Self-adaptive control of rotor inertia for virtual synchronous generator in an isolated microgrid

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Abstract. As an effective way to solve distributed generation, microgrid is getting increasingly extensive development. However, most of distributed generators are connected to the microgrid through power electronic converters, which makes the whole system present a small inertial network and the stability of the system face severe challenges. Virtual synchronous generator (VSG) technology has been widely applied in enhancing system stability because it enables inverters to mimic the outer characteristics of synchronous generator. Subsequently, aiming at the deficiency of traditional VSG control based on fixed rotor inertia, a self-adaptive control of rotor inertia for VSG is proposed in this paper. This method can change the inertia of the system and improve the stability of the system by adjusting the virtual rotor inertia adaptively. Finally, the effectiveness of the proposed control method is validated in MATLAB/Simulink environment.

1. Introduction

With the increasing energy crisis and environmental pressure, distributed energy, such as wind energy and solar energy, has attracted increasingly attention[1]. As an effective carrier of integrated distributed generation, microgrid connects distributed generation into the system through power electronic converters. These power electronic devices respond quickly, almost no inertia, and do not participate in frequency modulation and voltage regulation of the system[2]. Therefore, how to improve the stability of the microgrid has become an urgent problem.

In traditional power grids, the rotor of synchronous generator can contain a lot of kinetic energy owing to its mechanical rotational inertia. When disturbance occurs in the power grid, the rotor kinetic energy can be used to exchange energy with the power grid to provide greater inertial support for the system and maintain the stability of the system[3]. It is of great significance to enhance the stability of microgrid if we can learn from the operation experience of conventional grid and make grid-connected inverters mimic the operating characteristics of synchronous generator. For this reason, some scholars put forward the concept of VSG[4-5]. The basic idea of VSG is to make grid-connected inverters mimic the inertia, primary frequency modulation and primary voltage regulation characteristics of synchronous generator through control strategy[6].

Over the years, research on VSG control has attracted wide attention and development. Paper [7-8] refer to mechanical and electromagnetic equation of synchronous generator to control grid-connected inverter, which makes the inverter can match the synchronous generator in mechanism and external characteristics. This kind of control is called virtual synchronous generator technology, which is expected to play an important role in the future active distribution network and microgrid. In [9], the local linearization model of synchronous generator is introduced into traditional active power-
frequency droop control, which mimics the inertia, damping property and primary frequency modulation of synchronous generator on the basis of droop control. A small signal model of microgrid based on VSG and droop control is established in [10], by comparing and analyzing the transient response of two models, it is concluded that VSG control not only has the steady-state effect of droop control, but also can provide additional virtual inertia to improve the dynamic stability. An adaptive inertial control strategy is proposed in [11-12], different rotor inertia is selected according to the acceleration and slip of VSG, which can not be realized by traditional synchronous generator.

Compared with the fixed rotor inertia of traditional synchronous generator, the virtual rotor inertia of VSG can be selected adaptively according to the actual situation. In this paper, a self-adaptive control of rotor inertia for VSG is proposed to ensure good dynamic performance and stability of the system. Finally, the effectiveness of the proposed control method is verified by simulation.

2. Basic principle of the VSG

The essence of VSG is to make the inverters mimic outer characteristics of synchronous generator by control strategy, which mainly includes the main circuit and control system. Fig 1 shows the basic topology of VSG.

