

Chapter 2

Hybrid AC/DC Micro-Grids: Solution for High Efficient Future Power Systems

Peng Wang, Jianfang Xiao, Chi Jin, Xiaoqing Han and Wenping Qin

Abstract This chapter titled “Hybrid AC/DC Microgrids: Solution for High Efficient Future Power Systems” presents a new configuration for future power systems which is the hybrid AC/DC grid for high efficient connection of the inherent AC and DC sources and loads. Three-phase AC power systems have been in dominant position for over hundred years due to invention of transformer and the inherent characteristic from fossil energy-driven rotating machines. However, the gradual changes of load types and distributed renewable generation (DRG) in AC local distribution systems provide food for consideration of adding DC networks. Renewable sources such as fuel cells and solar photovoltaics are DC inherent and should be connected to AC grid through DC/AC conversion techniques whereas some AC inherent renewable sources like wind generators also need DC links in their conversion systems to increase efficiency and mitigate power variation caused by intermittency and uncertainty. The disadvantage of AC grids for connection of DC inherent sources and loads as well as AC loads with DC links is that additional DC/AC or AC/DC converters are required, which may result in efficiency loss from the reverse conversion. In the other hand DC grids are resurging due to the development and deployment of renewable DC power sources and their inherent advantage for DC loads in commercial, industrial and residential applications. The number of power conversions in a DC microgrid has been significantly reduced to enhance system energy efficiency. A more likely scenario is the coexistence of both

P. Wang (✉) · J. Xiao · C. Jin
Nanyang Technology University, Singapore, Singapore
e-mail: epwang@ntu.edu.sg

J. Xiao
e-mail: XI0012NG@e.ntu.edu.sg

C. Jin
e-mail: Jinchi@e.ntu.edu.sg

X. Han · W. Qin
Taiyuan University of Technology, Shanxi, China
e-mail: hanxiaoqing@tyut.edu.cn

W. Qin
e-mail: qinwenping1027@163.com

AC and DC microgrids, which is so-called the hybrid AC/DC microgrid in order to reduce processes of multiple reverse conversions in an individual AC or DC microgrid and facilitate the connection of various renewable AC/DC sources and loads to power system. Therefore the concept of hybrid microgrids, which can harmonize both AC and DC sources and loads, has been proposed for future high efficient power systems. Conventional AC and DC grids are interconnected together through the bidirectional AC/DC converter. The component model has been introduced. The control and operation of individual sources and energy storages are presented. The coordination control and power sharing techniques are also introduced.

1 Introduction

Three-phase AC power systems have been in dominant position for over 100 years due to invention of transformer and the inherent characteristic from fossil energy driven rotating machines. However, the gradual changes of load types and distributed renewable generation (DRG) in AC local distribution systems provide food for consideration of adding DC networks [1].

The limited fossil energy sources are reducing significantly due to the fast growth of energy demand in modern societies. Over dependent on fossil courses has caused severe environment problems such as air pollution, globe warming and extreme weather conditions. Therefore renewables like wind and solar as the alternatives of fossil sources have been integrated into power systems in last decades. Renewable sources can be connected to either the high voltage network of an AC grid such as wind solar farms or to the low voltage distribution networks as distributed generations like small backyard wind turbines and rooftop photovoltaic (PV) arrays. This is a major reason behind the appearance of AC microgrids [2–5]. However some renewable sources such as fuel cells and solar photovoltaics are DC inherent and should be connected to AC grid through DC/AC conversion techniques. Some AC inherent renewable sources like wind generators also need DC links in their conversion systems to increase efficiency and mitigate power variation caused by intermittency and uncertainty.

In the early stage, power systems were designed to supply the lighting, heating, and motor driving loads which are mainly AC type. However, load evolution in AC local distribution systems have been occurring quietly with the development of power electronics techniques and new lighting equipment for high efficiency of energy utilization and control flexibility. When we look around the loads in modern power systems, it is found that DC loads and AC loads with AC/DC/AC converters are in a dominate position. Common facilities such as computers, printers, videos recorders, TVs, microwave in offices and homes are direct DC loads. Traditional AC motors as direct drivers for washing machines, refrigerators, air conditioners and various industrial machines are being gradually replaced by power electronics based AC motors in order to control the motor speed and to save energy.

