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An Optimal-Oriented Quasi-Droop Control of Interlinking Converter in Hybrid Microgrid

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Abstract—In hybrid microgrid, interlinking converter (ILC) is a key component to connect the AC subgrid and DC subgrid. Its control strategy significantly affect the power flow management, power quality, system efficiency and stability. Traditionally, ILC is usually controlled as a current source, resulting in a poor dynamic stability when a remote weak AC subgrid is connected by a large linking impedance. In this study, a quasi-droop control scheme is proposed to control ILC as a current controlled voltage source (CCVS). Not only a flexible power flow management is achieved, but an ancillary function of voltage support is also provided. Moreover, this simple quasi-droop control enables ILC to synchronize with the AC subgrid autonomously without a phase-locked loop (PLL). Finally, simulations are presented to verify the system effectiveness.

Keywords—Droop control; frequency synchronization; hybrid AC/DC microgrid; intrlinking converter.

I. INTRODUCTION

Microgrid has become a cost-efficient solution to integrate the increased penetration of renewable generations in the modern power network [1]. According to the type of power supply, microgrid can be classified into three categories: AC microgrid, DC microgrid, and hybrid AC/DC microgrid [2].

In the early periods, AC microgrid is dominated to connect distributed microsources within the utility grid or to form an islanded microgrid system for rural areas [3]. But, recently, with the advancement of high-voltage DC technology and increased DC loads, DC microgrid has been proposed as a popular structure. Especially, the DC sources such photovoltaic generation, fuel cells and storages can directly connected to DC microgrid to avoid the losses of DC-AC conversion [4]. Now, an interlinking converter (ILC) is implemented to link the DC microgrid and AC microgrid together to form a hybrid microgrid [5].

In general, hybrid AC/DC microgrid has the advantages of both AC and DC microgrid, and thus hybrid microgrid is probably the most promising microgrid structure in the near future [6]. A typical structure of a hybrid AC/DC microgrid is shown in Fig. 1. The AC and DC subgrids are linked via one or more ILCs. As DC and AC sources/loads are allocated in the DC and AC subgrids respectively, the conversions between AC-DC are substantially reduced, and the system has the increased efficiency and less cost. Moreover, the hybrid microgrid is connected to the utility grid by a static switch, which can disconnect the hybrid microgrid when one fault

occurs in utility grid and reconnect the microgrid when the fault is cleared [7]. This research work focuses on the islanded mode of hybrid microgrid.

Fig. 1. A typical structure of a hybrid AC/DC microgrid.

The functions of ILC are to coordinate the AC and DC subgrids and flexibly regulate the power flow between them [8]. For AC subgrids, active power-frequency droop control is a well-established method to realize an accurate power sharing among distributed generations (DGs) [9]. Similarly for DC subgrid, power-voltage droop control is commonly adopted to achieve satisfactory power sharing among DGs [10]. With regarding to the ILC, a desirable control scheme is required to guarantee the proper and efficient power exchange between AC and DC subgrids.

Presently, the control schemes of ILC can be classified two categories: communication-based [11-13] and communication-less (decentralized) [14-16] methods. In the former methods, several central control [11], distributed control [12] and master-slave control [13] methods have been proposed. The power set-point of ILC is indicated from the superior power management system. Although they achieve entire-system-level coordination and high efficiency, communication networks may increase the system cost and complexity. Specially, the communication delay and failure are detrimental to stability. To address this issue, decentralized control method is an alternative without relying on any communication. In [14-16], an original and creative operation manner is proposed. It equalizes the AC-subgrid normalized frequency and DC-subgrid normalized voltage, and generates the determined power reference for ILC. As a result, the power can autonomously flow from under-loaded subgrid to over-loaded

subgrid. However, the developed control scheme of ILC is inherently a current-controlled method, which does not directly regulate the voltage of AC subgrid and deteriorate the voltage quality to some extent. Meanwhile, the nonlinear PLL is also necessary to synchronize ILC with the AC subgrid and acquire the frequency information for normalisation. Moreover, in practice, if the linking impedance (physical and virtual) between ILC and remote weak AC subgrid is large, it would lead to an unacceptable dynamic stability.

In this study, a novel quasi-droop control scheme is proposed to control ILC as a current controlled voltage source (CCVS), which is derived by a combination of P/Q control and droop control. The power flow command for ILC is depended according to the rated capacities of AC-DC subgrids and their real-time operation states. Then, from the local information, the voltage and frequency references of ILC are obtained by an improved droop control scheme. Such a control method can maintain a synchronization between ILC and AC subgrid in steady-state, and thus does not require a measurement of frequency information from a sophisticated PLL.