![Basic topology of VSG](image)

The current research principally focuses on the classical second-order model, including the electromagnetic part and the mechanical part. The electromagnetic part is modelled by the stator electrical equation as follows:

$$L \frac{d i_{abc}}{dt} = e_{abc} - u_{abc} - R_i i_{abc} \quad (1)$$

Equation (1) mainly considers the voltage-current relationship of the stator circuit, but does not reflect its flux linkage and inherent electromagnetic features. The electromagnetic model of synchronous inverter proposed by Professor Qingchang Zhong in [9] fully considers the electromechanical and transient characteristics of synchronous generator, enhances the coupling between virtual stator and rotor, and reflects the characteristics of synchronous generator better. The electric and flux equations between the stator and rotor are as follows:

$$e_{abc} = M_i i_i \varphi A - M_i \frac{d i_t}{dt} B \quad (2)$$

$$A = \begin{bmatrix} \sin \varphi & \sin(\varphi - 2\pi/3) & \sin(\varphi - 4\pi/3) \\ \end{bmatrix} \quad (3)$$

$$B = \begin{bmatrix} \cos \varphi & \cos(\varphi - 2\pi/3) & \cos(\varphi - 4\pi/3) \\ \end{bmatrix} \quad (4)$$

where $M_i$ is mutual inductance, $i_i$ is excitation current, and $\varphi$ is rotor angle.
The mechanical part is modelled by the rotor motion equation as follows:

\[
\begin{align*}
J \frac{d\omega}{dt} & = T_m - T_e - D(\omega - \omega_0) \\
\frac{d\theta}{dt} & = \omega
\end{align*}
\]

(5)

where \( J \) is the rotor inertia of VSG, \( T_m \) and \( T_e \) are mechanical torque and electromagnetic torque respectively, \( \omega \) and \( \omega_0 \) are the actual angular velocity and rated angular velocity respectively and \( D \) is the damping coefficient. Equation (5) shows that \( J \) provides inertial support for power and frequency dynamic processes of the system, while \( D \) provides the ability to damp power oscillations.

3. VSG control

3.1. Traditional VSG control

VSG control is divided into two parts: active power-frequency control and reactive power-voltage control. Active power-frequency control is actually to mimic the speed governor of synchronous generator, which is used to characterize the droop feature of active power and frequency. Fig 2 is an active power-frequency control block diagram.

![Fig 2. Active power and frequency control of VSG](image)

Where \( P \) and \( P_{\text{ref}} \) are measured and rated values of active power respectively and \( \theta \) is the phase angle of output voltage. As can be seen from Fig 2, the difference of active power determines the difference of torque, thus controlling the change of frequency. The relationship between \( \Delta \omega \) and \( \Delta T \) is expressed by parameters \( J \) and \( D \). These two parameters determine the performance of VSG controller.

Reactive power-voltage control is actually to mimic the excitation regulation function of synchronous generator, which is used to characterize the droop feature of reactive power and voltage amplitude. Fig 3 is a reactive power-voltage control block diagram.

![Fig 3. Reactive power and voltage control of VSG](image)

Where \( Q \) and \( Q_{\text{ref}} \) are measured and rated values of reactive power respectively, and \( E_m \) is the amplitude of output voltage. As can be seen from Fig 3, reactive power-voltage control adjusts the amplitude of the output voltage by the reactive power deviation and the voltage deviation, and \( k_u \) determines the voltage regulation capability of VSG.

3.2. Self-adaptive control of rotor inertia for VSG

According to equation (5), when the rotor inertia \( J \) is a larger value, the change rate of angular velocity in transient process can be slowed down. Moreover, when the angular velocity \( \omega \) deviates from the rated value after disturbance, the saltation of system frequency can be avoided and the dynamic stability of the system can be improved. When the rotor inertia \( J \) is a smaller value, the response of the system is fast. When \( \omega \) is restored to the rated value, the transition time can be reduced, which is
beneficial to the system stability. In order to synthesize the both advantages, we want rotor inertia $J$ to be larger when the system angular velocity $\omega$ deviates from the rated value, and smaller when $\omega$ restores to the rated value.