The disadvantage of AC grids for connection of DC inherent sources and loads as well as AC loads with DC links is that additional DC/AC or AC/DC converters are required, which may result in efficiency loss from the reverse conversion. Recently, DC grids are resurging due to the development and deployment of renewable DC power sources and their inherent advantage for DC loads in commercial, industrial, and residential applications. The DC microgrid has been proposed to integrate various distributed generators [6–11]. The number of power conversions in a DC microgrid has been significantly reduced to enhance system energy efficiency [1]. DC microgrid has been implemented for telecommunication system, data center, offshore platforms, renewable energy system, etc. However, AC sources have to be converted into DC before connected to a DC grid and DC/AC inverters are required for conventional AC loads. A more likely scenario is the coexistence of both AC and DC microgrids, which is so-called the hybrid AC/DC microgrid in order to reduce processes of multiple reverse conversions in an individual AC or DC microgrid and facilitate the connection of various renewable AC/DC sources and loads to power system. Therefore the concept of hybrid microgrids, which can harmonize both AC and DC sources and loads, has been proposed [1, 3] for future high efficient power systems. This chapter introduces basic network configuration. The major components and their functions will be presented. The control and operation of the major components will be discussed in detail to present the operating principle of the hybrid microgrid.

2 Hybrid AC/DC Microgrid Configuration and Components

A hybrid AC/DC microgrid is the combination of AC and DC networks as shown in Fig. 1 where various AC and DC sources and loads are connected to the corresponding DC and AC networks through transformers and converters, respectively. The DC and AC networks are connected together through the bidirectional AC/DC converters which may be transformerless or with transformer.

The PV conversion systems and fuel cell generators are connected to the DC network through DC/DC boosters. Light wind turbine which needs battery as energy buffer can also be connected to DC network. DC loads such as electric vehicles (EVs) and LEDs are connected to the DC network through DC/DC buck converters. Power electronics driven AC motors are connected to DC network through DC/AC converters. DC energy storages such as batteries and super capacitors are connected to the DC network through bidirectional DC/DC converters.

AC power generators such as wind turbine generators and small diesel generators are connected to the AC network. AC energy storages such as flywheels are connected to AC grid through AC/AC converters. AC loads such as AC motors and heaters are connected to the AC network. The three-phase AC network of the

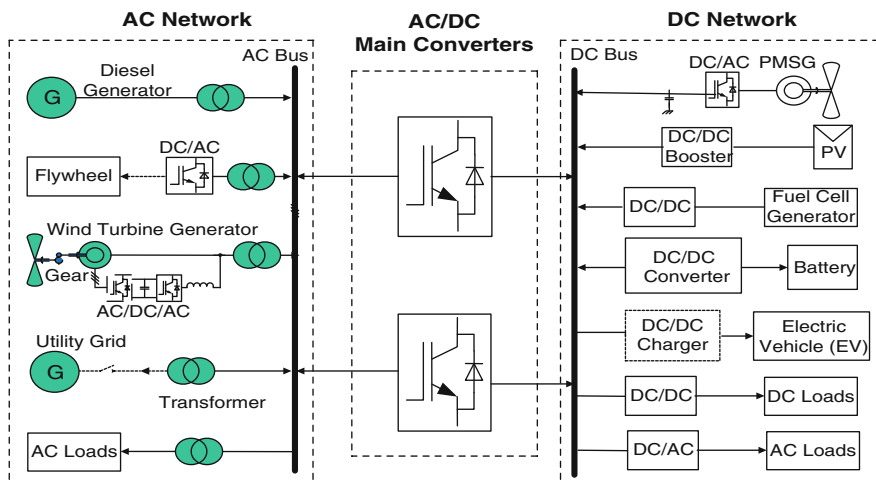


Fig. 1 A typical hybrid AC/DC microgrid configuration

hybrid grid can also be existing in low-voltage distribution network. Hybrid grid can be an isolated grid or connected to the utility grid through a transformer. It should be noted that a transformer may be required for the connection of some AC sources and loads if their output or input voltages are different with the AC network.

The voltage level of the AC grid is 400 V. There is still no standard voltage level for the DC network. The common voltage level currently used in most test systems is 380 V.

3 Modeling and Control of Wind Turbine Generator

Conventional AC power sources are usually synchronous generators and renewable power sources connected to the AC network are usually wind turbine generators. Basic equivalent circuit and operating principle of a synchronous generator can be found in many text books and are not presented in this chapter. The modeling and control of wind turbine generator have been well studied [12–15]. The control and operation of wind turbine generator are presented in this section. The mechanical power output P_m from a WTG can be calculated as

$$P_m = 0.5 \rho A C_p(\lambda, \beta) V_w^3, \quad (1)$$

where ρ is air density, A is rotor swept area, V_w is wind speed and $C_p(\lambda, \beta)$ is power coefficient which is the function of tip speed ratio λ and pitch angle β .

