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A Virtual Inertia Control Strategy of Interlinking Converters in Islanded Hybrid AC/DC Microgrid

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Abstract—In an islanded hybrid AC/DC microgrid, the existing intermittent distributed generations (DGs) and local loads variation frequently cause power fluctuation. And the DC bus voltage is sensitive to it. A virtual inertia control strategy of interlinking converters (ILCs) in an islanded hybrid microgrid is proposed in this paper, which restrains the DC bus voltage fluctuation and enhances the inertia of the hybrid microgrid. Traditional droop control methods of ILCs mostly only focus on power sharing. The proposed control strategy can not only maintain proportional power distribution between DC and AC subgrids, but also regulate the DC bus voltage directly. It can improve microgrid stability during DC-side loading transitions or distributed energy fluctuations. Moreover, no additional energy storage or inverters are required in a cost-effective manner. The validity of the proposed control method is verified by offline time-domain simulation in MATLAB/Simulink and real-time experiment in OPAL-RT digital platform.

Index Terms—Virtual inertia control, DC voltage stability, virtual synchronous machine (VSM), proportional power sharing, interlinking converters (ILCs), hybrid AC/DC microgrid.

I. INTRODUCTION

Nowadays, DC distributed generations (DGs), such as photovoltaics (PVs) and fuel cells (FCs), develop rapidly. Other DC systems, such as energy storages and DC loads like electric vehicles, gain more and more attention as well [1]. As a result, in recent years DC microgrids have gained an increasing interest. However, in consideration of the existing AC power systems, hybrid AC/DC microgrids have been considered as a cost-effective and efficient solution for future distribution network [2]. Fig. 1 shows the structure of a typical hybrid AC/DC microgrid. DGs are connected to AC and DC buses respectively, along with storage elements and AC and DC loads. Interlinking converters (ILCs) linked to the two buses are bridges between AC and DC subsystems.

A hybrid microgrid can operate in islanded mode or on-grid mode, depending on whether or not the point of common coupling (PCC) is kept open. ILCs coordinate the dual subsystems and exchange power proportionally between them and regulate AC and DC bus voltages stability. Considering the low Inertia of the intermittent DGs, microgrids often suffer

Fig. 1. Structure of hybrid AC/DC microgrid.

from stability problems. ILCs play a crucial part in the control of hybrid microgrids, especially in islanded mode when the system lacking the support of utility grid.

The existing control methods of ILCs can be generally divided into two categories: communication-less methods and communication-based methods [3]. Those communication-based methods are able to manage power flows accurately by collecting and exchanging essential local data through communication lines [4], [5]. Nevertheless, the existing of communication systems may reduce the reliability of the microgrid because any communication failure can lead to instability of the whole microgrid. Therefore, communication-less methods, such as traditional droop control strategies, are widely adopted, due to their simpler structure and higher reliability [6].

A communication-less method in [6] and [7] normalized the droop control of the AC-DC converter in the AC side and DC side, and can achieve proportional power sharing by keeping the per-unit frequency and per-unit DC voltage to the same point. A uniform control strategy based on hierarchical method is reported in [8]. However, these two methods do not discuss how to enhance the inertia and stability of DC bus.

Several recent researches involve how to increase system inertia, but the existing virtual inertia control methods usually

focus on the AC networks, such as virtual synchronous machine (VSM) technology [9]. In [10] and [11], the concept of synchronverter is proposed. By applying proper control methods over the power electronics converters systems, mechanical and electrical characteristics of the synchronous machine (SM) can be emulated. In [3] and [12], the dynamic frequency stability of AC subgrid is discussed. Reference [13]–[15] analyze the VSM control methods applied in DGs.

In the matter of DC networks, in order to restore the DC bus voltage, the improved droop control method in [16] also needs a low-bandwidth communication, which reduces its reliability. In [9] and [17], VSM technology in DC microgrid is mentioned but without considering the power sharing function of ILCs in hybrid microgrids.

To address the above-mentioned drawbacks, in this paper, a virtual inertia control strategy of ILCs is proposed, in order to improve DC subgrid voltage inertia and stability based on normalized droop control method. This method can not only maintain proportional power distribution between DC and AC subgrids, but also regulate the DC subgrid voltage directly and increase virtual inertia without any additional energy storage or inverters. It makes the ILCs appearing to have high inertia in order to suppress DC voltage disturbance during DC-side loading transitions and distributed energy fluctuation.

