Bidirectional Droop Control of Interlinking Converter in AC/DC Hybrid Micro-grid

JI Yu1,WU Ming1, LIU Haitao1,LI Yang1
1. China Electric Power Research Institute
Beijing 100192, China

ZHANG Ying2
2. College of Information and Electrical Engineering
China Agricultural University
Beijing 100083, China

Abstract**—The interlinking converter in an AC/DC hybrid micro-grid plays a crucial role in the stable operation and power allocation of power system. A bidirectional droop control method for the converter is proposed, which measures the power demand degree of AC sub-grid and DC sub-grid according to AC bus frequency and DC bus voltage respectively, and determines the direction and magnitude of the converter transmission power. Two droop control modules, DC voltage-active power and AC frequency-active power, are included in the control structure. The power reference value of the converter is achieved from the output subtraction of two modules. Meanwhile to reduce the deviation of voltage and frequency caused by droop control, a recovery control is designed to improve the power quality and the reliability of the hybrid micro-grid. The bidirectional droop control can accurately coordinate the transmission power between AC sub-grid and DC sub-grid and make full use of the distributed energy. The feasibility of the control method is verified by a simulation system built with DigSILENT.**

Keywords: AC/DC hybrid micro-grid; interlinking converter; bidirectional droop control; simulation

I. INTRODUCTION

With the increase of DC load such as EV, AC/DC hybrid micro-grid has got a rapid development. AC/DC hybrid micro-grid including AC source and DC source can supply power to AC/DC load at the same time, improving the flexibility of distribution and making full use of the distributed energy [1]. Because of the species diversity of distributed power and complex operation mode of micro-grid, AC/DC hybrid micro-grid is different from the traditional electric power system in control and simulation modeling [2-3]. The DC/AC convert that controls the electric energy conversion between AC and DC bus in AC/DC hybrid micro-grid is called interlinking converter (IC). On the one hand, the interlinking converter manages the bidirectional active power flow in sub-grids [4] and control the energy transmission between AC sub-grid and DC sub-grid. On the other hand, for the sub-grid in either side of the interlinking converter, interlinking converter presents the power characteristics of supply and load at the same time respectively. The effective control of interlinking converter affects the stable operation and power allocation of the AC/DC hybrid micro-grid directly.

Interlinking converter control method includes constant voltage control [5-7], droop control [8-9], etc. Constant voltage control strategy is simple and easy to implement, but it makes the transmission power of interlinking converter uncontrolled. Several interlinking converters running in parallel generate circulation and damage the equipment in micro-grid. Droop control simulates the frequency modulation characteristics of generator set, easy to realize the average load distribution, has been the mainstream of interlinking converter control method gradually. In [8] a DC voltage-active power (U_{dc} - P) droop control method is proposed. When the increase of DC load lead to the decrease of DC voltage, interlinking converter increases the transmission power to DC side and improves power supply reliability of DC sub-grid, but it is not sensitive to the change of AC load. In [9], one kind of segmented droop control strategy of AC/DC bidirectional converter applying to AC/DC hybrid micro-grid is proposed, which reduces the frequent operation of the converter. In [8], it proposed one kind of droop control strategy based on virtual coordinate transformation. In [8 - 9], it proposed AC frequency - active power (f - P) and AC voltage - reactive power (U - Q) droop control method, when the increase of AC loads lead to the decrease of AC frequency, interlinking converter increases the transmission power to AC side, but it is not sensitive to the change of DC loads. In [3] and [9], it proposed two kinds of approximate bidirectional droop control method of interlinking converter, but the control part is too complex and ignores the decline of DC bus voltage and AC bus frequency caused by droop control, which reduce the reliability of the control strategy.

In order to make the interlinking converter increasing the active transmission power to DC side when DC load increases and increasing the active transmission power to AC side when AC load increases, realizing the load allocation between DC and AC power source, according to the f - P and U - Q droop control and U_{dc} - P droop control method, the paper puts forward a DC voltage - AC frequency - active power (U_{dc} - f - P) bidirectional droop control strategy. In view of the decline of DC bus voltage and AC bus frequency caused by droop control, recovery control strategy is designed to improve the stability of the micro-grid. The feasibility of the control method and strategy is verified by a simulation system built with DigSILENT.