The circuit models of a DFIG are essential requirements for WTG control system. The voltage equations of an induction motor in a rotating d - q reference frame are as [12]

$$\begin{bmatrix} u_{ds} \\ u_{qs} \\ u_{dr} \\ u_{qr} \end{bmatrix} = \begin{bmatrix} -R_s & 0 & 0 & 0 \\ 0 & -R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} + p \begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} + \begin{bmatrix} -\omega_1 \lambda_{qs} \\ \omega_1 \lambda_{ds} \\ -\omega_2 \lambda_{qr} \\ \omega_2 \lambda_{dr} \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} -L_s & 0 & L_m & 0 \\ 0 & -L_s & 0 & L_m \\ -L_m & 0 & L_r & 0 \\ 0 & -L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (3)$$

The dynamic equation of a DFIG is as:

$$\frac{J}{n_p} \frac{d\omega_r}{dt} = T_m - T_{em} \quad (4)$$

$$T_{em} = n_p L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (5)$$

where the subscripts d , q , s and r denote d -axis, q -axis, stator and rotor, respectively, L represents the inductance, λ is the flux linkage, u and i represent voltage and current, respectively, ω_1 and ω_2 are the angular synchronous speed and slip speed, respectively, ω_r is the rotor speed, $\omega_2 = \omega_1 - \omega_r$, T_m is the mechanical torque, T_{em} is the electromagnetic torque, R_s and L_s are stator resistance and inductance repetitively, R_r and L_r are rotor resistance and inductance repetitively, L_m is the mutual inductance, J is the rotor inertial constant, and n_p is the number of poles.

If the synchronous rotating d - q reference is oriented by the stator voltage vector, the d -axis is aligned with the stator voltage vector while the q -axis is aligned with the stator flux reference frame. Therefore, $\lambda_{ds} = 0$ and $\lambda_{qs} = \lambda_s$. The following equations can be obtained in the stator voltage oriented reference frame as [12]:

$$i_{ds} = -\frac{L_m}{L_s} i_{dr} \quad T_{em} = n_p \frac{L_m}{L_s} \lambda_s i_{dr} \quad \sigma = \frac{L_s L_r - L_m}{L_s L_r} \quad (6)$$

$$u_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - (\omega_1 - \omega_r)(L_m i_{qs} + L_r i_{qr}) \quad (7)$$

$$u_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + (\omega_1 - \omega_r)(L_m i_{ds} + L_r i_{dr}) \quad (8)$$

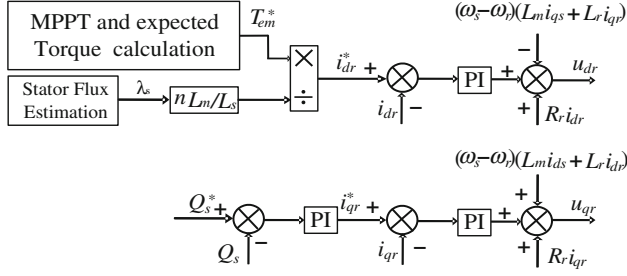


Fig. 2 The DTC control scheme for the rotor side converter

The AC/DC/AC converter of the DFIG is controlled to regulate rotor side current to achieve maximum power point tracking (MPPT), to synchronize with AC grid and to manage the stator side reactive power. Different control schemes such as the direct torque control (DTC) and direct power control (DPC) have been proposed for a DFIG [12–14]. The DTC scheme as shown in Fig. 2 is selected as the control method for the rotor side converter. The rotor rotational speed is obtained through the MPPT algorithm, which is based on the power and speed characteristic of the wind turbine [15]. The rotational speed ω_r and mechanical power P_m are used to calculate the electromagnetic torque T_{em}^* . The d -axis rotor side current reference is determined based on T_{em}^* through stator flux estimation. The rotor side d - q voltages are maintained through controlling the corresponding current with appropriate feed forward voltage compensation.

4 Modeling and Control of Photovoltaic System

One type of DC power sources is PV panels. Individual PV conversion systems have been well studied and the related techniques have been investigated [16–20]. A PV panel is simulated as a current source connected in parallel with a diode and a resistor R_p and in series with resistor R_s as shown in Fig. 3.

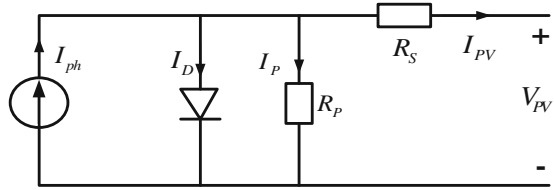
The output current I_{PV} of a PV panel can be calculated as [16, 17]

$$I_{PV} = n_p I_{ph} - n_p I_{sat} \times \left[\exp \left(\frac{q}{AkT} \left(\frac{V_{PV}}{n_s} + I_{PV} R_s \right) \right) - 1 \right] \quad (9)$$

$$I_{ph} = (I_{ss0} + k_i(T - T_r)) \times \frac{S}{1000} \quad (10)$$

$$I_{sat} = I_{rr} \left(\frac{T}{T_r} \right)^3 \exp \left(\left(\frac{qE_{gap}}{kA} \right) \times \left(\frac{1}{T_r} - \frac{1}{T} \right) \right) \quad (11)$$