II. AUTONOMOUS OPERATION WITHIN SUBGRIDS

As mentioned above, a typical islanded hybrid microgrid consists of AC and DC subgrids. This section reviews the droop control method applied in AC subgrids, and analyzes the similar control method within DC subgrids. The autonomous operation theories within subgrids are significant because they are the preconditions for deriving the ILCs control strategy in the next section. In addition, since the main subject of this paper is ILCs connecting AC and DC buses, only active power control method is discussed here.

A. Droop Control for AC Subgrid

Droop control applied to an AC subgrid with at least two paralleled DGs has widely been investigated [6]. As shown in Fig. 2, locally measured active power f_{ac} is relevant to the references of AC voltage frequency. Upon reaching steady state, without considering line impedance, these paralleled AC-DGs connected to the AC bus come to a common frequency

Fig. 2. P - f droop characteristics in AC subgrid.

autonomously. The P - f droop equation of the x th DG connected to AC bus can be appropriately written as:

$$f_{ac,x}^* = f_{ac_max} - m_{ac,x} p_{ac,x} \quad (1)$$

$$m_{ac,x} = (f_{ac_max} - f_{ac_min}) / P_{ac_rated,x} \quad (2)$$

where f_{ac_max} is the maximum AC voltage frequency at no load and f_{ac_min} is the minimum permissible frequency at rated load, respectively. $P_{ac_rated,x}$ is the rated power of the x th DG. $m_{ac,x}$ is the droop coefficient of the x th DG and is a positive number, representing the absolute value of the gradient of the lines (negative) shown in Fig. 2.

Since f_{ac_max} and f_{ac_min} are the same in the same subgrid, (3) can be inferred from (2):

$$\begin{aligned} m_{ac,1} P_{ac_rated,1} &= m_{ac,2} P_{ac_rated,2} \\ &= \dots \\ &= m_{ac,x} P_{ac_rated,x} \end{aligned} \quad (3)$$

As a result, in order to make sure all the AC-DGs share the power demand in proportional to their rated power, the droop coefficients should be tuned according to (3).

B. Droop Control for DC Subgrid

In DC subgrid, attention only should be paid to these two quantities: DC bus voltage and active power. Similar with the droop characteristics in AC subgrid, DC bus voltage falls linearly with the increase of output active power, as shown in Fig. 3. Ignoring line impedance, DC-DGs connected to the DC bus reach the same voltage at the steady-state point. The P - u_{dc} droop equation of the y th DG connected to the DC bus is given by:

$$u_{dc,y}^* = U_{dc_max} - n_{dc,y} p_{dc,y} \quad (4)$$

$$n_{dc,y} = (U_{dc_max} - U_{dc_min}) / P_{dc_rated,y} \quad (5)$$

where U_{dc_max} is the maximum DC voltage at no load and U_{dc_min} is the minimum permissible DC voltage at rated load, respectively. $P_{dc_rated,y}$ is the rated power of the y th DG. $n_{dc,y}$ is the droop coefficient of the y th DG and is a positive number, representing the absolute value of the gradient of the lines (negative) shown in Fig. 3.

Fig. 3. P - u_{dc} droop characteristics in DC subgrid.

Since U_{dc_max} and U_{dc_min} are the same in the same subgrid, it can be inferred from (5):

$$\begin{aligned} n_{dc,1}P_{dc_rated,1} &= n_{dc,2}P_{dc_rated,2} \\ &= \dots \\ &= n_{dc,y}P_{dc_rated,y} \end{aligned} \quad (6)$$

As a result, in order to make sure all the DC-DGs share the power demand in proportional to their rated power, the droop coefficients should be tuned according to (6).

III. IMPROVED CONTROL STRATEGY OF ILCs

Proportional power sharing must be realized throughout the whole AC/DC hybrid microgrid. And this function is often realized by the control of ILCs, the bridges between AC and DC buses. Besides, considering high penetration rate of low-inertia inverter-interfaced DGs, especially in the DC subgrid, it is also significant to guarantee the DC bus voltage stability during load transitions and distributed energy fluctuations. Non-schedulable DGs, such as PVs in maximum power point tracking (MPPT) mode, aggravate the stability issue.