Based on the above analysis, a self-adaptive control of rotor inertia for VSG is proposed in this paper, in which the value of rotor inertia $J$ change adaptive by the following equation:

$$J = J_0 + k(\omega - \omega_0) \frac{d\omega}{dt}$$  \hspace{1cm} (6)

Where $J_0$ is the initial value of virtual rotor inertia in steady state, and $k$ is a constant greater than 0 indicating the accommodation coefficient. From equation (6), when $\Delta \omega = \omega - \omega_0$ and $d\omega/dt$ have same sign, it means that the system angular velocity $\omega$ is gradually deviating from the rated value, so it is necessary to increase the value of $J$. On the contrary, when $\Delta \omega$ and $d\omega/dt$ have opposite sign, it means that the $\omega$ is gradually restoring to the rated value and the value of $J$ needs to be reduced.

Combining equation (6) and (5), the rotor motion equation of the proposed control method can be derived:

$$\left( J_0 + k \Delta \omega \frac{d\Delta \omega}{dt} \right) \frac{d\Delta \omega}{dt} = T_m - T_e - D\Delta \omega$$  \hspace{1cm} (7)

Equation (7) is a quadratic equation of one variable with respect to $d\Delta \omega/dt$. Two solutions of the equation can be obtained by formula of root. According to the above analysis, it is known that the product of $\Delta \omega$ and $d\omega/dt$ could be positive or negative. Therefore, after discarding the root which does not satisfy the condition, the only solution of the equation as follow:

$$\frac{d\Delta \omega}{dt} = \frac{2(\Delta T - D \Delta \omega)}{J_0 + k \Delta \omega \sqrt{J_0^2 + 4k \Delta \omega(\Delta T - D \Delta \omega)}}$$  \hspace{1cm} (8)

Where $\Delta T = T_m - T_e$. Since the value of $d\omega/dt$ is equal to $d\Delta \omega/dt$, the solution of $d\Delta \omega/dt$ can be brought into equation (6) to eliminate the differential term in the proposed control method, which avoids the influence of system noise on the control and is conducive to the system stability. Fig 4 is the control block diagram of the control method proposed in this paper.

Fig 4. Self-adaptive control of rotor inertia for VSG

4. Simulation Studies

To verify the effectiveness of the self-adaptive control of rotor inertia for VSG proposed in this paper, a simulation experiment was carried out based on MATLAB/Simulink software platform. The main parameters of the system are shown in table 1.

| Parameter                  | Symbol | Value  |
|----------------------------|--------|--------|
| Rated frequency            | $f_0$  | 50Hz   |
| Voltage reference          | $U_{\text{ref}}$ | 311V   |
| Input voltage              | $U_{\text{dc}}$ | 800V   |
| Active power reference     | $P_{\text{ref}}$ | 10kW   |
| Switching frequency        | $f_{\text{sw}}$ | 10kHz  |
| Initial rotor inertia      | $J_0$  | 15kg\cdot m² |
4.1. Simulation case 1

In order to analyze the response of the control method proposed in this paper when load changes, the load increases from 10kW to 12kW at 0.5s and restores to the initial value at 2.5s.

Fig 5 (a) shows the variation curve of the system frequency under different rotor inertia. In the figure, \( J_1 = 2 \) indicates that the rotor inertia \( J \) takes a small value, \( J_3 = 15 \) indicates that \( J \) take a large value, and \( J_2 \) represents \( J \) with self-adaptive control proposed in this paper. In these three cases, the value of \( D \) is fixed. Fig 5 (b) is the curve of the rotor inertia \( J \) corresponding to the control method proposed in this paper during load variation.

As can be seen from Fig 5, when the load varies, the system frequency decreases first and then returns to the initial stable state. Compared with taking a fixed value for \( J \), the rotor inertia \( J \) with self-adaptive control is larger than the initial value \( J_0 \) in the process of the system frequency \( f \) reducing and deviating from the rated value, and smaller than the initial value \( J_0 \) in the process of \( f \) rising to the rated value.

