Grid Connected Oscillation Mode of Virtual Synchronous Generator Based on Clean Energy

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Abstract:
Introduction: With the large-scale application of distributed generation in power grid, power grid is developing towards low inertia and low damping. As the virtual synchronous generator (VSG) has the characteristics of synchronous generator and inverter, it may face the risk of oscillation during grid connected operation.

Objectives: To solve this problem, this paper proposes current balance control and power oscillation suppression strategies without changing the characteristics of the virtual synchronous generator.

Methods: At varius vel pharetra vel turpis nunc eget lorem. Feugiat scelerisque varius morbi enim nunc. Cras semper auctor neque vitae tempus quam pellentesque nec. Faucibus purus in massa tempor nec feugiat nisl. Congue nisi vitae suscipit tellus mauris a. Est sit amet facilisis magna etiam tempor. Dictum varius duis at consectetur. Purus semper eget duis at tellus at urna. Ipsum consequat nisl vel pretium. Viverra maecenas accumsan lacus vel facilisis volutpat est. Bibendum arcu vitae elementum curabitur vitae nunc sed. Nisl tincidunt eget nullam non nisi est. Ac turpis egestas integer eget aliquet nibh praesent.

Results: On this basis, the relationship between VSG current inner loop, power outer loop, VSG parallel operation and different oscillation frequencies is analysed. In this paper, a small signal model is established under the condition of different influencing factors. At the same time, this paper systematically analyses the high frequency, power frequency and low frequency oscillation modes existing in VSG grid connected operation.

Conclusions: Finally, through MATLAB/Simulink simulation, this paper verifies the correlation between different oscillation modes and corresponding dominant influencing factors when VSG is connected to the grid.

Keywords: renewable energy, clean energy, distributed power generation, virtual synchronous generator.

INTRODUCTION

At present, the power generation mode in China is mainly thermal power generation, so fossil energy such as coal is still exploited and utilised on a large scale1. If fossil energy is exploited and used excessively, it will not only lead to the depletion of fossil energy, but also cause serious environmental pollution and a series of ecological problems, thus affecting people's physical and mental health2,3. Therefore, the development of renewable energy has become the focus of the world, because renewable resources are not only sustainable exploitation and utilization, but also clean and pollution-free4. At present, most renewable energy is connected to the large power grid in the form of distributed power generation5,6. Due to the randomness and instability of distributed generation, and the grid connected inverter is vulnerable to power fluctuations, the microgrid technology was born under the background of how to make distributed power generation more safe and effective. In grid connection mode, with the increase of distributed generation in micro grid, the inertia and damping of large grid will be gradually diluted7-9. Therefore, finding a reasonable control strategy of microgrid inverter has become an important topic of microgrid technology.

OBJECTIVES

This paper proposes current balance control and power oscillation suppression strategies without changing the characteristics of the virtual synchronous generator.

METHODS

STRUCTURE AND MODEL OF VIRTUAL SYNCHRONOUS GENERATOR SYSTEM

In the traditional power system, the stable operation of the system can not be separated from the synchronous generator. We want to simulate the relevant characteristics of synchronous generator to realise the control of microgrid inverter. In this paper, the pole pair 1 hidden pole synchronous generator is selected as the model. It is assumed that the rotor and stator windings of the synchronous generator are symmetrical, the magnetomotive force and magnetic flux are distributed as sine functions, and the saturation effect is ignored. The armature resistance in synchronous generator is very small, so its influence can be ignored. Self-inductance of stator winding is L, mutual inductance is - M, Maf, Mbf and Mcf are mutual inductance between rotor and stator, respectively.

The formula is noted as10:

$$\begin{cases} M_{af} = M_f \cos\beta \\ M_{bf} = M_f \cos(\beta - 120°) \\ M_{cf} = M_f \cos(\beta + 120°) \end{cases} \tag{1}$$

where β is the angle between the rotor axis and phase a.