As a result, a novel control strategy of ILCs is proposed in this section, which can directly regulate the DC bus voltage to realize proportional power distribution between two subgrids. What's more, It can improve the dynamic stability of microgrid as well, without any additional storage elements.

As shown in Fig. 4, the research object, ILCs, apply the traditional six-switch bidirectional converter topology, with a LC filter. The ILCs are controlled to operate in voltage source mode, in order to provide voltage support for the DC bus. During the operation of ILCs, instantaneous three phase voltage and current (u_{abc} , i_{abc}) are measured at AC side and DC voltage and current (u_{dc} , i_o) are measured at DC side. Fig. 4 also reveals that the improved control strategy includes

two key steps: Direct DC Voltage Control and Virtual Inertia Control. Their principles and functions are describes in detail in this section.

A. Proportional Power Sharing Technology

As mentioned in section 2, because most DGs adopt droop control, the DC voltage variation and AC frequency variation are linearly related to the output active power respectively. Therefore, the DC side and AC side, as a whole, appear droop characteristics as well. In other words, the frequency variation reflects the output active power of AC subgrid and the DC voltage variation reflects the output active power of DC subgrid.

However, frequency variations and DC voltage variation happen in two independent subsystems, and cannot be unified unless being brought to a common per unit range. The simple normalized droop control scheme in [6] shows a normalized droop control method. According to (1), (2), (4) and (5), the normalized equations is obtained as:

$$\begin{cases} f_{pu} = \frac{f_{ac}^* - 0.5(f_{ac_max} + f_{ac_min})}{0.5(f_{ac_max} - f_{ac_min})} \\ u_{dc,pu} = \frac{u_{dc}^* - 0.5(U_{dc_max} + U_{dc_min})}{0.5(U_{dc_max} - U_{dc_min})} \end{cases} \quad (7)$$

where f_{pu} and f_{ac}^* are the per unit frequency and instantaneous frequency of AC subgrid, respectively. $u_{dc,pu}$ and u_{dc}^* are the per unit voltage and instantaneous voltage of DC subgrid, respectively.

As long as keeping $f_{pu} = u_{dc,pu}$, the whole active power demand can be shared between AC and DC subgrids according to their rated power. That is to say, the whole active power demand can be shared among all AC-DGs and DC-DGs, according to their rated power.

Fig. 4. Block diagram of ILCs control strategy in an islanded hybrid microgrid.

However, traditional method usually use $(f_{pu} - u_{dc,pu})$ in their control loop, which can only realize proportional power sharing but not offer voltage support to DC bus.

As a consequence, the proposed improved control strategy adopts a direct DC voltage control to improve DC voltage response. According to (1), (2), (4) and (5), the droop characteristic of AC and DC subgrids can be unified in a novel way. Setting AC and DC instantaneous active power to be equal, real-time dynamic reference U_{dc} can be revised as:

$$u_{dc_ref} = u_{dc}^* = U_{dc_max} - k_{f-u} (f_{ac_max} - f_{ac}^*) \quad (8)$$

$$k_{f-u} = \frac{(U_{dc_max} - U_{dc_min}) P_{ac_rated}}{(f_{ac_max} - f_{ac_min}) P_{dc_rated}} \quad (9)$$

As long as keeping the instantaneous DC-side voltage u_{dc}^* to be equal with u_{dc_ref} , the output active power of AC and DC subgrids will be naturally proportional to their rated power in steady state. In addition, Equation (8) and (9) show that the control of ILCs is also an improved droop control as well. The droop characteristics can be better explained by Fig. 5. In Fig. 5, P_{ILC} is the active power transferred from DC side to AC side by ILCs. e_{udc} is the error of DC voltage ($e_{udc} = u_{dc,ref} - u_{dc}^*$) and is limited to a small range from e_{min} to e_{max} . There is a liner relationship between e_{udc} and P_{ILC} .

The control diagram of the proportional power sharing is shown in Fig. 6. k_n is the droop coefficient of the n th ILC, which realizes the proportional power sharing among parallel ILCs in the form of $k_1 P_1 = k_2 P_2 = \dots = k_n P_n$. The integral term $1/J_{ILC}s$ is adopted to realize zero steady-state error control of u_{dc} according to DC-side output current. The integral term also increases the DC voltage inertia the virtual

Fig. 5. P - e_{udc} droop characteristics in DC subgrid.