II. BASIC DROOP CONTROL METHOD

The typical structure of AC/DC hybrid micro-grid is shown in Fig. 1 [1]. The micro-grid is mainly consist of the

978-1-5090-2535-0/16 $31.00 © 2016 IEEE
DOI 10.1109/ICISCE.2016.192

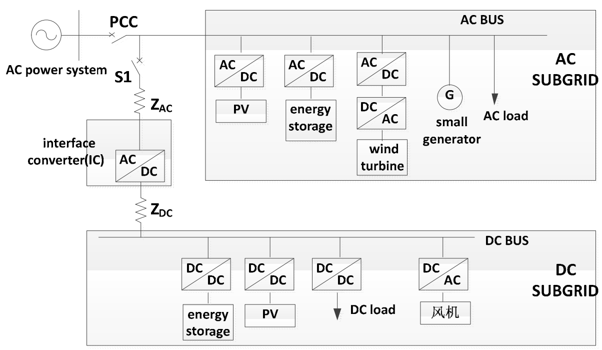


Figure 1. Typical Structure of hybrid micro-grid

AC sub-grid, DC sub-grid and interlinking converter. According to the actual demand, the micro-grid may include several interlinking converters and several DC sub-grids. Micro-grid connected with the AC sub-grid by the point of common coupling (PCC). DC bus connected with the AC bus by the interlinking converter, S1 is the AC side switch of interlinking converter. Distributed power supply, energy storage device and load connect with the bus by their export converters respectively.

Droop control of distributed power supply is one kind of control method that simulates static power frequency characteristics of generator set [1], don't need communication facilities, what's more, operation state can be changed by monitoring the local signal of interlinking converter [8], as a result, reasonable power allocation will be realized in this way. IC usually adopts two kinds of droop control, one is the frequency - active power (f - P) and voltage - reactive power (U - Q) droop control, the other is DC voltage-active power (U_{dc} - P) droop control.

A. f - P and U - Q droop control

$f-P$ and U - Q droop control takes AC bus frequency and voltage of the interlinking converter as reference, active and reactive power reference value can be achieved from the subtraction between measurements of frequency and voltage and rating value through the droop control unit respectively, as a result, the interlinking converters can be controlled in this way. Droop characteristic is shown in (1)

$$\begin{cases} P = P_0 + (f_0 - f)K_f \\ Q = Q_0 + (U_0 - U)K_u \end{cases} \tag{1}$$

In the formula, P and Q instead of the real value of active and reactive power respectively, we define the forwards direction is the direction from DC side to AC side. P_0 and Q_0 are the rating value of active and reactive power that interlinking converter exports respectively, suppose Q_0 is equal to 0 usually. f and U instead of the real value of interlinking converter's AC bus frequency and voltage. f_0 and U_0 are the rating value of interlinking converter's AC bus frequency and voltage respectively. K_1 and K_2 are droop coefficient of frequency and voltage respectively.

Droop coefficient can be achieved from the formula 2.

$$K_f = \frac{P_{\max} - P_0}{f_0 - f_{\min}} \tag{2}$$

$$K_u = \frac{Q_{\max}}{U_0 - U_{\min}} \tag{3}$$

In the formula, P_{max} instead of the allowed maximum of power that distributed power supply export when frequency is reducing. f_{min} instead of the allowed minimum of frequency that distributed power supply exports. Q_{max} is the reactive power that distributed power supply exports when voltage is reducing to the allowed minimum. U_{min} is the allowed minimum of voltage.

B. U_{dc} - P droop control

$U_{dc}-P$ droop control takes the DC bus voltage of the interlinking converter as the reference value, active power reference value can be achieved from the subtraction between the measurements value and rating value of DC voltage through the droop control unit, as a result, the interlinking converter can be controlled in this way. Droop characteristic is shown in (4) .

$$P = P_0 + (U_{dc} - U_{dc0}) K_d \tag{4}$$

In the formula, U_{dc} is the real value of DC side bus voltage. U_{dc0} is the rating value of DC side bus voltage . K_d is the droop coefficient.