The stator synchronous flux expression (2) is as follows:

$$\begin{cases} \phi_a = Li_a - Mi_b - Mi_c + M_{af} i_f \\ \phi_b = Li_b - Mi_a - Mi_c + M_{bf} i_f \\ \phi_c = Li_c - Mi_a - Mi_b + M_{cf} i_f \end{cases} \tag{2}$$

where ia, ib and ic are stator three-phase current, if is rotor excitation current, with ia + ib + ic = 0, which can be substituted into the above formula:

$$\begin{cases} \phi_a = (L+M) i_a + M_{af} i_f \\ \phi_b = (L+M) i_b + M_{bf} i_f \\ \phi_c = (L+M) i_c + M_{cf} i_f \end{cases} \tag{3}$$

According to the law of electromagnetic induction, the terminal voltage expression of synchronous generator is as follows:

$$\begin{cases} v_a = -\frac{d\phi_a}{dt} = -(L+M)\frac{di_a}{dt} - \frac{d(M_{af} i_f)}{dt} \\ v_b = -\frac{d\phi_b}{dt} = -(L+M)\frac{di_b}{dt} - \frac{d(M_{bf} i_f)}{dt} \\ v_c = -\frac{d\phi_c}{dt} = -(L+M)\frac{di_c}{dt} - \frac{d(M_{cf} i_f)}{dt} \end{cases} \tag{4}$$

where va, vb and vc are the voltage drop caused by stator current on the inductor, and the induced electromotive force ea, eb and ec are:

$$\begin{cases} e_a = -\frac{d(M_{af} i_f)}{dt} = -\frac{dM_{af}}{dt} i_f - \frac{di_f}{dt} M_{af} \\ e_b = -\frac{d(M_{bf} i_f)}{dt} = -\frac{dM_{bf}}{dt} i_f - \frac{di_f}{dt} M_{bf} \\ e_c = -\frac{d(M_{cf} i_f)}{dt} = -\frac{dM_{cf}}{dt} i_f - \frac{di_f}{dt} M_{cf} \end{cases} \tag{5}$$

When the synchronous generator operates in steady state, the change rate of excitation current is zero, that is, $\frac{di_f}{dt} = 0$. Substituting into the formula, we can get:

$$\begin{cases} e_a = \omega M_f i_f \sin\beta \\ e_b = \omega M_f i_f \sin(\beta - 120°) \\ e_c = \omega M_f i_f \sin(\beta + 120°) \end{cases} \tag{6}$$

DESIGN OF POWER FREQUENCY REGULATOR FOR VIRTUAL SYNCHRONOUS GENERATOR

Frequency is one of the important standards to measure power quality. The rated standard frequency in China is 50 Hz, the allowable deviation range is ± 0.2 Hz, and the allowable deviation range of small capacity system is ± 0.5 Hz. In the power system, if the power of the system is kept in balance, the system frequency will remain stable. The frequency stability of the synchronous generator is mainly reflected in the rotating shaft. If the input mechanical torque of the synchronous generator is equal to the electromagnetic torque, then the system is in stable operation at this time. If the load power is changed, the synchronous generator speed will also change, and the relationship between speed and frequency is:

$$n = \frac{60f}{P} \tag{7}$$

It can be seen from Formula (7) that when the speed of synchronous generator changes, the frequency will also change. When the deviation of frequency exceeds the allowable range, it will affect the normal operation of the system. At this time, it is necessary to control and adjust the frequency. Generally speaking, frequency regulation is divided into primary regulation and secondary regulation. For primary frequency regulation, when the load fluctuates, the governor will correspondingly change the active power, so that the generator input power and load consumption power reach a new balance point, and the corresponding frequency is also a new steady-state value. However, at this time, the frequency is not the rated value before the load change, so the primary frequency regulation is a poor regulation conducted spontaneously. Figure 1 shows the primary frequency regulation curve of the generator set. In the figure, P_L and P_G represent the power frequency change curves of load and generator, respectively. When the system operates stably, they intersect at point O, corresponding to frequency f_2 and power P_2. At this time, the active power of the load is suddenly increased by $\triangle P_L$ (the power frequency characteristic of the load becomes P_L'). At this time, the mechanical power sent by the prime mover cannot keep up with the change of the load power, and the power imbalance on the rotor causes the speed to drop, so does the frequency. As soon as the frequency decreases, the active frequency characteristic (curve LP) of the load will change along AB, and the active frequency characteristic (curve P_G) of the generator will change along OB, and finally intersect at point B to achieve a new balance, corresponding to frequency f_1.