Fig. 6. Block diagram of proportional power sharing control.

interrelating to damping coefficient J_{ILC} , which improves the dynamic DC voltage stability.

By adopting this direct DC voltage control, proportional power sharing as well as DC bus voltage support can be realized simultaneously.

B. Virtual Inertia Technology

In AC microgrids, the VSM technology is often used to emulate the inertia and damping characteristic of the SM, and realize its primary frequency regulation [9]. It is a kind of active power - angular frequency (P - ω) control. The mechanical equation of the VSM can be described as:

$$P_{set} - P_e - D_p (\omega^* - \omega_n) = J \omega^* \frac{d\omega^*}{dt} \approx J \omega_n \frac{d\omega^*}{dt} \quad (10)$$

where J is the virtual inertia coefficient of the virtual rotor and D_p is the virtual damping coefficient. ω_n and ω^* are the rated angular frequency and actual angular frequency, respectively. P_{set} and P_e are the active power reference value and the electromagnetic power of the VSM.

When AC microgrid reaches its steady state, the angular frequency remains constant, so $d\omega^*/dt = 0$, (10) can be written as:

$$\omega^* = \omega_n + \frac{P_{set}}{D_p} - \frac{1}{D_p} P_e \quad (11)$$

Equation (11) is actually an active power - angular frequency droop (P - ω droop) control:

$$\omega^* = \omega_{no_load} - m_\omega P_e \quad (12)$$

$$\omega_{no_load} = \omega_n + P_{set}/D_p, \quad m_\omega = 1/D_p \quad (13)$$

where m_ω is the droop coefficient of P - ω droop control. Comparing (1) and (12), it can be referred that $m_\omega = 2\pi m_{ac}$, since m_{ac} is the droop coefficient of P - f droop control mentioned in section 2 in equations (1), (2) and (3). Therefore, the VSM control actually can be seen as a modified droop control.

VSM technology used in the control of DG inverters can effectively improve the frequency stability of AC microgrids. Moreover, autonomous control in the DC subgrid is similar to that in AC subgrid, to some extent, in the respect of droop characteristics. Therefore, to address the stability issues of DC voltage, a virtual inertia control mimicking VSM can be applied.

In the DC subgrid, P - u_{dc} droop control is widely adopted, as (4), (5) and (6) has illustrated. Since P_{dc} approximately equals to $U_n i_o$, where U_n is the rated DC bus voltage, (4) can be rewritten in the form of voltage-current droop (u_{dc} - i_{dc} droop) control, described as:

$$u_{dc}^* = U_{dc,no_load} - n_i i_o \quad (14)$$

$$n_i = U_n n_{dc} \quad (15)$$

where n_i is the droop coefficient of u_{dc} - i_{dc} droop control and $n_i = U_n n_{dc}$ since n_{dc} is the droop coefficient of P - u_{dc} droop control mentioned in equations (3) and (4).

Given the similarities between AC and DC droop control algorithms, according to (10), the virtual inertia equation of DC subgrid can be written as:

$$I_{set} - i_o - D_b (u_{dc}^* - U_n) = C_v u_{dc}^* \frac{du_{dc}^*}{dt} \approx C_v U_n \frac{du_{dc}^*}{dt} \quad (16)$$

where I_{set} and i_o are the DC output current reference and DC output actual current of the ILCs, respectively. U_n is the rated DC bus voltage. D_b is the damping coefficient, reciprocal of droop coefficient n_i in (15). C_v is the introduced virtual capacitance of ILCs, that is, the virtual inertia coefficient. It is worth noting that C_v is related to the inherent storage element or capacity of the microgrid, but not exactly equivalent to the DC-side capacitor of ILC.

Similarly, with that in the AC subgrid, the virtual inertia control in the DC subgrid is actually a modified P - u_{dc} droop control, introducing virtual inertia and virtual damping into DC subgrid. This virtual inertia method can be applied in ILCs after the above-mentioned direct DC voltage control. Fig. 7 shows the block diagram of the virtual inertia control of ILCs.

According to (16), the loop including $1/C_v U_n$ helps realizing the increase of virtual inertia. The loop including D_b influences its sensitivity to the voltage deviation, which means the damping effect. The virtual inertia control part can enhance the inertia and stability of the DC bus by introducing the virtual inertia and virtual damping into the ILCs.