II. CONVENTIONAL CONTROL STRATEGY OF HYBRID AC/DC MICROGRID

In Fig. 2, an equivalent model of a hybrid AC/DC microgrid is presented. The autonomous operation of hybrid microgrid depends upon the control schemes of the individual subgrids and the ILC. In this section, conventional voltage and frequency control methods associated with AC and DC subgrids are firstly presented to regulate the power flow within each-grid separately. Then, the most common control scheme of ILC [14] is introduced, which paves the way for inspiring the proposed control scheme in the next section.

Fig. 2. An equivalent model of a hybrid AC/DC microgrid.

A. $P-\omega$ & $Q-V$ Droop Control of AC Subgrid

In AC subgrid, droop control is most widely implemented for AC source DGs by imitating the behavior of a synchronous generator [9-10], which is shown in Fig. 3. From the measured output active power P and reactive power Q , the voltage

amplitude reference V_{ac} and frequency reference f are determined according to the followed droop equations

$$\omega = \omega_{\max} - mP \quad (1)$$

$$V_{ac} = V_{ac,\max} - nQ \quad (2)$$

where P and Q are the output active power and reactive power of each DG, respectively. m and n are the $P-\omega$ and $Q-V$ droop coefficients, respectively. As shown in Fig. 3, $\omega_{\max}$ and $\omega_{\min}$ are the maximum and minimum value of permissible angular frequency. $V_{ac,\max}$ and $V_{ac,\min}$ are the maximum and minimum value of permissible voltage amplitude.

Fig. 3. Conventional droop characteristic for AC microgrid. (a) $P-\omega$ droop control. (b) $Q-V$ droop control.

B. $P-V$ Droop Control of DC Subgrid

In DC subgrid, the $P-V$ droop control is common for DC source DGs, which is shown in Fig. 4. Droop characteristic is given by

$$V_{dc} = V_{dc,\max} - kP \quad (3)$$

where P is the output active power of each DC source DG. k is the $P-V$ droop coefficient. As shown in Fig. 4, $V_{dc,\max}$ and $V_{dc,\min}$ are the maximum and minimum value of permissible voltage amplitude.

Fig. 4. Conventional $P-V$ droop characteristic for DC microgrid.

C. Conventional Current-based Control of ILC

The initial job of interlinking converter is to manage the power flow between AC subgrid and DC subgrid. In this part, the conventional current-based control of ILC is briefly explained [14].

According to the droop characteristic (1), (3), any increase of load demand within each-side will cause a decrease of the AC-subgrid frequency or DC-subgrid voltage. Thus, the relative deviation of AC frequency and DC voltage with respect to the rated value are favorable indications of the real-

Fig. 6. Proposed voltage-based quasi-droop control for ILC [14].

$$\omega_{ILC} = \omega_{ILC,max} - m_{ILC}P_{ILC} + m_{ILC}(k_p + \frac{k_i}{s})(a_{dc}V_{dc,pu} - a_{ac}f_{pu}) \quad (10)$$

$$V_{ILC} = V_{ILC,max} - n_{ILC}Q_{ILC} \quad (11)$$

where m_{ILC} and n_{ILC} are the $P-\omega$ and $Q-V$ quasi-droop coefficients, respectively. In (10), the angular frequency is regulated according to the operation states of AC and DC subgrids in real-time. In steady state, $a_{ac}f_{pu} = a_{dc}V_{dc,pu}$, and the above novel principle (6a) is achieved autonomously. In (11), the $Q-V$ droop is adopted for the voltage control and reactive compensation of ILC. The detailed voltage-based control scheme for interlinking converter is shown in Fig. 6.

IV. SIMULATION RESULTS

The proposed idea is verified with simulations carried out in Matlab/Simulink. The simulation model of a hybrid microgrid is described in Fig. 7. All DGs in DC subgrid are simplified to a droop-based equivalent DC source, and AC subgrid is treated in the same way. The proposed control scheme of ILC is shown in Fig. 6. The simulation parameters are listed in Table I. AC load is changed from 1 kW/2 kVar to 3.8 kW/3.8 kVar at $t=1$ s and recovered at $t=2$ s. The total capacity of DC subgrid is twice as much as that of AC subgrid.

