Bidirectional Virtual Inertia Control Strategy for Interlinking Converter in Hybrid AC/DC Microgrid

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Abstract. The AC/DC hybrid microgrid can realize the power flow between the two sub-microgrids by controlling the interconnected converters connected to the AC and DC sub-microgrids, thereby improving the system's ability to suppress power fluctuations. In order to achieve a reasonable power flow between the two sub-microgrids in the steady state and in the transient process, this paper analyzes that the traditional droop control of interconnected converter (ILC) pays less attention to the transient process of the hybrid microgrid. On the basis of virtual synchronous generator, a bidirectional virtual inertia control strategy for ILC is proposed. This control strategy can not only respond to the offset between the DC bus voltage and the AC frequency, but also achieve the goal of sharing the system power fluctuations between the two sub-microgrids in the steady state according to the voltage and frequency offset requirements. It can also respond to the DC bus voltage and The rate of change of the AC frequency realizes a reasonable inertial support between the two sub-microgrids in the transient process. In order to balance the transient target and steady-state target of the interconnected converter, this paper designs the parameters of the proposed control. Finally, a simulation model was built in PSCAD to verify the effectiveness of the proposed control strategy.

1. Introduction
With the increasing number of DC-type distributed power sources and loads, the AC-DC hybrid microgrid that includes both AC and DC subsystems, which can reduce power electronic conversion links and reduce energy loss, has attracted people’s attention[1-2]. The droop control adopted by the conventional grid-connected converter has the problem of fast response speed and almost no inertia, which leads to the weakening of the inertia of the system and the reduction of dynamic performance [3-4]. The hybrid
microgrid contains a large number of devices that are sensitive to frequency or voltage. In addition, there are currently existing protections that reflect $df/dt$ applied to the power system, which can act when $df/dt$ exceeds the allowable value [5]. Power fluctuations in the low-inertia AC/DC microgrid may cause this type of protection to malfunction.

In response to the problem of small inertia in droop control, scholars have proposed virtual synchronous generator (VSG) technology suitable for AC microgrid grid-connected converters [6-7], and virtual inertia control of grid converter suitable for DC microgrid grid-connected converters [8-9]. The above control responds to the rate of change of microgrid frequency or voltage, so that the power electronic converter has virtual inertia and improves the dynamic response of microgrid frequency or voltage. However, the above research only considered the improvement of the inertia of a single AC microgrid or DC microgrid.

Interlinking converter (ILC) is a bridge connecting AC microgrid and DC microgrid, so the overall inertia of hybrid microgrid is related to the control of ILC. Literature [10] proposes a VSG control method suitable for ILC, but it only reduces the impact of power fluctuations between the two microgrids, without considering the overall inertia of the hybrid microgrid.

Aiming at the above problems, this paper analyzes that ILC bidirectional droop control pays less attention to the transient process, proposing a bidirectional virtual inertia control strategy for interconnected converters by analogy to virtual synchronous generator control. This control strategy can not only respond to the offset between the DC bus voltage and the AC frequency, realizing the two microgrids to share the system power difference (including power surplus and loss) in the steady state, but also respond to changes in the DC bus voltage and AC frequency in the transient process. A reasonable inertial support between the two microgrids can be realized. In order to balance the transient target and steady-state target of the interconnected converter, this paper designs the parameters of the proposed control. Finally, simulations verify the effectiveness of the proposed control strategy.

2. Island hybrid microgrid structure and virtual inertia control

The typical topology of the AC/DC hybrid microgrid studied in this paper is shown in Figure 1, which is composed of AC microgrid, DC microgrid, and interlinking converter (ILC). The AC microgrid includes wind turbines, micro gas turbines, and AC loads, and the DC microgrid includes photovoltaics, batteries, and DC loads. The AC microgrid and the DC microgrid are connected to the solid-state switch STS through the ILC to achieve mutual power assistance on both sides.

