Coordinated power flow control of DC microgrid consisting of distributed generations and energy storage system

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Abstract. In this paper, to operate DC microgrid in a flexible and reliable way, a coordinated power flow control strategy of DC microgrid and control methodology of power electronic converters are presented in both the grid-tied mode or islanded mode. For this purpose, the operation algorithm and power flow of DC microgrid are selected based on the distributed generation power, load demand, and energy storage system (ESS) status. The effectiveness of the system power balance and power flow control method are verified during operation mode transition through the simulation studies based on the PSIM software.

1. Introduction
Recently, there has been a gradual interest on the integration of the renewable energy sources into the electrical power system because of the critical worldwide energy situation caused by the depletion of fossil fuel and the greenhouse gas emission limit. Because renewable energy sources are usually distributed in a wide area and have an intermittent output nature, the conventional generation and distribution schemes based on the centralized electrical power system are not sufficiently efficient and effective. Thus, the recent development trend constructing electrical power grid is to share distributed generation (DG) units with electrical power systems, which has a significant impact on the operation of electric distribution networks [1].

As DG systems are penetrated rapidly into electrical power grid, an innovative concept of microgrid began to emerge. Microgrid normally consists of multiple DG units, local loads, and energy storage systems (ESSs). This requires a coordinated operation and power flow control approach to integrate multiple DG units in the electrical network, which allows DG units to actively contribute to frequency and voltage regulation. Also, microgrid can provide more technical benefits and control flexibilities to utility grid as compared with the conventional electrical power system [2].

Microgrid provides more technical benefits and control flexibilities to both utility grid and microgrid participants as compared to the conventional power system. Microgrid also gives benefits of scale for the utility, and moreover, it can deliver the power with better power quality and high reliability for consumers [1]. The essential function of microgrid is to have the ability to operate either in grid-tied mode or islanded mode in case of the absence of the main utility grid [3]. Another important requirement is to exchange the active and reactive powers effectively between the microgrid and main utility grid. In addition to satisfying the essential requirements, power flow control methodologies have been developed to provide smartness to microgrid based on three levels of hierarchical structure which are the primary control, the secondary control, and the tertiary control [4]. According to common bus voltages, microgrid is classified as AC microgrid and DC microgrid [5].
DC microgrid is more attractive than AC microgrid due to several advantages. In particular, DC microgrid has higher efficiency and provides more natural power conversion interface with many types of DG and ESS systems. In addition, the reactive power flow and harmonic injection do not need to be considered in DC microgrid. In this regard, DC microgrid is recently preferred to AC microgrid.

In microgrid, a grid-tied inverter is generally operated in bidirectional mode to exchange the power between microgrid and utility grid. Furthermore, the ESS is normally combined in microgrid for the purpose of improving the stability in electrical power system supplying local loads as well as overcoming the inherent output fluctuation of DG units in microgrid configuration. As the critical loads are rapidly increasing in microgrid, the ESS has an important role in providing a very flexible power usage and effective system operation. Moreover, when microgrid is disconnected to utility grid and operates in an islanded mode due to the grid fault, the ESS can be effectively used to supply local loads within microgrid.

This paper presents a power flow control strategy and control methodology of power electronic converters for efficient operation of DC microgrid which consists of a utility grid connection system, a permanent magnet synchronous generator (PMSG) based wind power generation system (WPGS), a battery ESS, and DC loads. Microgrid operation and power flow control scheme are selected based on the generation power of WPGS, power demand of load, and state of charge (SOC) level of ESS under the grid-tied condition as well as islanded condition. In a grid-tied mode, microgrid should control the active and reactive powers to grid by maintaining the synchronization to grid while supplying local loads. The grid-tied inverter not only maintains a supply-demand power balance of DC microgrid but also injects high-quality currents into the utility grid according to microgrid operation modes. The ESS is linked to microgrid with a bidirectional interleaved DC/DC converter to provide microgrid with operation flexibility. The system power balance and power flow control strategy of DC microgrid are validated through the simulation studies based on the PSIM software.

2. Configuration of DC microgrid

Figure 1 shows the configuration of DC microgrid consisting of four main units which are a PMSG-based WPGS, battery ESS, grid-tied bidirectional converter, and DC loads. In WPGS, a PMSG is used to convert the mechanical power from wind turbine output into electrical power. This output power is injected into the DC bus through AC/DC power converter. A battery ESS is also connected to the DC bus through a bidirectional interleaved DC/DC converter. For the purpose of interacting DC microgrid with the utility grid, a grid-tied inverter is employed.

![Image]

**Figure 1.** Configuration of DC microgrid interconnected with DG and ESS.

In view of power flow, three-phase AC/DC power converter interfacing the WPGS has
unidirectional power flow because it should only deliver the generated power by a wind turbine into the DC bus. On the other hand, the grid-tied inverter should have bidirectional power flow according to the power demand in DC microgrid. When the generated power from the WPGS is sufficient, the operation of the grid-tied inverter is to deliver the surplus power to the utility grid. The grid-tied inverter should also operate as converter mode to charge the ESS or to supply DC loads when the power from the WPGS is not enough. The interleaved DC/DC converter to interface battery ESS has bidirectional power flow to charge the battery or to discharge it by controlling the battery current with constant level in either direction. In DC microgrid, the ESS plays an important role of mitigating the power fluctuation from DG units as well as of enhancing the stability of the entire power system.

