Study on dynamic characteristic optimization of virtual inertia control for the grid-connected converters in DC micro grid

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Abstract. In order to reduce the transient time and voltage deviation due to voltage variation while increasing the system inertia of the DC microgrid, a new adaptive control method for the parameters of the grid-connected end is proposed. Firstly, a grid-connected converter control strategy mathematical model is established. Secondly, the influences of different control parameters on the dynamic characteristics of the system are studied. An adaptive equation based on the parameters of voltage deviation and voltage change rate of DC bus is proposed. Finally, through MATLAB/Simulink simulation, the simulation results of the traditional drooping control, the virtual inertial control with fixed parameters and the control strategy proposed in this paper are compared and analyzed. The result shows that the proposed control method has better dynamic characteristics.

1. Introduction

Nowadays, the number of distributed new energy connected to the power grid is increasing gradually. Its discontinuity and random fluctuation have more and more influence on the safe operation of power network \cite{1}. Similar to AC micro grid, DC micro grid uses many power electronic components for control, resulting in low inertia of the system. It is easy to cause sudden change or large oscillation of DC bus voltage \cite{2-3}. Among them, grid-connected converter, as a connecting device between micro grid and large power grid, has a decisive influence on DC bus voltage and power support of micro grid. Therefore, in order to improve the inertia and stability of the DC microgrid system, it has become an important research topic to study the control strategy of grid-connected converter.

At present, the grid-connected converter of DC micro grid generally adopts constant voltage control or droop control, but the traditional droop control is difficult to meet the requirements of dynamic performance of the system, and does not have the ability to provide inertial support. The peak overshoot generated by it is easy to affect the sensitive load. A new power sharing control method is proposed for a DC microgrid to restore the bus voltage \cite{4}. But it requires the use of low bandwidth communication lines to obtain the information of each distributed power source, which cannot achieve independent self-regulation. A droop control method for the grid-connected converter in the AC-DC hybrid micro-grid is studied \cite{5}. The control of the DC micro-grid was optimized through fuzzy sliding mode speed reduction control.

Virtual synchronous generator (VSG) technology provides sufficient frequency and voltage support for AC microgrids and has been widely researched and applied in AC microgrids \cite{6}. A power shock
damping reduction method is proposed by using VSG control technology in order to avoid low-frequency oscillation caused by large-capacity distributed power in the system[7]. A control method of rotational inertia is proposed[8]. The anti-disturbance ability is enhanced after introducing the rotational inertia into VSG control strategy, but the dynamic regulation time is also increased. However, only the dynamic influence of rotational inertia on frequency regulation of micro grid is considered, the damping parameter introduced by VSG control is not specifically analyzed.

To sum up, this paper proposes a self-adaptive equation based on the DC bus voltage deviation and voltage change rate adjustment parameters in order to improve the inertial regulation capability and dynamic response performance of the grid-connected converter control strategy.

2. Principle analysis of virtual inertia control strategy

The parameters of the control strategy are analyzed and adjusted by analogy with VSG technology. VSG technology is based on the active power-frequency droop control and the rotor mechanical equation of synchronous generator. The governing equation is:

$$P_m - P_e - D_e(\omega - \omega_n) = J\omega \frac{d\omega}{dt}$$

According to FIG. 1 and Kirchhoff laws we can get equation(2):

$$u_{dc\_ref}i_{out} - u_{dc\_ref}i_{dc} = C_{vir}u_{dc\_ref} \frac{du_{dc\_ref}}{dt}$$

$u_{dc\_ref}$ is the reference value of DC bus voltage.

The AVSG virtual inertia equation can be obtained by multiplying both ends by $u_{dc\_ref}$ and introducing the damping part:

$$P_{out} - P_{dc} - D_{vir}(u_{dc\_ref} - U_n) = C_{vir}u_{dc\_ref} \frac{du_{dc\_ref}}{dt} \approx C_{vir}U_n \frac{du_{dc\_ref}}{dt}$$

$C_v$ is the equivalent virtual capacitance of the converter virtual inertia control strategy. Let the virtual capacitance parameter $C_{vir} = C + C_v$ be DC side total equivalent capacitance of G-VSC. $D_{vir}$ is the virtual damping coefficient, and $U_n$ is the nominal voltage of DC bus. $P_{out} = u_{dc\_ref}i_{out}$, $P_{dc} = u_{dc\_ref}i_{dc}$.