III. Bidirectional Droop Control

$f-P$ droop control of active power considers the influence caused by AC signals only. Meanwhile, $U_{dc}-P$ droop control of the active power considers the influence caused by DC signals only. On this basis, considering these two kinds of variables' influence on power flow at the same time, we need to accurately coordinate the transmission power between AC sub-grid and DC sub-grid by interlinking converter and make full use of the distributed energy. Therefore, the paper proposes the method of bidirectional droop control, then distributes the active power according to the voltage of DC bus and the frequency of AC bus.

When AC/DC hybrid micro-grid runs stably, active power of each sub-grid should satisfy the following relation:

$$P_{g\_k} + P_{I\_k} + P_{s\_k} = P_{L\_k} \tag{5}$$

In the formula, K is the serial number of sub-grid, P_{g_k} instead of the active power that flows into the sub-grid from power distribution network, P_{I_k} is the active power that flows into the sub-grid through interlinking converter, P_{s_k} is the output power of distributed generation and energy storage equipment in the sub-grid, P_{L_k} is the total active power load in the sub-grid.

P_{I_k} is an important factor to make sure the direction of interlinking converter transmission power, reflecting the degree of imbalance for local electricity supply and demand. If the load or source changed, system power flow will change, furthermore, the voltage of DC bus and the frequency of AC bus will change finally. Therefore, a new stable state can be achieved by adjusting P_{I_k} according to the state of bus.

A. Control theory

Bidirectional droop control takes AC bus frequency and DC bus voltage as the input, which controls the active power that flows through the interlinking converter (positive direction from DC side to AC side). For an interlinking converter runs independently, the control structure is shown in Fig. 2. Bidirectional droop control consists of U_{dc} - f - P droop control loop and power-current control loop, meanwhile, interlinking converter adopts voltage source converter.

In Fig. 2, I_{uvw} is three phase current in AC side, U_{uvw} is three phase voltage in AC side, K_u and K_f are the DC voltage and AC frequency droop coefficient respectively, P_{ref_u} and P_{ref_f} are the reference power component got after voltage and frequency get through the droop control unit respectively. P_{ref} got by bidirectional droop control is reference active power of interlinking converter. The function of power-current double loops is to get the reference current I_{ref} [1] though PI control unit, according to the subtraction between power reference value and power measurement value. Suppose reactive power reference value is 0. Then adopt decoupling control of dq0 rotating coordinate system, get the subtraction between current measurement value decoupled and its reference value in the grid side, obtain P_{md} and P_{mq} that is d-q axis control signals of the converter by PI control unit. After the coordinate transformation and sine pulse width modulation, we get the interlinking converter modulation signal m_{abc} , working on converter [1]. Power-current double loops make the output power of the converter track the reference power exactly.

We can conclude the following equations which are followed in Fig. 2.

$$\Delta U = U_{dc0} - U_{dc} \tag{6}$$

$$\Delta f = f_0 - f \tag{7}$$

$$P_{ref\_u} = (U_{dc0} - U_{dc}) \cdot K_u \tag{8}$$

$$P_{ref\_f} = (f_0 - f) \cdot K_f \tag{9}$$

$$e_k = P_{ref\_f} - P_{ref\_u} \tag{10}$$

$$P_{ref} = e_k + P_0 \tag{11}$$

In the above, ΔU and Δf are the deviations of DC voltage and AC frequency respectively, e_k is the subtraction of reference power. P_{ref_u} and P_{ref_f} reflect the changing level of active power demand in DC side and AC side. e_k is the subtraction of reference power in sub-grid reflects the changing level of power demand in both sides of interlinking converter. Transmission power is determined by e_k in bidirectional droop control. Considering the effects of U_{dc0} on the reference power P_{ref} of interlinking converter, an appropriate reference value is necessary. The reference power can be get from Eq.12.

$$P_{ref} = P_0 - K_u(\,U_{dc0} - U_{dc}\,) + K_f(f_0 - f) \tag{12}$$

Assuming several converters run in parallel, we take a method which is different from droop coefficient calculation method in (2) - (3) to recognize DC sub-grid and AC sub-grid as an entirety, the converters distribute the load according capacity uniformly, the droop coefficient of converter n can be determined by the type (13) - (14), its droop characteristic can be obtained from (15).