Fig. 3 The circuit model of a PV panel



where V_{PV} is the terminal voltage of PV panel, I_{ph} is the photocurrent, I_{sat} is the saturation current, q is the electron charge, A is the ideality factor, k is the Boltzman constant, I_{ss0} is the short circuit current, k_i is the short circuit current temperature coefficient, T_r is the reference temperature, I_{rr} is the reverse saturation current at T_r , E_{gap} is the gap energy, n_p is the number of parallel solar cells, n_s is the number of series solar cells, S is the solar irradiation level and T is the junction temperature.

The output power of a PV panel depends on I-V curve as shown in Fig. 4 where I_{sc} and V_{oc} are the short circuit current and open-circuit voltage, respectively. Because of nonlinear relationship between the output current and the terminal voltage described in Eq. (9), the output power P_{PV} changes with the output current. A Maximum Power Point (MPP) exists at the terminal voltage V_{mp} and the output current I_{mp} . Therefore, a PV panel should be controlled to operate at the MPP.

A PV panel is connected to the DC bus through a DC/DC buck, booster or buck-boost converter which depends on the terminal voltage of the panel and the DC bus voltage. The layout and control schematic diagram of a basic DC/DC booster for the integration of a PV system is shown in Fig. 5. The PV system is normally controlled to operate in MPPT mode to harness the maximum power. The MPPT techniques including Perturbation & Observe (P&O), Incremental

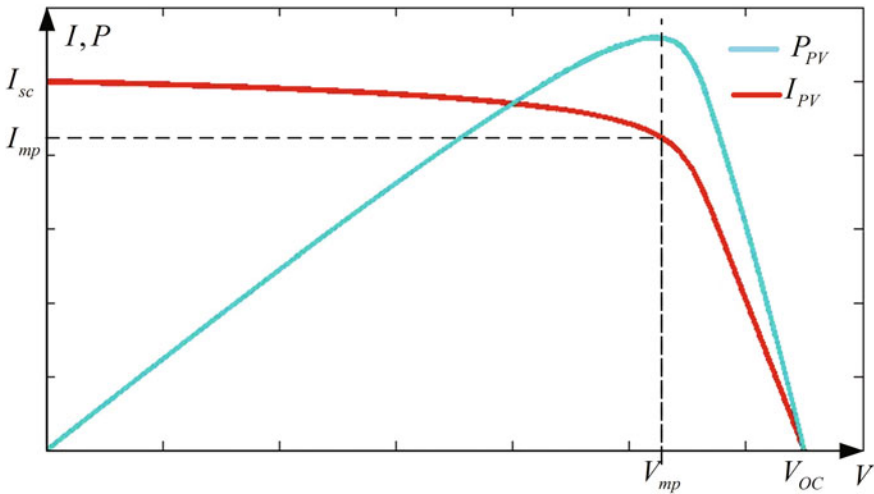


Fig. 4 The I-V and P-V curves of a PV panel

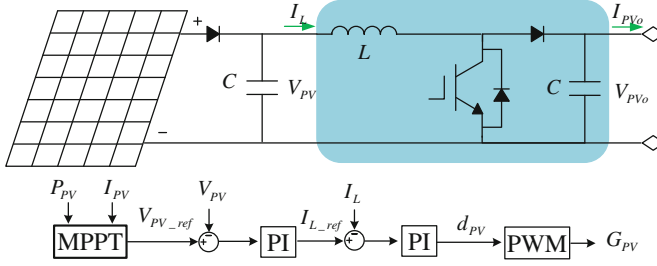


Fig. 5 DC/DC booster converter and the control block diagram for a PV panel

Conductance (IC), fractional open-circuit voltage, etc., have been well developed and introduced in [18–20]. The reference terminal voltage V_{PV_ref} is generated in the MPPT function block as shown in the figure and tracked by the conventional double-loop PI controller. In the outer voltage loop, the actual terminal voltage V_{PV} is compared with V_{PV_ref} and the error is processed with PI controller to generate the reference inductor current I_{L_ref} . The inductor current is tracked by a PI controller to generate the duty ratio d_{PV} which is sent to the pulse-width-modulation (PWM) generator to produce the switching signal G_{PV} for generating the maximum power.