It can be seen from the above analysis that an analogy can be drawn between the two approaches. According to equation (3), when $P_{out} - P_{dc} - D_{vir}(u_{dc\_ref} - U_n)$ is constant, the system voltage change rate is inversely proportional to virtual capacitance. That is, the larger the virtual capacitance is, the smaller the system voltage change rate will be. When $P_{out} - P_{dc} - C_{vir}U_n \frac{du_{dc\_ref}}{dt}$ is constant, the system voltage deviation is inversely proportional to the virtual damping, and vice versa.

Since the drooping control of grid-connected converter is convenient for the DC microgrid to realize hierarchical coordinated control of voltage and allocation of power without additional communication equipment, droop control is generally adopted at the grid-connected converter. In this paper, voltage-power droop control is used to coordinate with the inertial link. The control equation is as follows:

$$u_{dc\_ref} = U_n - k_p P_{out}$$

According to equation (3) and (4), the control strategy block diagram of grid-connected converter involved in AVSG virtual inertia link can be obtained. The control strategy equivalent circuit of grid-connected converter G-VSC is shown in Fig 1, which is composed of filtered inductance, three-phase rectifying and inverting bidirectional bridge circuit, and load-side capacitance. In Fig 1: $v_a, v_b$ and $v_c$
is AC side voltage of the G-VSC; \( u_a, u_b \) and \( u_c \) is the three-phase grid voltage; \( i_a, i_b \) and \( i_c \) is the grid-connected current of G-VSC; \( u_{dc} \) is DC side voltage of G-VSC; \( i_{dc} \) is the direct current flowing into the DC bus from the G-VSC; \( i_{out} \) is the DC output current of G-VSC.

Virtual Inertial Control
\[
\frac{1}{sC_{vir}Un} + \frac{1}{sCUn} + \frac{1}{sC_{vir}P_{out}}\]

\[\begin{align*}
L & C \\
\text{Virtual Inertial Control} & \text{Current Decoupling Control}
\end{align*}\]

Current
P
W
M

Fig. 1 Equivalent circuit of G-VSC and its control block diagram

3. Self-Adapting adjustment strategy

The virtual capacitance and virtual damping parameters in AVSG control with fixed parameters is constant, so that the system can obtain a large inertia. However, it has some problems such as long transient time, being unable to stabilize voltage rapidly and adjust the voltage deviation. According to the regular of voltage value and voltage change rate when load shedding is carried out with traditional droop control, the transient process of voltage variation can be divided as the voltage far away from bus nominal voltage part and the process close to nominal voltage part.

\[\Delta u_{dc} = u_{dc} - U_n\] is the instantaneous deviation of system voltage, and \( \frac{du_{dc}}{dt} \) is the instantaneous rate of system voltage change. DC bus voltage deviates from the nominal voltage when load or output in the network fluctuates. A larger virtual capacitance and a smaller virtual damping are needed to increase the inertia of the system and reduce the rate of voltage change. In this stage, both \( \Delta u_{dc} \) and \( \frac{du_{dc}}{dt} \) are positive or negative, that is, \( \Delta u_{dc} \) * \( \frac{du_{dc}}{dt} \) is greater than 0. In order to shorten the transient time of voltage change, the virtual capacitance should be reduced when the voltage is approaching the steady-state value. So the inertia of the system can be decreased and make the voltage can be stabled quickly. In the process of voltage restoring to the rating, smaller virtual capacitance and larger virtual damping are needed to reduce the system inertia and bring the voltage closer to the rating as soon as possible. Meanwhile, the steady-state deviation of voltage is reduced. In this stage, the sign of \( \Delta u_{dc} \) is not same as that of \( \frac{du_{dc}}{dt} \), that is, \( \Delta u_{dc} \) * \( \frac{du_{dc}}{dt} \) is less than 0.

Therefore, based on above analysis, this paper proposes an self-adaptive virtual inertia parameter adjustment equation which is determined by the voltage change rate and voltage deviation. In this paper, the inverse tangent function is used to establish the adaptive equation of parameters, as follows:
\[ C_{\text{vir}} = \begin{cases} 
C_0 & -k_v \leq \Delta u_{dc} \frac{du_{dc}}{dt} \\
C_0 + m_1 \arctan m_2 \Delta u_{dc} \frac{du_{dc}}{dt} & \Delta u_{dc} \frac{du_{dc}}{dt} > k_v, \frac{du_{dc}}{dt} > 1 \\
C_0 - m_1 \arctan m_2 \Delta u_{dc} \frac{du_{dc}}{dt} & \Delta u_{dc} \frac{du_{dc}}{dt} > k_v, \frac{du_{dc}}{dt} \leq 1 \\
C_0 - m_1 & \Delta u_{dc} \frac{du_{dc}}{dt} < -k_v 
\end{cases} \] (5)

\[ D_{\text{vir}} = \begin{cases} 
D_0 & \frac{\Delta u_{dc}}{U_n} \leq k_d \\
D_0 + n_1 \arctan n_2 \frac{\Delta u_{dc}}{U_n} & \frac{\Delta u_{dc}}{U_n} > k_d 
\end{cases} \] (6)