$$K_{fn} = \frac{P_{ac\max} - P_{ac\min}}{f_{\max} - f_{\min}} \cdot \frac{S_n}{S_{total}} \tag{13}$$

$$K_{un} = \frac{P_{dc\max} - P_{dc\min}}{U_{\max} - U_{\min}} \tag{14}$$

$$P_{refn} = P_0 - K_{un}(U_{dc0} - U_{dc}) + K_{fn}(f_0 - f) \tag{15}$$

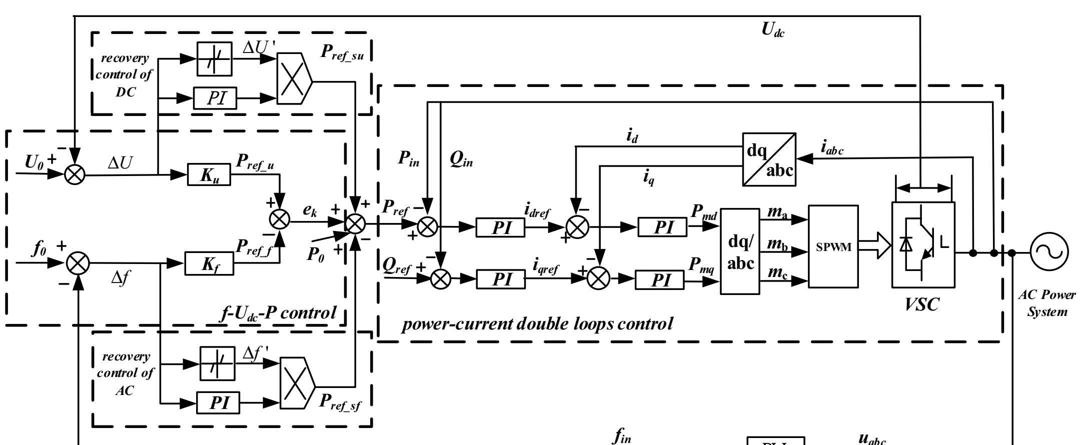


Figure 2. Bidirectional droop control structure of interlinking converter

In the formula, K_{fn} and K_{un} are the droop coefficients of AC frequency and DC voltage in the converter n respectively. P_{acmax} and P_{acmin} are maximal and minimal power that AC sub-grid exports to DC sub-grid. P_{dcmax} and P_{dcmin} are the maximal and minimal power that DC sub-grid exports to AC sub-grid respectively. f_{min} is the minimum of frequency, U_{max} is the maximum of voltage. S_n is the rated capacity of the interlinking converter n. S_{total} is the total rated capacity of interlinking converters in parallel. P_{refn} is the output power of the converter *n*.

Power is in positive direction when $P_{ref} > 0$, energy flows from DC bus to AC bus and interlinking converter works on inverter state. Power is in negative direction when $P_{ref} < 0$, energy flows from AC bus to DC bus and interlinking converter works on rectifier state. When $P_{ref} = 0$, the demand level of active power is very close in both sides of the interlinking converter, there is no power flow between two sub-grids of interlinking converter. Adjusting the transmission power of interlinking converter with bidirectional droop control, energy always flows to the sub-grid whose load demand is greater.

Due to the bidirectional droop control may lead to the decline of DC bus voltage or AC bus frequency, put forward the recovery control structures shown in Fig.2, get $\Delta U1'$,$\Delta U2'$,$\Delta f1'$, $\Delta f2'$ through PI control and dead zone control, then multiply $\Delta U1'$ by $\Delta U2'$,multiply $\Delta f1'$ by $\Delta f2'$, obtain the compensation value of active power P_{ref_su} and P_{ref_sf} , then keep the stability of DC voltage and AC frequency and improve power quality in this way. When ΔU and Δf within the scope allowed, the compensation value is 0, taking no effect on transmission power. When ΔU and Δf is beyond the scope allowed, dead zone control output $\Delta U'$ and $\Delta f'$ are not equal to zero any more. PI control will play an efficient role to bring DC voltage value and AC frequency value to the allowed range. Eq. (11) can be rewritten as follow,

$$P_{ref} = P_0 + e_k + P_{ref\_sf} - P_{ref\_su} \tag{16}$$

IV. SIMULATION ANALYSIS

A structure of AC/DC hybrid micro-grid built with DigSILENT is shown in Fig. 3. AC bus rating voltage is 0.4 kV, DC bus rating voltage is 0.7 kV.