![Figure 1. Structure of an islanding hybrid microgrid.](image-url)
Wind turbines and photovoltaics belong to intermittent distributed micro-sources (IMDG). In this study, they all adopt maximum power point tracking (MPPT) control to make full use of electrical energy of the intermittent power source [11]. This article regards the power generated by IMDG as a negative load. Micro gas turbines and batteries are dispatchable distributed micro-sources (DPDG). The DPDG in this paper uses virtual inertia control to improve the inertia of the hybrid microgrid.

2.1 Virtual inertia control in AC microgrid

The virtual inertia control of the micro gas turbine in the AC microgrid is obtained by using VSG control for its outlet converter [12], that is, the active power-frequency control is achieved by simulating the mechanical motion equation of the traditional synchronous generator:

\[
P_{\text{set1}} - P_{\text{MT}} - k_1(\omega - \omega_n) = J_{\text{vir}} \frac{d\omega}{dt} \approx J_{\omega} \omega \frac{d\omega}{dt}
\]

Where, \(\omega\) is the angular frequency of the VSG; \(n\) is the rated angular frequency of the AC microgrid; \(P_{\text{set1}}\) is the active power setting value; \(P_{\text{MT}}\) is the measured value of the micro gas turbine output active power; \(k_1\) is the active power-frequency droop coefficient; \(J_{\text{vir}}\) is the virtual rotation inertia. Due to the existence of \(J_{\text{vir}}\), the AC microgrid has a certain inertia.

2.2 Virtual inertia control in DC microgrid

As shown in Figure 2, when the DC microgrid load has a disturbance \(\Delta P\), due to the existence of the DC bus capacitor, the DC bus voltage \(u_{dc}\) can’t change suddenly. If the battery outlet converter B-DC adopts droop control, the power \(P_1\) which flows from B-DC to DC side capacitor cannot be changed suddenly, so it is all borne by the DC bus capacitor:

\[
\Delta P = P_2 - P_1 = P_c = C_{dc} \frac{du_{dc}}{dt}
\]

where \(C_{dc}\) is the capacitance value of the DC bus capacitor.

In fact, the DC side capacitance \(C_{dc}\) is small, so the inertia of the DC microgrid is small. The virtual inertia control characteristics of the battery in the DC microgrid in this paper are obtained through analogy reasoning:

\[
P_{\text{set2}} - P_0 - k_2(u^*_{\text{dc}} - U_{dcN}) = C_{\text{vir}} u^*_{\text{dc}} \frac{du^*_{\text{dc}}}{dt} = C_{\text{vir}} U_{dcN} \frac{du^*_{\text{dc}}}{dt}
\]

Where \(P_{\text{set2}}\) is the given value of the output power of the battery; this article takes \(P_{\text{set2}}\) as 0; \(P_0\) is the measured value of the battery output active power; \(k_2\) is the active power-voltage droop coefficient; \(u^*_{\text{dc}}\) is the bus of the DC microgrid Voltage reference value; \(U_{dcN}\) is the DC bus voltage rating; \(C_{\text{vir}}\) is the virtual capacitance value.

Due to the addition of virtual capacitors, formula (2) can be reduced to the following formula:

\[
\Delta P = -(C_{dc} + C_{\text{vir}}) u_{dc} \frac{du_{dc}}{dt}
\]
3. Bidirectional virtual inertia control of ILC

ILC is a bridge connecting AC and DC microgrids. Through reasonable control, it can achieve reasonable mutual assistance between AC and DC microgrids. ILC main circuit includes IGBT three-phase bridge circuit, DC side energy storage capacitor $C_{dc}$, AC side equivalent filtering parameters $L_f$, $R_f$ and $C_f$.

![Figure 3. Topology of ILC of a hybrid microgrid.](image)

3.1 Analysis of the limitations of bidirectional droop control

The traditional ILC adopts bidirectional droop control. The basic idea is to detect the bus voltage or frequency offset of the microgrids on both sides of the ILC to determine the active power of the microgrids on both sides, and then to realize the reasonable distribution of active power of the hybrid microgrid system.