5 Modeling and Control of Battery Energy Storage

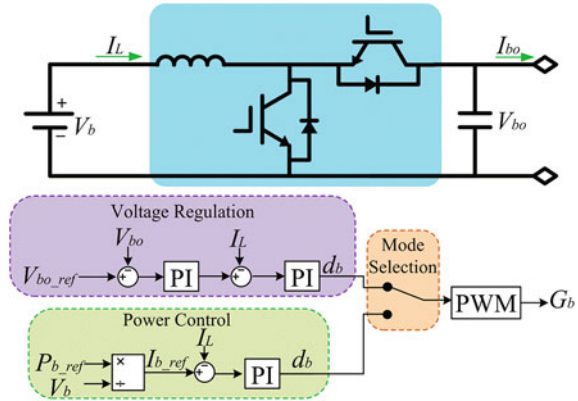
Battery energy storage system (BESS) is usually designed and connected to the DC bus to maintain power balance between power generation and loads in the DC network. The integration techniques of BESSs to AC and DC microgrids have been well developed [21–27]. A Bidirectional DC/DC converter is used to interface the battery bank output with the DC bus. The layout and control schematic diagram of a DC/DC buck–boost converter for battery control is as shown in Fig. 6. The converter is controlled as a booster when battery operates in discharging mode and a buck in charging mode.

The upper and lower switches in Fig. 6 are controlled to operate in complementary manner with the certain dead-time to prevent short circuit fault. The relationship between the converter output voltage V_{bo} and the battery output voltage V_b is as

$$V_{bo} = \begin{cases} \frac{1}{1-d_{bl}} V_o(\text{discharging}) \\ \frac{1}{d_{bu}} V_o(\text{charging}) \end{cases} \quad (12)$$

where d_{bl} and d_{bu} are the duty ratio for the lower and upper switches of the battery converter, respectively.

Fig. 6 The circuit and the control block diagram of a bidirectional battery converter



Battery converter can be controlled to operate in both voltage regulation and power control modes [21]. In voltage regulation mode, the reference voltage V_{bo_ref} of the battery converter is defined. The conventional double-loop PI control is implemented to track the reference voltage. BESS maintains system power balance autonomously through charge and discharge. The battery output power P_{b_ref} is defined in the power control mode. Reference battery output current I_{b_ref} is obtained by dividing the power reference with battery terminal voltage. The battery converter duty ratio is generated in the current control loop with the PI controller. Upon the determination of the operating mode in the mode selection block, the duty ratio is sent to the PWM generator. The constraints of BESS operation include the limitations of battery charge/discharge current and the rated energy capacity. Over-current charge/discharge degrades battery lifetime. Therefore, battery current is monitored in real time. In case of battery current exceeding the predefined threshold value, converter power/current control will be activated. The maximum allowable charge/discharge current is set as the current reference. The actual energy stored in battery is normally indicated by the State of Charge (SoC) or the Depth of Discharge (DoD). When the SoC exceeds the upper or lower limitation, over-charge/discharge damage is induced. When the SoC reaches the maximum value, battery is controlled to operate in only the discharging mode, and vice versa.

6 Operation and Control of DC Network

Operation and control techniques of AC power systems are very mature and will not be discussed in this chapter. Reliable and economic operation of the DC network depends on the coordinated control of multiple sources, loads, and energy storages. The control techniques for the DC microgrid have been proposed [6, 7, 8, 9, 10, 11, 28]. DC bus voltage is an important indicator of power balance of the DC network. The relationship between DC bus voltage and net power of DC network at time t is as

$$CV_{dc} = \frac{dV_{dc}}{dt} = (P_{RESs} + P_{DGs} + P_{BESs} + P_{BIC} - P_{Loads}), \quad (13)$$

where C and V_{dc} are the equivalent capacitance and voltage of the DC bus, P_{RESs} , P_{DGs} , and P_{BESs} are the output powers of renewable energy sources, other distributed DC sources, battery energy storages, and bidirectional converter, respectively, and P_{Loads} is the total load of DC network. The sign of a P_{BES} indicates the operating mode. When the total load is less than the total generation, DC bus voltage drops, and vice versa. The DC network is in the steady state, the net power is as

$$P_{RESs} + P_{DGs} + P_{BESs} + P_{BIC} - P_{Loads} = 0 \quad (14)$$

Keeping the real-time power balance of the DC bus is a complicated control problem when considering multiple objectives of system operation including maximizing renewable energy harvest, optimizing usages of BESSs and maintaining stable DC bus voltage within its limits under loads and resources variations. A three-level hierarchical level (HL) control of HLI, HLII, and HLIII is proposed to achieve reliability and economic operation of the DC network.