At the beginning of simulation, power source supplies the rating voltage in the system. AC distributed power supplies with f - P and U - Q droop control, DC distributed power adopts constant voltage control to make its DC/DC converter voltage constant. AC load 1 (0. 1 MW) and DC load 1 (0. 6 MW) connect to grid, AC load 2 (0. 3 MW) and DC load 2 (0. 3 MW) in the state of off-grid; 5s later, connect the AC load 2 to micro-grid, 10s later, connect the DC load 2 to micro-grid. Setting the recovery control to start 15s later, then observe the function of recovery control.

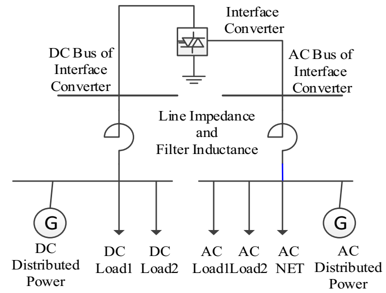
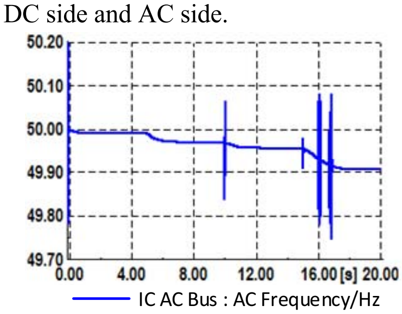


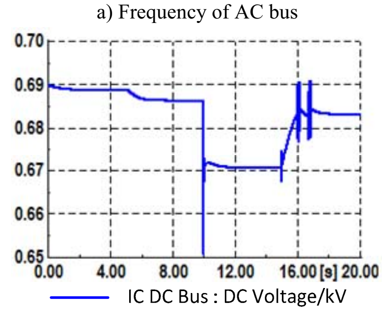
Figure 3. Structure of simulation grid

According to the bidirectional droop control designed in this paper, the AC bus frequency, DC bus voltage and transmission power are shown in Fig. 4. We define the direction from DC side to AC side is the forwards direction of transmission power. Droop coefficient K_U of interlinking converter is 4.3 MW/kV, K_f is 2.0 MW/Hz. Threshold voltage of recovery control is 0.7 ± 0.2 kV, threshold frequency of recovery control is 50±0.1 Hz. Using the same grid and droop coefficient and basing on the traditional $f-P$ and $U-Q$ droop control strategy, transmission power curve of interlinking converter is shown in Fig. 5.

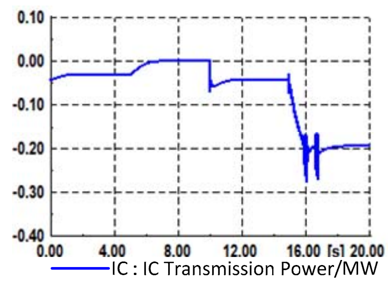
As is shown in Fig. 4, when the simulink time is 5s, DC voltage drops to 0.686 kV, AC frequency drops to 49. 97 Hz, transmission power rises to 0 MW. When simulink time is 10s, load in DC side increases, the DC voltage drops to 0. 671 kV, AC frequency drops to 49.96 Hz, transmission power drops to -0.04 MW. When AC load increases, the output power to AC side of interlinking converter increases, when DC load increases, the output power to DC side of interlinking converter increases, realizing the power allocation in DC side and AC side.



a) Frequency of AC bus



b) Voltage of DC bus



c) Transmission power

Figure. 4 Simulation results of bidirectional droop control

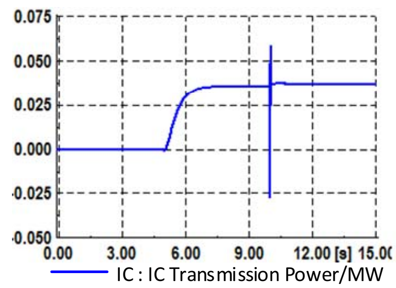


Figure. 5 Transmission power curve under f-P and U-Q droop control

As is shown in Fig. 5, when load in AC side increases, transmission power of interlinking converter under the f - P and U - Q droop control decreases, but it is not sensitive and did not change obviously if load fluctuations occur in DC side. As a result, it's not able to accommodate the power allocation in DC side of the grid.