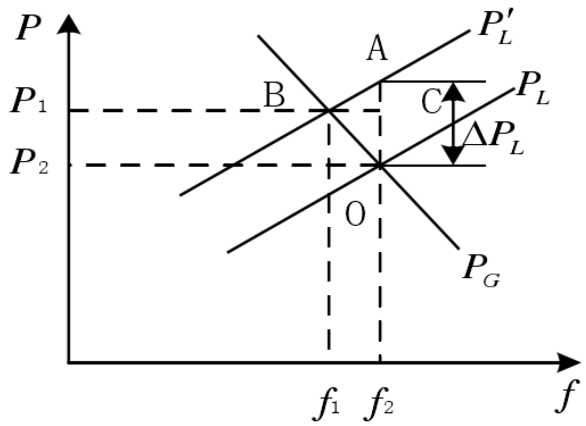

Fig. 1. Schematic diagram of primary frequency modulation

The frequency variation of power system will not only affect users, but also affect the power system itself to a certain extent. Therefore, it is necessary to keep the frequency stable, and its deviation cannot exceed the allowable range. The active frequency droop characteristics of synchronous generators are shown in Fig. 2.

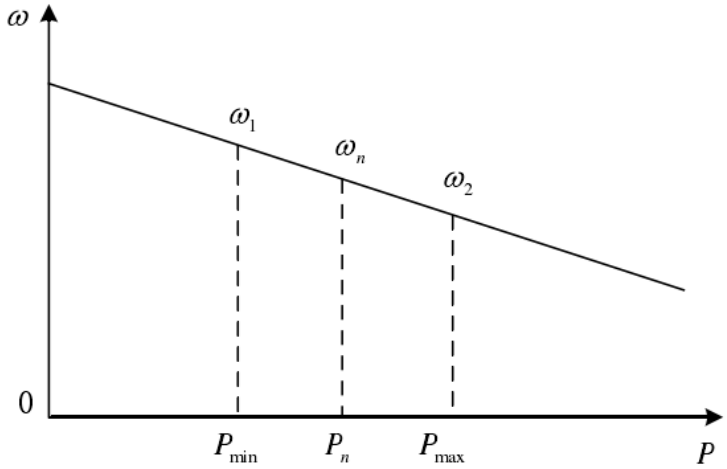

Fig. 2. Active frequency droop curve of synchronous generator

If the frequency modulation coefficient of synchronous generator is K_w:

$$K_{\omega} = -\frac{P_{ref} - P}{\omega_0 - \omega} = -\frac{\Delta P}{\Delta \omega} \tag{8}$$

The operation stability of the system depends on the frequency stability. If the actual frequency of the system is equal to the given frequency, then the output power of the system is equal to the power consumed by the load, that is, the power is balanced. At this time, the system is in a stable state. If the frequency is not equal and there is deviation, it must be adjusted to reach a new balance point. The droop equation of active power and frequency in VSG control is obtained from the structure of virtual governor:

$$P_m - P_{ref} = K_{\omega}\left(\omega_0 - \omega\right) \tag{9}$$

where ω_0 is the given angular frequency; ω - the actual angular frequency of the inverter; K_ω - the frequency modulation coefficient; P_{ref} - the given active power of the inverter, and the final P_m is equivalent to the mechanical power input by the prime mover in the synchronous generator.

In short, inertia is the ability to maintain the original state of motion. The moment of inertia of a synchronous generator is related to the rotor's own factors. Generally, in large power plants, the rotor of synchronous generator has a large mass and volume, so the inertia is also large. For synchronous generators with large inertia, when the load power of the system changes suddenly, the speed of the rotor with large mass and large inertia changes slowly and its frequency will not change suddenly.