When the ILC adopts bidirectional droop control, the reference value of the active power is obtained by the following formula:

$$P_{ref} = k(u_{dc.pu} - f_{ac.pu}) + P_0$$  \hspace{1cm} (5)

Where $k$ is the active power droop coefficient and is greater than zero; $P_0$ is the active power that the ILC should output when the load balance of the microgrids on both sides is balanced.

3.2 Bidirectional virtual inertia control

In order to achieve reasonable inertia support between the AC and DC microgrids in the transient process, through analogy VSG control, this paper proposes a bidirectional virtual inertia control of ILC. The control strategy obtains the active command of ILC by the following formula:

$$P_{ref} = J_{ILC} [(du_{dc}/dt)_{pu} - (df/dt)_{pu}] + D_{ILC} (u_{dc.pu} - f_{ac.pu})$$ \hspace{1cm} (6)

Where $J_{ILC}$ is the virtual moment of inertia of ILC; $D_{ILC}$ is the damping coefficient; $(du_{dc}/dt)_{pu}$ and $(df/dt)_{pu}$ respectively represent the normalized AC frequency change rate and DC voltage change according to formula (7) rate standard unit value.

$$\begin{align*}
(df/dt)_{pu} &= df/dt/df/dt_{max} \\
(du_{dc}/dt)_{pu} &= du_{dc}/dt/du_{dc}/dt_{max}
\end{align*}$$ \hspace{1cm} (7)

Where $df/dt_{max}$ and $du_{dc}/dt_{max}$ are the absolute maximum values of the AC frequency change rate and DC voltage change rate allowed by the hybrid microgrid after comprehensively considering the requirements of the hybrid microgrid power supply, load and protection devices for the voltage and frequency change rate.
When the system reaches a steady state, the DC bus voltage and AC frequency are stable, and equation (6) can be transformed into:

\[ P_{\text{ref}} = D_{\text{ILC}} (u_{\text{ac,pu}} - f_{\text{ac,pu}}) \]  

(8)

Therefore, in this paper, the right side of equation (7) is called the steady-state component of the ILC transmission power, which is used to achieve steady state. The goal of power mutual assistance between AC and DC microgrids: \( u_{\text{dc,pu}} = f_{\text{ac,pu}} \).

4. Small signal modeling of bidirectional virtual inertial control

In order to analyze the control characteristics of the proposed strategy, it is necessary to establish a small signal analysis model for the bidirectional virtual inertial control of the interconnected converter ILC.

As shown in Figure 3, according to KVL and dq transformation has:

\[
\begin{align*}
e_d - u_d + L_f \omega i_q &= (R_f + L_f D) i_d \\
e_q - u_q - L_f \omega i_d &= (R_f + L_f D) i_q
\end{align*}
\]

(9)

Where \( u_d \) and \( u_q \) are the \( d \) and \( q \) components of the grid voltage in the \( dq \) coordinate system; \( D \) is the differential operator; \( \omega \) is the grid voltage angular frequency; \( i_d \) and \( i_q \) are components of the current \( i_j \) in the \( dq \) coordinate system respectively; \( e_d \) and \( e_q \) are the \( d \) and \( q \) components of voltage \( e_j \) in the \( dq \) coordinate system.

According to (9), it can be seen that the \( d \) and \( q \) axis variables of ILC are coupled with each other, which makes the controller design difficult. In order to realize the decoupling control of \( d \)-axis and \( q \)-axis, the control equations of \( e_d \) and \( e_q \) are designed as follows:

\[
\begin{align*}
e_d &= u_{d1} - L_f \omega i_q + u_d \\
e_q &= u_{q1} + L_f \omega i_d + u_q
\end{align*}
\]

(10)

\( U_{d1} \) and \( U_{q1} \) in (11) are the output of the current inner loop PI regulator:

\[
\begin{align*}
u_{d1} &= G_d(s)(i_{d\text{ref}} - i_d) \\
u_{q1} &= G_q(s)(i_{q\text{ref}} - i_q)
\end{align*}
\]

(11)

Where, \( i_{d\text{ref}} \) and \( i_{q\text{ref}} \) are the command values of the \( d \)-axis and \( q \)-axis currents.