As in Fig. 4, recovery control starts when simulink time is 15s, frequency doesn't cross the threshold, DC voltage is lower than minimum of the threshold. Under the action of voltage recovery control, DC voltage returns to 0. 68 kV, and transmission power of interlinking converter changes into -0.20 MW, which proves the effectiveness of recovery control. Due to the load in DC side changes a lot, the DC voltage offset increases. In order to recovery the stability of DC voltage, transmission power of the interlinking converter should be adjusted sharply, the frequency and voltage of the micro-grid are affected a lot, consequently, the function of secondary control bring an obvious fluctuation when simulink time is about 15s. What's more, it may lead to a result that voltage value and frequency value are lower or higher than the allowable values, this is caused by the power imbalance in system. Therefore, if load fluctuation is very big or the voltage and frequency exceed the limit value at the same time, except adjusting power depending on the interlinking converter, adjusting the output power of distributed power supply is needed to keep the power balance, reduce the transmission power of interlinking converter variation and ensure the quality of electric energy.

Above all, in the case of power demand of DC side or AC side changes, the bidirectional droop control makes the output power of converter flow to the side in which active load increases, complementing the deficiency of active power. But the traditional droop control only sensitive to the electrical signal of a single side, making it can't regulate the power balance of DC side and AC side at the same time. When DC voltage or AC frequency exceeds the allowable value, recovery control will complement the reference power to make the DC voltage and AC frequency values return to the allowed range.

V. CONCLUSION

The bidirectional droop control of AC/DC hybrid micro-grid is proposed in this paper and one kind of calculation method of its droop coefficient is given. Different from the traditional droop control, bidirectional droop control analyzes the working condition of DC bus and AC bus at the same time, confirms the working state of interlinking converter comprehensively, adjusts the power flow of micro-grid, makes full use of the distributed energy and improves the reliability of power supply. Put forward to the recovery of control strategy to avoid the decline of AC frequency and DC voltage caused by droop control. The feasibility of the droop control and recovery control method is verified by modeling and simulation with DigSILENT.

ACKNOWLEDGMENT

This work is supported by the National High Technology Research and Development Program of China (2015AA050104), and Innovation fund project of China Electric Power Research Institute (PD83-16-038).

REFERENCES

[1] Wang Chengshan, Analysis and simulation theory of microgrids, Beijing : Science Press, 2013, pp. 119-164.

[2] Wang Chengshan,Wu Zhen, Li Peng. Research on key technologies of microgrid. [J]. Transactions of China Electrotechnical Society, 2014, vol. 29(2), pp. 1-12.

[3] Loh P, Li Ding, Chai Yikang, "Autonomous operation of hybrid microgrid with AC and DC subgrids," IEEE TRANSACTIONS ON POWER ELECTRONICS, vol. 28(5), 2013, 2214 : 2 : 23.

[4] Li Xi, Yang Jianhua, Yang Rengang, Su Jian, Liu Haitao, "The optimal sitting and access capacity of a microgrid in the distribution System by PSO and GIS," Southern Power System Technology,2014, vol. 8(1), pp. 50-54.

[5] Sun Wentao, LIU Dichen, Zhao Jie, Dong Feifei , Chen Enze , Zeng Zheng, " PSASP /UPI simulation modelling and analysis of the PV power station in grid integration, " Southern Power System Technology, 2014, vol. 8(3), pp. 67-71.

[6] Zhang Mingrui, Du Zhichao, Wang Shaobo, "Research on droop control strategy and parameters selection of microgrids," Transactions of China Electrotechnical Society, 2014, vol. 29(2), pp. 136-144.

[7] Jing Long, Huang Xing, Wu Xuezhi, "Research on improved microsource droop control method," Transactions of China Electrotechnical Society, 2014, vol. 29(2), pp. 145-152+184.

[8] Fan Yuanliang, Miao Yiqun, Jiang Quanyuan,Cao Yijia, "Generator control design based on droop control architecture for microgrid," Automation of Electric Power Systems, 2012, vol. 32(6), pp. 125-130.

[9] Peng Chunhua, Wang Lina, Li Yunfeng, "Strategy of power-coupling droop control for three-phase inverter in low-voltage microgrid", Automation of Electric Power Systems, 2014, vol.34(3), pp. 28-33+46.