, that leads to decrease in V_{DC}. As V_{DC} is less than 335V, the control mode of PV converters is changed from CV to MPPT, then the output power of PV array 1 and PV array 2 are increased to the maximum power. At this time, the total load is 7 kW while total generated power is 8 kW, thus dc bus voltage will rise as batteries are disabled due to overcharging protection. When V_{DC} is equal to 335 V, PV array 1 works with MPPT, whereas PV array 2 operates in power limiting mode, with generated power 4 kW. The system operates in mode 2.

At 1.7s, the PV array 1 is taken offline and dc load 2 is increased to 4 kW. Since the load exceeds the power available from PV arrays, the control mode of PV array 2 is switched from CV to MPPT.

At 1.8s, the PV array 2 is disabled, dc load 1 is 5 kW and dc load 2 is 4 kW. The total load (9 kW) is supplied only by batteries, as there is no power available from PV arrays. The system operates in mode 1 with batteries discharging.

The simulation results have demonstrated that the DBS successfully allows the system to operate according to the aforementioned control law. The operation states of these different microsources can be automatically switched to maintain the power balance in this dc microgrid. And the dc bus voltage fluctuation is within the acceptable range (310 V, 340 V) during changes in solar radiation and load.

CONCLUSION

A distributed power control strategy of an isolated dc microgrid is proposed in this study. The dc bus acts as a communication link between different microsources. Each source and storage interface converter can operate independently and provides the plug-and-play feature. The results obtained from the research work are as follows:

- MPPT of the PV arrays has been implemented to make the system efficient
- Smooth transitions between the different operation modes are realized only using DBS
- Sharing of load among different battery converters has been implemented by using voltage droop characteristics

In a word, the proposed control strategy is feasible and effective. The dc microgrid works stably with providing an uninterrupted power supply for sensitive loads under any operation conditions.

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