Substituting (10) and (11) into (9), we can get

\[
\begin{align*}
(R_f + L_f D) i_d &= G_d(s)(i_{d\text{ref}} - i_d) \\
(R_f + L_f D) i_q &= G_q(s)(i_{q\text{ref}} - i_q)
\end{align*}
\]

(12)

Write the state variable in equation (12) as the sum of steady-state quantity and small disturbance, that is, \( i_d = I_d + \Delta i_d \), \( i_q = I_q + \Delta i_q \), substituting it into equation (12), and carrying out the Laplace transform, we can get the loop current control small signal equation is:

\[
\begin{align*}
\Delta i_d(s) &= G_d(s)(\Delta i_{d\text{ref}}(s) - \Delta i_d(s)) / (R_f + L_f s) \\
\Delta i_q(s) &= G_q(s)(\Delta i_{q\text{ref}}(s) - \Delta i_q(s)) / (R_f + L_q s)
\end{align*}
\]

(13)

Secondly, the small signal analysis model of ILC power outer loop control is established. The active power transmitted by the ILC can be expressed by the following formula:

\[ P = \frac{3}{2} (e_d i_d + e_q i_q) \]  

(14)

When ILC adopts AC bus voltage directional control in this article, \( E_q = 0 \). In this paper, the value of reactive current component \( I_q \) is equal to 0. So the formula (14) can be simplified to:

\[ \Delta P = \frac{3}{2} (E_d \Delta i_d + \Delta e_d I_d) \]  

(15)

According to the superposition theorem, the Laplace transform of equation (15) can get the relationship between \( \Delta P(s) \) and \( \Delta i_d(s) \), \( \Delta e_d(s) \) respectively:
The small signal decomposition of the bidirectional virtual inertia control equation (6) can be obtained:

\[
\frac{\Delta P(s)}{\Delta i_r(s)} = \frac{3}{2} E_d
\]

\[
\frac{\Delta P(s)}{\Delta e_l(s)} = \frac{3}{2} I_d
\]

(16)

The small signal decomposition of the bidirectional virtual inertia control equation (6) can be obtained:

\[
\Delta P_{ac} = J_{ac,c} \left( \frac{d\Delta u_c}{dt} \right) / M_1 - \frac{d\Delta f}{dt} / M_2 + D_{ac,c} \left( \frac{\Delta u_c}{m_1} - \frac{\Delta f}{m_2} \right)
\]

(17)

Where, \( M_1 = \left| \frac{d\Delta u_c}{dt} \right|_{\text{max}}; \quad M_2 = \left| \frac{d\Delta f}{dt} \right|_{\text{max}} \).

Laplacian change of equation (17) can be obtained:

\[
\Delta P_{ac}(s) = J_{ac,c} \frac{d\Delta u_c(s)}{m_1} - \frac{d\Delta f(s)}{m_2} + D_{ac,c} \left( \frac{\Delta u_c(s)}{m_1} - \frac{\Delta f(s)}{m_2} \right)
\]

(18)

Based on the above derivation, the small signal model of ILC bidirectional virtual inertial control can be obtained as shown in Figure 4.

**Figure 4.** Small-signal model of the bidirectional virtual inertia control for ILC.

5. **Simulation verification**

In order to verify the effectiveness of the virtual inertial control of the interconnected converter proposed in this paper, a simulation model as shown in Figure 1 is built in PSCAD. The simulation parameters are selected according to the Table 1. The working condition is set: at the beginning, the power of the two microgrids is balanced, the AC load is 30kW, the wind power output is 20kW, and the micro gas turbine output is rated the power is 10kW; the DC load is 10kW, and the photovoltaic output is 10kW; when \( t=0.3s \), the AC side load increases by 8kW.