Damping windings are usually installed on the rotor surface of large and medium-sized synchronous motors. Damping simply means that when the system oscillates, the damping winding will prevent the rotor and the rotating magnetic field from relative motion, which will reduce its oscillation effect. In addition to the damping winding, the structure of the synchronous generator itself will also have a certain damping effect on the system oscillation, and the two together bear the ability of the system to suppress oscillation. In traditional large power plants, due to inertia and damping, when the system frequency changes suddenly, the frequency change of large power grid is a very slow process. However, since a large number of distributed generators in the microgrid are added, the inertia of the large grid will be diluted layer by layer by the microgrid.

The premise of the terminal voltage stability of synchronous generator is that the reactive power should be kept in balance. The design of VSG controlled virtual excitation regulator in this paper is to adjust the inverter output terminal voltage *U* and reactive power *Q* through the virtual excitation electromotive force amplitude *E*. The amplitude *E* of virtual excitation electromotive force consists of three parts:

$$E = E_0 + \Delta E_q + \Delta E_u \tag{10}$$

where E_0 is voltage reference value; ΔE_q - the voltage amplitude variation in the reactive voltage droop characteristic.

$$\Delta E_q = \frac{1}{K_q s}\left(Q_{ref} - Q\right) \tag{11}$$

where K_q is the reactive power adjustment coefficient; Q_{ref} - the set value of reactive power; Q - the reactive power actually generated by the inverter, and there is:

$$Q = \frac{(u_a - u_b)i_c + (u_b - u_c)i_a + (u_c - u_a)i_b}{\sqrt{3}} \tag{12}$$

ΔE_q is the adjustment part of the output terminal voltage amplitude by using the reactive power adjustment coefficient and voltage adjustment coefficient:

$$\Delta E_q = \frac{1}{K_q s}\left[K_u\left(U_{ref} - U\right)\right] \tag{13}$$

where K_u is the voltage regulation coefficient; U_{ref} - the given amplitude of inverter output voltage, and U - the actual amplitude of inverter output voltage. Then there are:

$$E = E_0 + \frac{1}{K_q s}\left[\left(Q_{ref} - Q\right) + K_u\left(U_{ref} - U\right)\right] \tag{14}$$

After the amplitude E of the virtual excitation electromotive force is calculated, the virtual excitation electromotive force generated in the actual VSG control process can be expressed:

$$E = \begin{pmatrix} E\sin\theta \\ E\sin(\theta - 2\pi/3) \\ E\sin(\theta + 2\pi/3) \end{pmatrix} \tag{15}$$

According to the VSG control strategy proposed above, the overall control structure diagram of the VSG is drawn. The active power reference value and reactive power reference value obtained by the system are all carried out by instructions. The reference value will pass through the control module of the system, and then the value obtained is the phase angle and voltage. The output voltage and current are transformed into the components in dq rotating coordinates. Then, these component values and measured values are sent into the voltage and current closed loop. After comparison, the reference voltage and phase angle are obtained through the PI regulator, and SVPWM modulation is used to output drive signals to control the on-off of the inverter switch.

RESULTS

POWER ALLOCATION PROBLEM

When the load of the system changes, the corresponding frequency will change. At this time, the active frequency modulation link will automatically adjust the input power of the generator to meet the load demand. In the process of operation, not only the frequency of each parallel unit should be the same, but also the power response speed should be the same. If the power response speed is different, it will lead to the possibility of power scrambling if the power response speed is fast when the load changes suddenly, so the frequency will also drop instantaneously. Therefore, the response speed of each unit must be consistent, and specific analysis will be made later. The response speed is related to the inertia, so it is necessary to analyze the matching principle of the moment of inertia. The precondition of power distribution is that the voltage amplitude and phase of the inverter must be the same.

Taking the parallel operation of two VSG as an example, Fig. 3 shows the ideal model of microgrid parallel operation, where $U_1 < \theta_1$ and $U_2 < \theta_2$ is the output voltage of two VSG controlled microgrids, $X_1 < \alpha_1$ and $X_2 < \alpha_2$ are their equivalent reactance respectively. $Z < \alpha_z$ is the common load.