Fig. 8 is the detailed and complete control block diagram, include five parts: Phase-locked loop (PLL), direct DC voltage control (for proportional power sharing), virtual inertia control (for increasing DC bus inertia and stability), voltage and current dual-loop control and PWM generator.

The U/I dual-loop consists of a PI voltage outer loop control to track DC bus voltage reference, and a current inner loop using the well-known decoupled current control based on synchronous reference frames (SRFs). After the DC voltage

Fig. 7. Block diagram of virtual inertia control.

Fig. 8. Detailed block diagram of the proposed improved control strategy of ILCs.

reference value u_{dc}^* is calculated, it is compared with the local measured actual DC voltage u_{dc} . The error then input into a PI controller, to get the reference value of current loop. The detailed discrimination of SRF current control can be found in [9]. Moreover, since there is no reactive power in the DC side, reactive current reference value i_q^* is set to be zero during the operation of ILCs.

IV. SIMULATION AND EXPERIMENTAL VERIFICATIONS

In this section, a time-domain simulation platform of a hybrid microgrid is built in Matlab/Simulink according to Fig. 9, in order to validate the functions of the proposed virtual inertial control scheme of ILCs. The DC subgrid including several DC-DGs is simulated by a bidirectional DC-DC converter connected to the DC bus. Similarly, the AC subgrid is mimicked by a bidirectional AC-DC converter connected to the AC bus. As is mentioned in section 2, the AC and DC subgrids are controlled by the P - f droop control and P - u_{dc} droop control methods respectively. The ILC and AC subgrid converter both adopt a traditional six-switch full bridge topology with an LC filter, as shown in Fig. 4.

The rated power of AC and DC subgrids are both 20 kW. AC frequency is from 49 Hz to 51 Hz while DC bus voltage range is 590 V to 600 V. System parameters of the hybrid microgrid is illustrated in Table. I. It can be observed that DC load demand has two modes, equal to 1.2 kW in light mode while 6.2kW in heavy mode. Similarly, AC load demand

TABLE I
SYSTEM PARAMETERS OF HYBRID MICROGRID

Global parameters	Value
AC subgrid rated active power	$P_{dc,max} = 20kW$
DC subgrid rated active power	$P_{ac,max} = 20kW$
AC frequency range	$49Hz < f < 51Hz$
AC RMS voltage range	$215V < v_{RMS} < 225V$
DC voltage range	$590V < U_{dc} < 600V$
Circuit parameters	Value
ILC DC-side capacity	$C_{dc} = 4700\mu F$
LC filter	$L_f = 8mH, C_f = 4700\mu F$
Line impedance	$L_Z = 0.3mH, R_Z = 0.3\Omega$
DC load	1.2kW(Light) , 6.2kW(Heavy)
AC load	3.8kW (Light) , 8.8kW(Heavy)
Control parameters	Value
Virtual inertia coefficient	$C_v = 0.00167$
Virtual damping coefficient	$D_b = 10$

Fig. 9. Detailed structure of the tested hybrid AC/DC microgrid.

equals to 3.8kW in light mode while 8.8 kW in heavy mode. The difference between light and heavy mode is 5 kW. The performance of ILC can be verified by load transition process between two modes.

A. Proportional Power Sharing

Fig. 10 and Fig. 11 show the simulation results during load transitions. From 0 s to 1 s (Stage 1: 0 s to 1 s), DC load is in light mode load while AC load is heavy. At 1 s (Stage 2: 1 s to 3 s), DC load change to heavy mode while AC side remains unchanged, so total power demand increases 5 kW. At 3 s (Stage 3: 3 s to 5 s), AC load change to heavy mode while DC side remains heavy, so the total power demand increases 5 kW, either.

In Fig. 10 (a), when reaching steady state, frequency falls about 0.25 Hz everytime the total load demand increases 5 kW, no matter which side does it happened. In Fig. 10 (b), DC voltage both droops about 1.3V at steady state in Stage 1 and Stage 3, corresponding to the load increase (5 kW both), either. As is discussed in in section 2, according to the AC side P - f droop control and DC side P - u_{dc} droop control, frequency droops linearly due to AC load raising while DC voltage droops linearly due to DC load raising. As a consequence, Fig. 10 (a) and Fig. 10 (b) not only proves the droop control methods in both subgrids respectively, but also verified the effectiveness of the ILC, which can coordinate the power flows between AC and DC subgrids.