**Table 1. Simulation parameters.**

| microgrid | Parameters and units | Value |
|-----------|----------------------|-------|
| AC microgrid | Operating frequency range /Hz | 50 ±0.5 |
| | \( |df/dt|_{\text{max}} \) Hz/s | 5 |
| | MT rated power/kW | 10 |
| | MT maximum output power/kW | 20 |
| | M-AC droop coefficient \( k_1/(Hz/kW) \) | 0.05 |
| | M-AC virtual inertia \( J_{ac}(kg\cdot m^2) \) | 0.5 |
| DC microgrid | Operating voltage range \( U_{dc}/V \) | 800 ±50 |
| | \( |dU_{dc}/dt|_{\text{max}} \) kV/s | 0.38 |
| | Maximum charge power of battery/kW | 5 |
| | B-DC droop coefficient \( k_2/(V/kW) \) | 10 |
B-DC virtual capacitor $C_{vir}/\mu F$ 0.01
DC capacitor $C_{dc}/\mu F$ 1000

Figure 5 is the simulation waveform of working condition 1 when ILC adopts bidirectional droop control and the bidirectional virtual inertia control mentioned in this paper.

![Simulation waveform](image)

(a) AC frequency
(b) DC bus voltage
(c) output power of ILC

Figure 5. Simulation results of working condition.

This paper also observes the effect of inertial support between the two microgrids by measuring the absolute maximum values of AC frequency and DC voltage change rate $|\frac{df}{dt}|_m$ and $|\frac{du_{dc}}{dt}|_m$ in the transient process. Table 2 shows $|\frac{df}{dt}|_m$ and $|\frac{du_{dc}}{dt}|_m$ in working condition under different control methods.

| Control Method                  | $|\frac{df}{dt}|_m$ | $|\frac{du_{dc}}{dt}|_m$ |
|--------------------------------|--------------------|--------------------------|
| Bidirectional droop control    | 12                 | 0.2                      |
| Bidirectional virtual inertia control | 3.8             | 0.25                     |

Compared with ILC adopting bidirectional droop control, when ILC adopts the bidirectional virtual inertia control mentioned in this paper, it takes about 34ms for the AC frequency to drop to 49.9Hz, and the dynamic characteristics are significantly improved; $|\frac{df}{dt}|_m$ is reduced to 3.8, which satisfies the AC microgrid's requirement for frequency change rate and reduces the impact on frequency-sensitive loads. ILC transmission power increases rapidly, and it only takes about 19ms to increase from 0 to 2kW;
\[ \frac{du_{dc}}{dt} \] increases to 0.25. The voltage change rate of the DC microgrid is within the allowable range, which indicates that the DC microgrid provides reasonable inertial support.

It can be seen from Figure 5 that the steady-state values of AC frequency and DC bus voltage when ILC adopts the bidirectional virtual inertia control proposed in this paper and the bidirectional droop control are basically the same characteristic. From the above analysis, it can be seen that, compared with the bidirectional droop control, the bidirectional virtual inertia control proposed in this paper can respond to the AC frequency and the change rate of the DC bus voltage, so it can make more reasonable use of the inertial support between the two microgrids in the transient process. It is used to avoid the transient process of the power fluctuation of the hybrid microgrid, when the output of one microgrid is insufficient, and the output of the other microgrid is too much, causing the voltage or frequency change rate to exceed the allowed value.

6. Conclusion
This paper mainly focuses on the limitation of ILC traditional bidirectional droop control that pays less attention to the transient process of hybrid microgrid. Through the analogy of virtual synchronous generator control, a bidirectional virtual inertial control strategy for interconnected converters is proposed. Then effectiveness of the proposed control strategy is verified through simulation. In the end, the following conclusions are reached:

1) The proposed control strategy can respond to the offset between the DC bus voltage and the AC frequency, and achieve the power mutual assistance goal that the deterioration of the AC frequency offset in the steady state is consistent with the deterioration of the DC voltage offset.

2) This control strategy can respond to the rate of change of the DC bus voltage and AC frequency realizes reasonable inertial support between AC and DC microgrids in the transient process.

7. References
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