In the hierarchical control, the DC bus voltage is divided into five regions using the four predefined voltage thresholds whose values are determined by system operation requirements. The relationship among the threshold values are as.

$$V_{L2} < V_{L1} < V_{dcn} < V_{H1} < V_{H2}, \quad (15)$$

where V_{dcn} is the nominal DC bus voltage, V_{L2} and V_{H2} are the low and up limits of the DC network, respectively, V_{H1} and V_{L1} are threshold values for activating the battery charging and discharging, respectively. It should be noted that the threshold value varies based on the nominal voltage and operation requirements of a particular system. V_{H2} and V_{H1} are usually set to be 10 and 5 % above the nominal voltage, respectively, while V_{L1} and V_{L2} are 5 and 10 % below nominal voltage, respectively. For stable operation of the DC network, at least one of the DC sources should be controlled to regulate bus voltage (slack terminal). The five voltage regions are as follows:

Region 1: $V_{L1} \leq V_{dc} \leq V_{H1}$

Region 2: $V_{H1} < V_{dc} \leq V_{H2}$

Region 3: $V_{L2} \leq V_{dc} \leq V_{L1}$

Region 4: $V_{H2} \leq V_{dc}$

Region 5: $V_{L2} \geq V_{dc}$

6.1 Operation and Control of DC Network in HLI

The main objective of HLI control is to harvest the maximum powers from renewable energy sources and maintain basic operating reliability. The control schemes for different operation regions are as follows.

Region 1: To prevent frequent battery charging/discharging due to random variation of loads or renewable sources, Region 1 is the operation band in which all BESSs operate in the idle mode. PV converters work in MPPT mode to harness the maximum renewable energy to supply load. Power is balanced between power sources and loads through voltage regulation. Due to the lack of slack terminal, the bus voltage is allowed to change within the Region 1 according to power variation of loads and sources.

Region 2: In this region, there is power generation surplus from renewable sources. PV converters are controlled to operate in MPPT mode and the BESSs are activated to store the surplus power. All other nonrenewable power sources are in idle mode. Charging power sharing among BESSs is implemented by the droop control. The charging current of i th BESS is determined by the linear droop as

$$V_{\text{boi}}^{\text{ref}} = V_{\text{H1}} - m_{\text{bi}} I_{\text{boi}}, \text{ (charging)}, \quad (16)$$

where $V_{\text{boi}}^{\text{ref}}$, I_{boi} and m_{bi} are the reference voltage, the output current of i th battery converter and the droop coefficient of i th BESS, respectively.

Region 3: In this region, the DC bus voltage is low because power generation is less than load. PV converters are controlled to operate in the MPPT mode and BESSs are in discharging mode to compensate the power shortage. When BESSs reach the maximum discharging rate, to prevent bus voltage from collapsing, nonrenewable power sources change from the idle mode to the voltage regulation mode at V_{L2} . The discharging current of i th BESS is determined by the linear droop as

$$V_{\text{boi}}^{\text{ref}} = V_{\text{L1}} - m_{\text{bi}} I_{\text{boi}}, \text{ (discharging)} \quad (17)$$

6.2 Operation and Control of DC Network in HLII

The limitation of the HLI control is that all the resources are controlled by local voltage signal. The utilization of the resources is not optimal. This can be improved by real-time information sharing among converters through communication links and energy management system in HLII control. Communication link generally brings full observability over DC microgrid including the real-time bus voltage, power flow, and operation status of converters, thus system optimal operation in term of reliability and cost could be achieved through coordination control on system elements. Although the effectiveness of system operation depends heavily

on the communication quality in HLII, the system reliability would not be degraded due to HLI as the backup. Once failure happens in the communication links, all elements including PV modules and battery storages can retain the system stability under HLI control with the cost of losing global optimization. The control strategy for Region 1 in HLII is the same as the one in HLI. The PV modules operate in MPPT mode and BESSs are idle. The main objective of HLII control is to solve the power sharing problems among PV modules and BESSs when there is PV power surplus or shortage.

6.3 Operation and Control of DC Network in HLIII

Over or under voltage may occur due to sudden loss of loads or PV modules in system operation, which may damage system components or lead to malfunction of system control. To protect those abnormal conditions, HLIII control is therefore designed to maintain the DC bus voltage within allowable band when abnormal system conditions occur.

Region 4: When load demand is low, renewable generation is high, and all BESSs are fully charged, the DC bus voltage may be over the limitation. In this case, some of PV converters have to be switched from the MPPT mode to voltage regulation mode to maintain system normal operation.

Region 5: When all renewable and nonrenewable sources and BESSs are operate in their maximum capacity and still cannot supply the load, the DC bus voltage may be under the limitation. In this case, some of DC load have to be curtailed.