When focusing on the performance of ILC under these circumstances, Fig. 10 (c) shows the simulation results of ILC output DC current to DC side (I_o), positive in rectification mode. In Stage 1, I_o is negative, which means ILC transfers power to from DC subgrid to AC subgrid, the ILC operates in rectification mode. This is because, at this moment, the power shortage is higher in AC side than in DC side. In Stage 2, DC load is heavier than AC load, so the ILC operates in inversion mode, transmitting power from AC subgrid to DC subgrid (I_o is positive). In Stage 3, after AC load sudden raises at 3 s, I_o drop from +2 to -2 rapidly and smoothly, and ILC operates in inversion mode again at steady state.

Fig. 11 shows the active power flows from Stage 1 to Stage 3. No matter in which stage, the output power of the dual subgrids are always approximately the same at steady states, equal to half of the total power demand, as shown in Fig. 11 (a) and Fig. 11 (b). As a result, Its verified to be effective for the ILC to manage proportional power flows, since the rated active power of AC and DC subgrids are the same.

Fig. 10. Simulation results of the hybrid microgrid.

B. Improved DC Voltage Stability

Fig. 12 shows the DC bus voltage under the condition that DC load suddenly increase from light to heavy mode (at 1 s) and then decrease back to light mode (at 3 s). Without virtual inertial control (blue waveform), u_{dc} waveform oscillate during the DC load sudden changes. However, with the proposed virtual inertia control (red waveform), u_{dc} reaches the steady-state value smoothly whether the load sudden increases or decreases, without any voltage oscillation. Though there is still an inevitable small voltage spike at the moment of load switching, but it returns to the smooth curve quickly. The peak value of the DC voltage spike depends on the value of line impedance or DC capacitor, and is not affected by the value of virtual inertia coefficient (C_v) or virtual damping coefficient (D_b).

It shows that inertia and stability can be improved when the proposed virtual inertia control method is used in ILC.

Fig. 11. Simulation results of output active power with virtual inertia control.

Fig. 12. Simulation results of output active power with virtual inertia control.

Fig. 13. Simulation results of DC output voltage with $C_v = 0.00167$ but different D_b .

Fig. 14. Experimental results of output active power with virtual inertia control.

Fig. 15. Experimental results of DC output voltage with proposed virtual inertia control.

In addition, it is worth noting that the influence of virtual damping coefficient D_b . Fig. 13 reveals the simulation results of DC output voltage when virtual inertia coefficient $C_v = 0.00167$ but virtual damping coefficient D_b is different. It can be seen from the three curves that when C_v is properly tuned, the value of D_b influences the magnitude of fluctuation and the time required to reach steady state. The bigger D_b is, the greater the fluctuation is and the slower the steady state is reached.

C. Experimental Results

The proposed virtual inertia control method of ILCs is further verified by the experiment results on OPAL-RTLAB real-time digital simulator platform. The hybrid microgrid is built according to Fig. 9.

Fig. 14 reveals the experimental results of output active power with proposed virtual inertia control under the same conditions as Fig. 11. As can be seen in the picture, from

Stage 1 to Stage 3, active power of AC side (p_{ac}) and active power of DC side (p_{dc}) are approximately equal when reaching steady state. And the active power of ILC ($p_{I/L/C}$) equals to the power shortage of each side. It verified the effectiveness of the proportional power sharing function of the ILC.

In addition, Fig. 15 gives the experimental results of DC output voltage with proposed virtual inertia control under the same conditions as Fig. 12. DC voltage achieves its steady states smoothly after DC side loads sudden change, and no oscillation occurs. It proves that by introducing direct DC voltage control and virtual inertia, system inertia increases and the stability DC voltage is improved.

V. CONCLUSION

In this paper, a communication-less virtual inertia control scheme of ILCs for AC/DC hybrid microgrid is presented. The proposed control scheme can increase the DC bus voltage inertia and stability during DC-side load transients and distributed energy fluctuations. Compared to the conventional normalized droop control method, a direct DC voltage control is adopted to realize proportional power sharing and applies virtual inertia technology to ILCs to increase system inertia. Finally, the effectiveness of the control scheme has been verified by the simulation and experimental results.

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