Virtual Synchronous Generator Grid Connected Control Method Based on Virtual Impedance

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Abstract. The virtual synchronous generator technology is used to simulate the working principle of the synchronous generator, which provides the inertia and damping support for the power grid. At present, the measurement of the phase, amplitude and frequency of the virtual synchronous generator is used to measure the output voltage of the distributed generation system. To solve this problem, this paper proposes a virtual synchronous machine grid virtual impedance control method based on the virtual impedance calculation of virtual current in the virtual synchronous machine from the network state and the grid between the assumption of power exchange, puts forward the pre synchronization strategy based on virtual impedance, and gives the simulation results. The results show that compared with the existing methods, the proposed method is more practical and more smooth.

1. Introduction

With the rapid development of the national economy, the problem of lack of energy has become increasingly prominent. The use of clean energy to supplement or replace traditional fossil energy is an important means of ensuring sustainable development in the energy sector. In the field of power systems, distributed power generation, as an important form of clean energy generation, has received strong support from the government and industry and is expected to become an important part of the future power supply.

However, the rapid development of distributed power generation has brought many challenges to the operation of power systems. The existing distributed power generation system uses power electronic devices to be integrated into the power grid, which is more flexible than the traditional power generation system. Meanwhile, it has such disadvantages as low inertia and weak damping, which affects the friendly compatibility of the distributed power generation system with the existing power grid. In response to the above-minded problems, some researchers proposed virtual synchronous machine technology that ensures the stable operation of the system by changing the external characteristics of the grid-connected inverter and absorbing the advantages of synchronous generators. In 2007, the European VCYNC project first proposed the concept of virtual synchronization [1]. Zhong Changqing proposed Synchronverter algorithm to realize the modeling of virtual synchronous machine [2]. Research institutions such as Tsinghua University, the Institute of Electrical Engineering and Hefei University of Technology have contributed to the improvement of system stability in this field [3].
On the basis of previous theoretical research, the virtual synchronous machine technology has been put into practice. In 2016, State Grid Corporation transformed the inverter of wind turbine and photovoltaic power generation in Zhangbei Wind Storage and Demonstration Project, which becomes the world's largest virtual synchronous machine demonstration project, and China Electric Power Research Institute distribution station put into use the photovoltaic virtual synchronous machine researched and developed in the new Tianjin Eco-city smart business micro-grid. At present, the technical function of virtual synchronous machine is basically realized. The relevant research has initially shifted from the research and development stage to the optimization stage, and there is room for further research in the aspect of system-level grid-connected application.

The frequency regulation method of micro grid is studied based on virtual synchronous machine to realize different operation modes \[4-5\]. The charge and discharge strategy of the virtual synchronous machine energy storage unit is studied, and the capacity configuration method is given \[6-7\]. A wind turbine grid-connected system based on virtual synchronous machine is proposed to achieve a friendly and grid-connected target with stable voltage \[8\]. The above literatures all focus on the application technology of virtual synchronous machines in existing distributed generation systems. In addition, Based on the future active distribution network operation, the application of virtual synchronous machine technology is discussed \[9\], and an electric vehicle charging method based on virtual synchronous machine technology is proposed \[10\]. These research results are established on the same basic principles in terms of the level of inverter control strategy, but the difference lies in the application occasions, which does not involve the improvement of the "ontology" in the application process of virtual synchronous machine, and fails to dig into the flexible characteristics of virtual synchronous machine.

In summary, an improved virtual synchronous machine grid-connecting method is proposed to solve the problem that Additional measuring devices in traditional grid-connecting restrict flexible output of distributed generation systems, avoiding the problems such as that the phase-locked loop has nonlinearity, slow response, and difficult parameter design, and a smoother and more efficient virtual synchronous machine is realized.

2. Virtual synchronous machine synchronous grid-connected grid equivalent model

If the virtual synchronous machine is equivalent to a voltage source, a typical grid-connected system equivalent circuit is shown in Figure 1.

\[ u_s = U_g \sin \alpha \]

\[ e = E \sin \alpha \]

Figure 1. Equivalent circuit diagram

In the above figure, \( e \) is the virtual synchronous machine output port voltage; \( X_s \) is the synchronous reactance connected to the grid; \( u_s \) is the grid voltage.