While the interleaved bidirectional DC/DC converter operates like a buck converter during charging mode operation, it operates like a boost converter during discharging mode operation depending on the SOC level of ESS, DC load demand, and generated power from the WPGS. Figures 2 and 3 show the charging and discharging mode operations of the interleaved bidirectional DC/DC converter, respectively. Whereas the power flow of DC/DC converter is from the DC bus to battery ESS in the charging mode, it is from battery ESS into the DC bus in the discharging mode operation.

In DC microgrid operation, the DC bus voltage is primarily considered as a signal to indicate the power balance among interconnected power systems. Therefore, the DC bus voltage should be controlled in every circumstance by at least one power converter among WPGS converter, grid-tied inverter, or battery ESS converter.

![Figure 2. Charging operation mode of bidirectional DC/DC converter.](image1)

![Figure 3. Discharging operation mode of bidirectional DC/DC converter.](image2)

### 3. Coordinated power flow control scheme of DC microgrid

The system power balance of DC microgrid can be achieved by means of a coordinated operation of interconnected power systems such as the utility grid, DGs, ESSs, and DC loads by regulating the DC bus voltage. Figure 4 shows a coordinated power flow control strategy of DC microgrid both in grid-tied and islanded modes considered in this paper based on the correlation of the WPGS, utility grid, battery ESS status, and load demand. According to the SOC level of battery, the developed power from WPGS, and load power demand, microgrid operation is classified into eight operating modes. These operating modes are mainly divided as grid-tied or islanded mode depending on the presence or absence of the utility grid.

When DC microgrid is operated in the grid-tied mode, the DC bus voltage is controlled by the grid-tied inverter. In this operating condition, the SOC of ESS and load power demand determine the microgrid operating modes and charging/discharging of ESS through the bidirectional DC/DC converter. For instance, if the WPGS generation power $P_{WT}$ is sufficiently larger than load power demand $P_{Load}$, and the SOC level of ESS is higher than $SOC_{max}$, microgrid operation is selected as operating mode 1 to deliver the power from the WPGS and ESS to utility grid and local loads as shown in the power flow of figure 5. Figure 6, figure 7 and figure 8 denotes the power flow diagram in operating mode 2, operating mode 5, and operating mode 8, respectively.
4. Simulation results
For the performance evaluation of a presented coordinated power flow control strategy of DC microgrid, the simulations have been done by using the PSIM software. To implement the entire power system, five PSIM DLL blocks are used as follows:
- DLL block 1: Controller implementation for WPGS converter
- DLL block 2: Controller implementation for grid-tied inverter
- DLL block 3: Controller implementation for bidirectional DC/DC converter
- DLL block 4: Implementation of wind turbine model
- DLL block 5: Implementation of battery model.

Figure 4. Coordinated power flow control strategy of DC microgrid.

Figure 5. Power flow in operating mode 1.

Figure 6. Power flow in operating mode 2.

Figure 7. Power flow in operating mode 5.

Figure 8. Power flow in operating mode 8.
Figure 9 shows the simulation results under DC microgrid operation transition from operating mode 5 to operating mode 8. Initially, DC microgrid operates stably in operating mode 5, in which the WPGS as well as the utility grid supplies the power into the DC bus and the battery is charged with current of 3 A. When the grid suddenly has a fault at $t = 0.3\, \text{s}$, DC microgrid operation is changed into the islanded mode with operating mode 8. At this instant, to maintain the system power balance by

Figure 10. Simulation results under microgrid operation transition from operating mode 2 to operating mode 7.
compensating the power deficit, the ESS changes its operation into discharging mode to control the DC bus voltage stably.

Figure 10 shows the simulation results under DC microgrid operation transition from operating mode 2 to operating mode 7. Initial microgrid operation is in operating mode 2. In this operating mode, the grid-tied inverter operates in inverter mode to transfer the power from the DC bus to utility grid. The WPGS supplies the power into the DC bus and the battery is charged with current of 3 A. In spite of a grid fault at t = 0.1 s, if the WPGS power $P_{WT}$ is sufficiently large and the SOC of ESS is low, microgrid stably maintains the current operation except for the operation of grid-tied converter, which results in operating mode 7.

5. Conclusions
In this paper, to validate a flexible and reliable operation of DC microgrid, a coordinated power flow control method of DC microgrid as well as the control structure of power converter circuits have been presented in both the grid-tied mode and islanded mode. The power flow control scheme for a proper DC microgrid operation is selected based on the generation power of the WPGS, the power demand of DC load, and the ESS SOC level. The proposed power control method well confirms that the operation mode of DC microgrid can be reliably and stably changed in accordance with the supply power, load demand, and ESS status even during operating mode transition periods. The system power balance and power flow control are verified during operation mode transition through the simulation studies based on the PSIM software.

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