\( k_v \) is the starting threshold of the virtual capacitor which can avoid the influence of noise or small disturbance; \( k_d \) is the starting threshold considering the effect of power averaging; \( C_0 \) and \( D_0 \) are the virtual capacitance and virtual damping under the stable voltage state of the system; \( m_1, m_2, n_1 \) and \( n_2 \) are the adjustment coefficients of virtual capacitance and virtual damping under different states;

When the voltage change rate is greater than 1, the virtual capacitance will be increased to suppress the increase of the voltage change rate; otherwise, the virtual capacitance will be reduced to speed up the system voltage to restore the steady state value.

In order to ensure the power quality of the DC system, the parameters of the adaptive equation should be adjusted by the constraints of the system on voltage deviation, limit output power and voltage change rate were considered respectively.

Due to the symmetrical-effect of power positive fluctuation and negative fluctuation parameter regulation, this paper only discusses the parameter tuning when the grid-connected converter absorbs power. In order to ensure that the system has enough inertia, the transient time of the system should not be too long. The voltage change rate constraint is:

\[ \min_{\text{dc}} \max_{\text{dc}} \frac{du_{dc}}{dt} \leq \frac{du_{dc}}{dt} \leq \max_{\text{dc}} \min_{\text{dc}} \frac{du_{dc}}{dt} \]

In order to ensure the power quality of the system and the average power distribution effect of droop control, the voltage should not be too low when the minimum load is switched. And when the G-VSC output rated power, the system voltage deviation should be small enough to avoid destroying the coordinated control mode with other terminals. So the constraint of voltage deviation is:

\[ \Delta u_{dc, \min} \leq u_{dc} \leq \Delta u_{dc, \max} \]

Considering the maximum transmitted power of G-VSC, the constraint of the power absorbed by the grid-connected side is:

\[ 0 \leq -P_{dc} \leq P_{dc, \max} \]

In order to obtain the appropriate parameters of the adaptive equation, the upper and lower limits of virtual capacitance and virtual damping should be selected to satisfy the robustness requirements. Substituting equation (4) into equation (3), it can be obtained that the relationship between virtual capacitor parameters and G-VSC output power variation, voltage deviation and voltage change rate is:

\[ P_{dc} = D_{\text{vir}} \Delta u_{dc} + C_{\text{vir}} U_n \frac{du_{dc, \text{ref}}}{dt} + \frac{\Delta u_{dc}}{k_p} \] (7)
For the virtual capacitor parameter, the voltage change rate is the largest at the moment of power grid fluctuation, and the voltage deviation is 0. Equation (8) can be deduced from equation (7):

\[
C_0 = \frac{P_{dc\_max}}{2U_n} \left( \frac{1}{\frac{du_{dc}}{dt}_{\min}} + \frac{1}{\frac{du_{dc}}{dt}_{\max}} \right)
\]

\[
\max_0 \min_{max} \max_1 \min_{max} \max_2
\]

\[
m_1 = \frac{P_{dc\_max}}{2U_n} \left( \frac{1}{\frac{du_{dc}}{dt}_{\max}} - \frac{1}{\frac{du_{dc}}{dt}_{\min}} \right)
\]

\[
m_2 = \frac{\pi \epsilon}{2\Delta u_{dc\_max}} \frac{du_{dc}}{dt}_{\max}
\]

For the virtual damping parameter, when the system voltage tends to be stable again after the occurrence of power fluctuation, the voltage deviation reaches the maximum, and the voltage change rate is 0. Equation (9) can be deduced from equation (7):

\[
D_0 = \frac{P_{dc\_max}}{\Delta u_{dc\_max}} - \frac{1}{k_p}
\]

\[
n_1 = \left( \frac{1}{\Delta u_{dc\_min}} - \frac{1}{\Delta u_{dc\_max}} \right) P_{dc\_max}
\]

\[
n_2 = \frac{\pi \epsilon U_n}{2\Delta u_{dc\_max}}
\]

\(\epsilon\) is the rate coefficient of virtual parameter regulation. The smaller \(\epsilon\) means the faster the change speed of virtual capacitance and virtual damping is. In order to retain \(\epsilon\) certain adjustment margin, \(\epsilon\) is set as 0.8~0.9.