Under the assumption of a single-machine infinite system, the virtual synchronous machine transmits the active power as shown in equation (1).

\[ P = \frac{3U_g E}{2X_s} \sin (\alpha - \alpha_g) \]  \hspace{1cm} (1)

In the equation, \( \alpha \) is the virtual power angle, controlled by the virtual input mechanical torque. The virtual synchronous machine transmits reactive power as shown in equation (2).
The connection of virtual synchronous machine to the grid needs to ensure the frequency, phase and amplitude of the output voltage and the grid voltage is similar, which is represented by equation (3).

\[
\begin{align*}
\min & f - f_g \leq f_{\text{min}} \\
\min & E - U_g \leq U_{\text{min}} \\
\min & \alpha - \alpha_g \leq \alpha_{\text{min}}
\end{align*}
\] (3)

As is shown in the equation, \( f, E, \alpha \) is respectively the voltage frequency, amplitude and phase of the virtual synchronous machine; the subscript \( g \) is the grid side variable; the subscript \( \text{min} \) is the set safety threshold, and the safety threshold of the grid connection optimum condition is zero.

It can be seen from equations (1) and (2) that the grid-connected power transfer equation of the virtual synchronous machine mainly depends on the voltage amplitude and phase angle, that is, in order to satisfy the smooth grid connection, the safety threshold needs to satisfy the formula (4).

\[
\begin{align*}
U_{\text{min}} &= 0 \\
\alpha_{\text{min}} &= 0
\end{align*}
\] (4)

Substituting the formulas (3) and (4) into the formula (1) and (2) respectively, we obtains the formula (5) as follows.

\[
\begin{align*}
P &= 0 \\
Q &= 0
\end{align*}
\] (5)

It can be seen that the synchronous synchronization of the virtual synchronous machine can be further understood as a conclusion: the virtual power and the reactive power of the virtual synchronous machine transmitted to the grid are zero.

The output power of the virtual synchronous machine is based on the assumption of the virtual synchronous machine grid-connected condition, but the actual situation is that the virtual synchronous machine has no output power in the off-network state. In order to give a grid-connected control strategy of virtual synchronous machine that satisfies the zero output power, it is necessary to virtualize the power exchange between the two. Therefore, this paper proposes pre-synchronization control strategy based on virtual impedance, as shown in the following section.

3. The Synchronous Grid-connected Control Strategy of Virtual Synchronous Machine

Currently, the virtual synchronous machine system is composed of a DC power supply and a DC/AC inverter. The DC power supply provides the power required by the virtual synchronous machine, and the operation control method adopted by the inverter control unit is the key to the virtual synchronous machine technology.

The topology of the virtual synchronous machine is the same as that of the general three-phase DC/AC inverter, thus not necessary to be described here. This paper mainly considers the electromagnetic relationship and mechanical characteristics of the virtual synchronous machine simulation, as well as its external characteristics such as active frequency modulation and reactive voltage regulation.

The mathematical model of the virtual synchronous machine is shown in equation (6).
\[
\begin{align*}
    v &= -Ri - L_m \left( \frac{di}{dt} \right) + e \\
    e &= M_f i, \theta \sin \theta \\
    J\theta &= T_m - T_e - D\theta \\
    P &= \langle i, M_f i, \theta \sin \theta \rangle \\
    Q &= -M_f i \langle i, \cos \theta \rangle \theta 
\end{align*}
\]

(6)

Where, \( T_m \) is the virtual mechanical torque; \( D \) is a virtual damping coefficient; \( M_f \) is mutual inductance; \( v, i \) is to measure voltage and current; \( T_e \) is the virtual electromagnetic torque; \( i_f \) is the excitation current; \( \theta \) is the virtual power angle; \( e \) is the output electromotive force.