![Fig 5. Simulation results of frequency and rotor inertia under load variation](image)

4.2. Simulation case 2

Similarly, in order to analyze the response of the proposed control method under step change of the active power reference, the \( P_{\text{ref}} \) varies from 10kW to 15kW at 0.5s, and then restores to the initial value at 2.5s. Fig 6 are variation curves of the corresponding frequency and rotor inertia \( J \).

As can be seen from Fig 6, when the active power step varies, the system frequency rises first and then returns to the initial stable state. With the control method proposed in this paper, the rotor inertia \( J \) with self-adaptive control is larger than the initial value \( J_0 \) in the process of the system frequency \( f \) rising and deviating from rated value, and smaller than the initial value \( J_0 \) in the process of \( f \) reducing to the rated value.

![Fig 6. Simulation results of frequency and rotor inertia when active power reference changes](image)
5. Conclusion
This paper has proposed a self-adaptive control of rotor inertia for VSG on the basis of the conventional VSG control strategy, which can improve the frequency stability in an islanded microgrid. This control method regulates the value of rotor inertia $J$ adaptively and simultaneously according to the relationship between the angular velocity $\omega$ and its deviation and variation rate. At last, Simulation studies in MATLAB/Simulink indicates that the trend of change of angular velocity is more reasonable and practical under disturbance, thus the system stability has a further enhancement.

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References
[1] Yang, X., Song, Y., Wang, G., Wang, W. (2010) A comprehensive review on the development of sustainable energy strategy and implementation in china. IEEE Transactions on Sustainable Energy, 1(2): 57-65.
[2] LÜ, Z.P., Sheng, W.X., Zhong, Q.C., Liu, H.T., Zeng, Z., Yang, L., Liu, L. (2014) Virtual Synchronous Generator and Its Applications in Micro-grid. Proceedings of the CSEE, 34(16): 2591-2603.
[3] Cheng, C., Yang, H., Zeng, Z., Tang, S.Q., Zhao, R.X. (2015) Rotor Inertia Adaptive Control Method of VSG. Automation of Electric Power Systems, 39(19): 82-89.
[4] Driesen, J., Visscher, K. (2008) Virtual synchronous generators. In: IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century. Pittsburgh. pp. 1-3.
[5] Zheng, T.W., Chen, L.J., Chen, T.Y., Mei, S.W. (2015) Review and Prospect of Virtual Synchronous Generator Technologies. Automation of Electric Power Systems, 39(21): 165-175.
[6] Wu, H., Ruan, X.B., Yang, D.S., Chen, X.R., Zhong, Q.C., LU, Z.P. (2015) Modeling of the Power Loop and Parameter Design of Virtual Synchronous Generators. Proceedings of the CSEE, 35(24): 6508-6518.
[7] Chen, Y., Hesse, R., Turschner, D., Beck, H.P. (2011) Improving the grid power quality using virtual synchronous machines. In: International Conference on Power Engineering, Energy and Electrical Drives. Malaga. pp. 1-6.
[8] Zhong, Q.C., Weiss, G. (2011) Synchronverters: inverters that mimic synchronous generators. IEEE Transactions on Industrial Electronics, 58(4): 1259-1267.
[9] Du, W., Jiang, Q.R., Chen, J.R. (2011) Frequency Control Strategy of Distributed Generations Based on Virtual Inertia in a Microgrid. Automation of Electric Power Systems, 35(23): 26–31+36.
[10] Liu, J., Miura, Y., Ise, T. (2015) Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators. IEEE Transactions on Power Electronics, 31(5): 3600-3611.
[11] Alipoor, J., Miura, Y., Ise, T. (2013) Distributed generation grid integration using virtual synchronous generator with adoptive virtual inertia. In: IEEE Energy Conversion Congress and Exposition. Denver. pp. 4546-4552.
[12] Alipoor, J., Miura, Y., Ise, T. (2015) Power system stabilization using virtual synchronous generator with alternating moment of inertia. IEEE Journal of Emerging & Selected Topics in Power Electronics, 3(2): 451-458.