7 Operation and Control of Bidirectional DC/AC Converter

The hybrid grid can operate in two modes [29]. In grid-connected mode, the main converter is to provide stable DC bus voltage and required reactive power and to exchange power between the AC and DC buses. The PV converters and WTG are controlled to provide the maximum power. When the output power of the DC sources is greater than the DC loads, the converter should be controlled as an inverter and injects power from DC to AC side. When the total power generation is less than the total load at DC side, the main converter transfers power from the AC to DC side. When the total power generation is greater than the total load in the hybrid grid, it will produce power to the utility grid. Otherwise, the hybrid grid will absorb power from the utility grid. In grid-tied mode, the battery converter is not very important in system operation because power is balanced by the utility grid.

In autonomous mode, battery plays a very important role for both power balance and voltage stability. Control objectives for various converters can be centrally

dispatched by energy management system (EMS) or decentralized. The DC bus voltage is maintained stable by battery converters or boost converters according to different operating conditions. The main converter is controlled to provide a stable and high quality AC bus voltage. Both PV and WTG can operate in MPPT or off-MPPT mode based on system operating requirements.

There are PV and storage converters in the DC network, the DFIG back-to-back converters in the AC network and the main converter interconnecting AC/DC networks. Those converters have to be coordinately controlled with the utility grid to supply an uninterrupted, high efficiency, and high quality power to variable DC and AC loads under variable solar irradiation and wind speed when the hybrid grid operates in both isolated and grid-tied modes. The control algorithms for PV, BESS, and WTG converters have been introduced in previous sections. The control and operation of the bidirectional main converter are presented in this section.

There are the centralized and decentralized control methods for operation of hybrid microgrids. Decentralized control for multiple converters without communication links provides a good solution to ride through communication malfunction and therefore enhance the system reliability. The fully decentralized control for an autonomous hybrid microgrid is not straightforward if power exchange between two sub-grids is required. In this section, a fully decentralized control for power management in individual sub-grid and throughout the entire hybrid system is presented by means of local power sharing in individual AC and DC networks and global power sharing between two networks.

7.1 Local Power Sharing in the AC Network

WTGs in the AC network are controlled to operate in MPPT mode. Power balance between generation and load is maintained by controlling the outputs from the conventional DGs (CDGs). Power sharing among the CDGs can be realized by the droop control method [30]. The P - f droop curve for x th CDG unit can be expressed as

$$f = f^* + m_x P_{ac_x} \quad (18)$$

$$m_x = \frac{f_{\min} - f_{\max}}{P_{ac_x}^{\max}} \quad (19)$$

where f^* is the reference frequency of the AC network, P_{ac_x} is power output, m_x is the droop coefficient, $f_{\min}$ and $f_{\max}$ are the minimum and maximum allowable frequency respectively, and $P_{ac_x}^{\max}$ is the maximum active power. Based on the same system frequency for all DGs, the power sharing among u CDGs can be obtained as

$$\frac{P_{ac_1}}{P_{ac_1}^{max}} = \frac{P_{ac_2}}{P_{ac_2}^{max}} = \dots = \frac{P_{ac_u}}{P_{ac_u}^{max}} \quad (20)$$

7.2 Local Power Sharing in the DC Network

As discussed in the previous section, all the renewable sources are controlled to operate in MPPT mode. The DC bus voltage is maintained by charging or discharging of BESSs. The droop control is applied for power sharing among BESSs. The droop curve of y th BESS in the DC network is as

$$V_{dc_y} = V_{dc}^* + d_y P_{dc_y} \quad (21)$$

$$d_y = \frac{V_{dc}^{min} - V_{dc}^{max}}{P_{dc_y}^{max}} \quad (22)$$

where V_{dc}^* is the reference DC bus voltage and configured as the maximum allowable voltage, V_{dc_y} is the terminal voltage of BESS and d_y is the negative droop coefficient, V_{dc}^{min} and V_{dc}^{max} are the minimum and maximum allowable DC bus voltage in the DC network, respectively, and $P_{ac_y}^{max}$ the is maximum output power for y th BESS.

The terminal voltages of BESSs are slightly different with bus voltage V_{dc} due to the different voltage drop in the cable. The voltage difference would lead to the inaccurate power sharing among BESSs. To solve this problem in DC network, a modified droop equation is developed as

$$V_{dc_y} = V_{dc}^* + d_y P_{dc_y} + i_{dc_y} Z_{dc_y}, \quad (23)$$

where i_{dc_y} and Z_{dc_y} are the output current and cable impedance. The power sharing equation among v BESSs can be obtained as

$$\frac{P_{dc_1}}{P_{dc_1}^{max}} = \frac{P_{dc_2}}{P_{dc_2}^{max}} = \dots = \frac{P_{dc_v}}{P_{dc_v}^{max}} \quad (24)$$

7.3 Global Power Sharing Among AC and DC Networks

Based on DC bus voltage and frequency of AC network, the control algorithm for power exchange between two networks is required. Because of the complexities of control and power sharing in two networks, a normalization process is proposed to determine the control parameters of bidirectional converter. The two separate droop

characteristics are normalized and combined to determine the power transfer between AC/DC networks [29].