4. Results & Discussion

In order to compare the effects of traditional droop control, fixed parameter AVSG control and adaptive virtual parameter AVSG control proposed in this paper, the model was used to simulate various load switching situations under three kinds of controls at \(t=1.5s\). Simulate the phenomenon of inputting large loads suddenly and removing regional loads instantaneously. The difference of the transient change process under different control is compared. Fig. 2 and Fig.3 show the situation when the switching load is 10kW, and Fig. 4 shows the situation when the switching load is 20kW and the G-VSC outputs maximum power.

The rated capacity of G-VSC is 20kW; The nominal voltage of the DC bus is 500V, and the output power of the G-VSC is 0kW under the rated operation state. The other parameters are shown in Table 1.

| Parameter name | The numerical | Parameter name | The numerical |
|----------------|---------------|----------------|---------------|
| \(k_p\)        | 0.002         | \(k_{pwm}\)   | 290           |
| \(C\)          | 0.008F        | \(C_0\)       | 0.004F        |
| \(k_{pi}\)     | 5             | \(m_1\)       | 1             |
| \(k_{iq}\)     | 100           | \(m_2\)       | 0.0007        |
| \(k_{pv}\)     | 0.2           | \(D_0\)       | 1500          |
According to Fig.2, when 1.5s put in 10kW load, the voltage suddenly dropped to 486.4V, then the voltage stabilized at 490.9V, and the voltage deviation was -9.1V. When the 10KW load was cut off, the voltage suddenly rose to a maximum of 503.6V, and then the voltage stabilized around the rated value. It is easy to see from the simulation results that the traditional droop control is prone to large overshoot when load suddenly switches. The voltage rose and then fell within 0.01s, resulting in a great voltage change rate at that time. After the steady state was restored again, the DC bus voltage deviation was large.

| $k_n$ | $n_1$ | $n_2$ | $L_3$ | $r$ |
|-------|-------|-------|-------|-----|
| 69    | 3800  | 70.69 | 0.0027H | 0.00242Ω |

Fig. 2 Voltage variation waveform under traditional droop control when 10kW load was switched

According to Fig 3, after 1.5s putting in 10kW load, fixed parameter AVSG control suppressed the occurrence of overshoot. After 0.33s, the bus voltage stabilized at 494.5V and the voltage deviation was -5.5V. Compared with the former, the absolute value of the voltage deviation of the self-adaptive AVSG control was reduced by 1.4V, and the voltage was stabilized after 0.23s, with shorter transient time. However, when the voltage began to deviate from the rated value the inertia of the system at the early stage was greater than that of the fixed parameter AVSG control, and the voltage change was more sluggish. After cutting off the 10kW load system, the system under the self-adaptive AVSG control could restore the nominal voltage more rapidly and still maintained a certain inertia, which could shorten the time of the transient process without causing a big impact on the system.

Fig. 3 Voltage variation waveform comparison between fixed parameter and self-adaptive parameter AVSG control when 10kW load was switched

It can be seen from Fig 4 that the G-VSC output maximum power after 1.5s putting in 20kW load. At this time, the voltage deviation was the maximum allowable voltage deviation within the adjustment range of the grid-connected converter. After the system stabilized, the voltage deviation
under the control of fixed parameter AVSG and adaptive AVSG had similar values. In the early stage of power fluctuation, the system under the adaptive AVSG control still quickly adjusted the virtual capacitor parameters to suppress the rapid voltage change. Then the virtual capacitance was reduced when the voltage change rate dropped to 1. The voltage dropped quickly and was lower than the bus voltage under fixed parameter AVSG control. After the 20kW load was cut off, it was still restored to the rated operating state at a faster speed.

Fig. 4 Voltage variation waveform comparison between fixed parameter and adaptive parameter AVSG control when 20kW load is switched

5. conclusion
This paper analyzes the influence of virtual capacitance and virtual damping on system inertia and stability under different conditions and proposes a self-adaptive control strategy based on AVSG control technology. Under the self-adaptive AVSG control, the voltage change speed is slightly slower than that under the fixed parameter AVSG control, but the transient time is shorter. Meanwhile, the proposed control method makes the absolute value of voltage deviation smaller. On the premise of meeting the requirement of power quality, the dynamic characteristics of the system are optimized.

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