The basic control of the virtual synchronous machine includes two aspects: virtual speed control and virtual excitation control. The virtual speed control is based on the mathematical model of the virtual synchronous machine and the typical active frequency drooping characteristic, and the double loop structure of the inner loop of the power outer loop frequency is used to simulate the active-frequency characteristics of the synchronous machine and the inertia and damping links. The virtual excitation control does not involve the aforementioned mathematical model, and mainly takes into account the external characteristics of the virtual synchronous machine, so the conventional reactive-voltage droop control structure is adopted.

It can be seen from the foregoing that the purpose of designing the virtual impedance is to virtualize the power exchange between the virtual synchronous machine and the power grid, and propose a control strategy that satisfies the virtual synchronous machine output power of zero.

Therefore, considering the characteristics of droop control, the pre-synchronization control method proposed in this paper is shown in Figure 2.

The grid-connected process of virtual synchronous machine is as follows:

In the off-grid state, the Sa switch is closed, the Sc switch is off, and the B1 switch is closed. Considering that the virtual synchronous machine's off-grid actual output current is zero, we assume that there is a virtual impedance between the output port voltage and the grid voltage, and the virtual current can be calculated as shown in equation (7).

\[
i_s = \frac{e - u_s}{L_s R_s} 
\]

(7)

The active power and reactive power of the virtual output can be calculated from the above formula to satisfy the power exchange assumption between the virtual synchronous machine and the grid.

Equation (8) can be satisfied by controlling the output voltage amplitude and phase angle of the virtual synchronous machine.

\[
\begin{align*}
    T_m &= T_e \\
    Q_{set} &= Q
\end{align*}
\]

(8)

If \( P_{set} \) and \( Q_{set} \) are set to zero, the grid-connected condition that the zero power exchange showed by Equation (5) is satisfied. At this time, the grid-connected operation can achieve smooth grid connection.

In the grid-connected state, the \( B_2 \) switch is closed and the virtual synchronous machine enters the grid-connected operation mode.
Figure 2. The grid-connected control block diagram of virtual synchronous machine

Where, $i_g$ is the virtual synchronous machine output current; $i_s$ is the virtual current, and $L_1$ and $R_1$ form the virtual impedance.

4. Engineering case analysis

Based on the above research, this paper is to verify the simulation by using Matlab/Simulink software. Some parameters are shown in Table 1.

| Table 1. Simulation parameters |
|--------------------------------|
| Parameter                      | Value            |
| Power voltage                  | 220V             |
| Supply voltage                 | 400V             |
| Filter inductance              | 2mH0.1Ω          |
| Filter capacitor               | 40µF             |
| Line impedance                 | 2mH0.1Ω          |
| Switching frequency            | 6.4kHz           |

The simulation system is shown in Figure 3.

![Simulation system diagram]

Figure 3. Simulation system

The comparison between the grid-connected control method proposed in this paper and the direct grid-connected method is as follows:

There is a phase difference between the output voltage and the grid voltage when the virtual synchronous machine is running with load, as shown in Figure 4.
The direct grid connection will generate an inrush current with a large amplitude. As shown in Figure 5, it has an adverse effect on the stable operation of the virtual synchronous machine and cannot meet the requirements of smooth grid connection.

Using the virtual impedance-based grid-connected control method, the virtual synchronous machine tracks the grid voltage phase by continuous adjustments, as shown in Figure 6.

After adopting the pre-synchronization control strategy proposed in this paper, we can see the output voltage of the virtual synchronous machine is consistent with the grid voltage, and there is no inrush current after the grid-connected operation, which satisfies the smooth grid-connected demand, as shown in Fig. 7.

5. Conclusion

In order to solve the problem that the additional measurement device in traditional grid-connecting restricts the flexible output of distributed generation system, this paper proposes a grid-connected control strategy of the virtual synchronous machine based on virtual impedance:

By designing the virtual impedance link to make the virtual synchronous machine output power zero, the controller itself can be used to synchronize with the power grid before the closing, without the help of a special synchronization unit, and the smooth synchronization of the virtual synchronous machine is realized.

Compared with the traditional virtual synchronous machine grid-connected method, the proposed pre-synchronization method is simpler and more effective, avoiding the problems, such as nonlinear phase-locked loop, slow response and difficult parameter design.

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