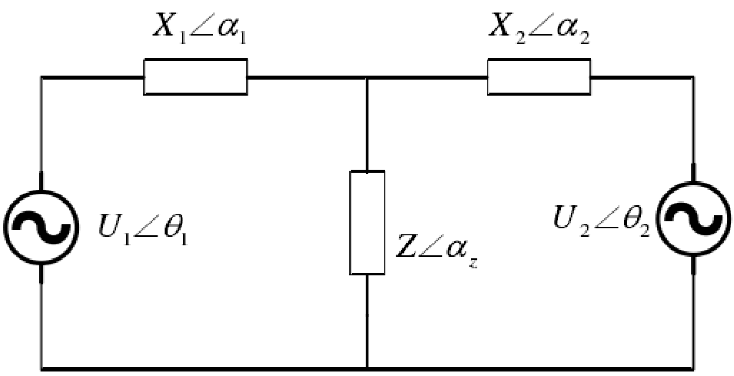

Fig. 3. VSG parallel model

POWER COUPLING PROBLEM

In the grid connection mode, the power formula under the resistive inductive line can be obtained according to the analysis:

$$\begin{cases} P = 3\frac{UE}{Z}\cos(\alpha-\delta) - 3\frac{U^2}{Z}\cos\alpha \\ Q = 3\frac{UE}{Z}\sin(\alpha-\delta) - 3\frac{U^2}{Z}\sin\alpha \end{cases} \tag{16}$$

The output power of VSG system under different line impedance is as follows:

(1) When the line impedance is inductive:

$$\begin{cases} P = \frac{3UE}{Z}\delta \\ Q = \frac{3U(E-U\cos\delta)}{Z} \end{cases} \tag{17}$$

(2) When the line impedance is resistive:

$$\begin{cases} P = \frac{3U(E-U\cos\delta)}{Z} \\ Q = -\frac{3UE}{Z}\delta \end{cases} \tag{18}$$

From the above analysis, it can be seen that when the system line is inductive, the degree of system decoupling is high, that is, *P* mainly depends on the power angle difference δ, *Q* mainly depends on the voltage difference, but due to the existence of LC filter, the line cannot show pure resistance. In order to make the output impedance sensitive, the virtual impedance technology can be used to adjust the line impedance characteristics.

In low voltage micro grid, the line impedance generally presents resistance inductance. If traditional droop control is adopted, *P* and *Q* will be related to the amplitude and frequency of the voltage, and there is strong coupling. The power coupling has been analysed previously. Power coupling will not only affect the stability of the control process, but also cause errors in the power distribution of the system. In order to overcome the shortcomings of virtual impedance and virtual power, this paper proposes a virtual power decoupling method, which makes the power allocation of the system more accurate and more stable. In the low-voltage microgrid, the line is resistive and inductive. Therefore, in the new controller, the output impedance of the VSG needs to be modified by adding virtual components. The function of this virtual impedance can only balance the impedance matching conditions between VSG parallel machines, and then use the virtual power to decouple the power of the VSG, so as to achieve the purpose of reasonable power distribution.

First, construct the virtual impedance, the expression is:

$$Z_v = R_v + jX_v \tag{19}$$

Then the equivalent impedance is:

$$Z' = Z + Z_v = (R + R_v) + j(X + X_v) \tag{20}$$

DISCUSSION

This paper mainly studies the control strategy of VSG. The demand for renewable energy has become an important topic in today's society. The randomness of distributed generation and the inverter's vulnerability to frequency and power fluctuations make it unable to directly operate in parallel with the large power grid. This paper first introduces the model of traditional synchronous generator, and then designs the VSG control strategy.

According to the self synchronization tracking principle of VSG terminal voltage and grid voltage, the grid connection conditions are analysed, and a grid connection pre synchronisation controller is designed to make the difference between VSG terminal voltage and grid voltage amplitude, phase and frequency meet the specified conditions, so that the microgrid can be effectively incorporated into the large grid. The power allocation problem and power decoupling problem of VSG dual machine parallel system are analysed in detail, and the conditions of power allocation are derived. In order to solve the power coupling, a virtual impedance is added. The simulation results show that the virtual impedance can significantly improve the power coupling problem. Based on the virtual impedance, a power decoupling method is designed to control. The simulation results show that the power decoupling method designed in this paper can better solve the power coupling problem, and improve the output voltage quality of double parallel machines.

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