TABLE I. Simulation Parameters		
Parameter	Symbol	Value
Parameters of DC subgrid		
Max-/ Nom-/ Min- voltage	$V_{dc,max}/V_{dc}^*/V_{dc,min}$	700/ 685/ 670 V
Max-/ Nom-/ Min- power	$P_{dc,max}/P_{dc}^*/P_{dc,min}$	10/ 5/ 0 kW
$P-V$ droop coefficient	k	$3e^{-3}$
Line resistance	R_{line1}	0.3Ω
Line resistance	R_{line2}	0.05Ω
DC Load	$P_{dc,load}$	5 kW
Parameters of AC subgrid		
Max-/ Nom-/ Min- voltage	$V_{ac,max}/V_{ac}^*/V_{ac,min}$	321/ 311/ 301 V
Max-/ Nom-/ Min- power	$Q_{ac,max}/Q_{ac}^*/Q_{ac,min}$	4 / 2/ 0 kVar
$Q-V$ droop coefficient	n	$5e^{-3}$
Max-/Nom-/Min- frequency	$f_{ac,max}/f_{ac}^*/f_{ac,min}$	50.5/ 50/ 49.5 Hz
Max-/ Nom-/ Min- power	$P_{ac,max}/P_{ac}^*/P_{ac,min}$	5/ 2.5/ 0 kW
$P-f$ droop coefficient	m	$2e^{-4}$
Line impedance	Z_{line1}	$0.3+j0.6 \Omega$
Line impedance	Z_{line2}	$0.4+j0.8 \Omega$
AC Load at $t \in [0, 1], [2, 3]$ s	$P_{ac,load}$	1 kW / 2 kVar
AC Load at $t \in [1, 2]$ s	$P_{ac,load}$	3.8 kW/ 3.8 kVar
Parameters of ILC		
Max- voltage	$V_{ILC,max}$	321 V
$Q-V$ droop coefficient	n_{ILC}	$4e^{-3}$
Max- frequency	$f_{ILC,max}$	50.5 Hz
$P-f$ droop coefficient	m	$2e^{-4}$
PI coefficients	k_p/ k_i	$5e^2/ 2e^4$

Fig. 7. Simulation model of a hybrid microgrid with a DC subgrid and an AC subgrid.

Fig. 8. Simulation result of **case I**. (a) Active power, (b) reactive power, (c) A-phase voltage/current, (d) DC bus voltage, (e) AC frequency, (f) per-unit.

Fig. 9. Simulation result of **case II**. (a) Active power, (b) reactive power, (c) A-phase voltage/current, (d) DC bus voltage, (e) AC frequency, (f) per-unit.

Two cases are considered in this simulation part. In the first case, an equal weight $a_{ac}=a_{dc}=0.5$ is employed to verify the autonomous operation mode in [14]. In the second case, with considering the capacity of AC and DC subgrids, different weights $a_{ac}=2/3$ & $a_{dc}=1/3$ are adopted according to (8).

Simulation results of case I and case II are shown in Fig. 8 and Fig. 9, respectively. Meanwhile, their comparative analysis is given in Table II to have a clear presentation.

A. Case I: Autonomous Operation under $a_{ac}=a_{dc}=0.5$ without Considering the Capacity of AC and DC Subgrids

From Fig. 8 and Table II, the system can achieve $f_{pu}=V_{dc,pu}$ in Fig. 8(f). That is, the total power demand of hybrid microgrid are shared among two AC/DC DGs proportional to their power rating ($P_{dc,g}=2P_{ac,g}$) as shown in Fig. 8(a). By combing the actual load within each subgrid, the ILC works as a rectifier at $t \in [0, 1s]$, and as an inverter at $t \in [1s, 2s]$. Moreover, compared with the current-based control scheme [14], this study provides a satisfied voltage support for AC subgrid as shown in Fig. 8(c).

B. Case II: Optimized Operation under $a_{ac}=2/3$ & $a_{dc}=1/3$ with Considering the Capacity of AC and DC Subgrids

Compared with case I, only different weights $a_{ac}=2/3$ & $a_{dc}=1/3$ are adopted from (8). As the capacity of AC and DC subgrids are fully considered, the minimum of object function is achieved ($J=0.016 < 0.02$ at $t \in [0, 1s]$, $J=0.011 < 0.0128$ at $t \in [1s, 2s]$). In steady-state, the system can achieve $V_{dc,pu}=2f_{pu}$ in Fig. 9(f). And from Fig. 9(d)-(e), the frequency deviation of AC subgrid has been obviously decreased with a little compromise of DC subgrid voltage.

TABLE II.
Comparative Analysis

		Case I		Case II	
		$t \in [0, 1s]$	$t \in [1s, 2s]$	$t \in [0, 1s]$	$t \in [1s, 2s]$
DC-side Power (kW)	Source	4	5.85	3.8	6
	Load	5	5	5	5
AC-side Power (kW)	Source	2	2.93	2.2	2.8
	Load	1	3.8	1	3.8
ILC Power (kW)	P_{ILC}	-1	+0.85	-1.2	+1
Indication	$f_{pu}/V_{dc,pu}$	0.1/ 0.1	-0.08/ -0.08	0.057/ 0.114	-0.048/ -0.096
Optimized Object (6)	J	0.02	0.0128	0.016	0.011

V. CONCLUSIONS

In this study, a novel principle of power flow for ILC is introduced, and a voltage-based quasi-droop control scheme is proposed. It realizes a flexible power flow management and provide an ancillary function of voltage support for weak AC microgrid as well. In practice, the proposed method is simpler and more robust than conventional current-based method since the PLL with some delay is removed. Simulation test has verified the feasibility and validity of the proposed decentralized power control. For a future work, a complex hybrid microgrid with multiple subgrids will be extended, and the entire system stability will be analyzed.

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