Considering u CDGs in the AC network, the combined AC droop characteristics of the AC network is as

$$f = f^* + M \sum_{x=1}^u P_{ac_x} \quad (25)$$

$$M = 1 / \sum_{x=1}^u \frac{1}{m_x} \quad (26)$$

where $\sum_{x=1}^u P_{ac_x}$ is the total active power generated from u CDG units. M is the combined droop coefficient of the AC network.

Considering all BESSs in the DC network, the combined DC droop characteristics of DC network is as

$$V_{dc} = V_{dc}^* + D \sum_{y=1}^v P_{dc_y} \quad (27)$$

$$D = 1 / \sum_{y=1}^v \frac{1}{d_y} \quad (28)$$

where $\sum_{y=1}^v P_{dc_y}$ is the total power generated from all v BESS units in the DC network. D is the combined droop coefficient of the DC network.

Based on the combined droop equations of AC and DC networks, a normalization method is used to unify two control variables f and V_{dc} with different dimensions. The two combined droops in (25) and (27) are normalized as

$$(\gamma)' = \begin{cases} \frac{\gamma - \gamma_n}{\gamma_{\max} - \gamma_n}, & \text{for } \gamma > \gamma_n \\ \frac{\gamma_n - \gamma}{\gamma_n - \gamma_{\min}}, & \text{for } \gamma < \gamma_n \end{cases} \quad (29)$$

where γ represents f or V_{dc} , $(\gamma)'$ is normalized γ , γ_n is the nominal value of γ , and $\gamma_{\max}$, and $\gamma_{\min}$ are the maximum and minimum values of γ , respectively. For $(\gamma_{\max} - \gamma_n) = (\gamma_n - \gamma_{\min})$, $(\gamma)'$ can be written as

$$(\gamma)' = \frac{\gamma - 0.5(\gamma_{\max} + \gamma_{\min})}{0.5(\gamma_{\max} - \gamma_{\min})} \quad (30)$$

The normalized value $(\gamma)'$ varies between -1 and 1 . Substituting (30) into (25) and (27), the normalized droop characteristics for the respective AC and DC networks are as

$$(f)' = 1 + \frac{M}{0.5(f_{\max} - f_{\min})} \sum_{x=1}^u P_{ac_x} \quad (31)$$

$$(V_{dc})' = 1 + \frac{D}{0.5(V_{dc}^{\max} - V_{dc}^{\min})} \sum_{y=1}^v P_{dc_y} \quad (32)$$

Considering the definitions of m_x and d_y , (31) and (32) can be manipulated into (33) and (34), respectively.

$$(f)' = 1 - \frac{1}{0.5 \sum_{x=1}^u P_{dc_x}^{\max}} \sum_{x=1}^u P_{dc_x}^{\max} \quad (33)$$

$$(V_{dc})' = 1 - \frac{1}{0.5 \sum_{y=1}^v P_{dc_y}^{\max}} \sum_{y=1}^v P_{dc_y}^{\max} \quad (34)$$

The combined droop characteristics of two subnetworks have same dimensions on x and y axis and can be placed in the same reference frame with common vertical and horizontal axis. Global power sharing can then be inferred from the local power sharing in AC or DC network, whose f/V_{dc} are inherently unique to ensure proportional power sharing among all the units in both AC and DC networks. The attempt is to employ a PI controller to equalize $(f)'$ and $(V_{dc})'$ by exchanging power P between the AC and DC networks as

$$P = [(f)' - (V_{dc})'] (k_p + k_i/s) \quad (35)$$

where k_p and k_i are controller gains, and P is the power flows from AC to DC network. If $(f)'$ is larger than $(V_{dc})'$, power is transferred from AC to DC network. If $(f)'$ is less than $(V_{dc})'$, power is transferred from DC to AC network. If $(f)'$ equals to $(V_{dc})'$, there is no power transfer. The control scheme based on (35) ensure that all DGs in AC or DC networks can share the total load of hybrid grid in proportion to their maximum powers throughout the hybrid AC/DC system.

8 Summary

This chapter presents a new configuration for future power systems which is the hybrid AC/DC grid for high efficient connection of the inherent AC and DC sources and loads. Conventional AC and DC grids are interconnected together through the

bidirectional AC/DC converter. The component model has been introduced. The control and operation of individual sources and energy storages are presented. The coordination control and power sharing techniques are also introduced.

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