Functional Location Analysis of Inertia Support and Primary Frequency Modulation of Virtual Synchronous Generator in Power System

Zijiao Han¹, Yanfeng Ge¹, Zhengwen Li¹, Chenqi Wang², baoshi Wang, Jiapeng Wei*

¹State Grid Liaoning Electric Power Co., Ltd, Shenyang 110006, China
²Fuxin Power Supply Company, State Grid Liaoning Electric Power Co., Ltd, Fuxin 123000, China
*Corresponding author’s e-mail: 18640023515@163.com

Abstract. With the continuous improvement of renewable energy penetration, the inertia and primary frequency modulation capability of synchronous power grid are declining. If the virtual synchronous generator (VSG) technology is used for renewable energy generation, it can make due contribution to reducing the frequency variation and frequency deviation of the system under the impact of high power gap. The inertia support and primary frequency modulation function positioning in VSG research are not clear. In this paper, the inertia support function of VSG and its physical significance are analyzed, the expression of inertia support power of VSG is deduced, the location distinction between inertia support function of VSG and primary frequency modulation function is analyzed, and the different control function pairs of VSG in the process of large synchronous power grid frequency accident are simulated and analyzed, and study the effect of system frequency variation.

1. Introduction

In order to meet the demand of sustainable development of resources and environment, China has vigorously developed new energy power generation in recent years. The installed capacity of wind power and photovoltaic power continues to grow rapidly, and the contribution of new energy to power grids in some areas has exceeded 50%. Wind power and photovoltaic grid-connected inverters are static components without rotational inertia and can not spontaneously respond to frequency changes like synchronous machines. In order to maximize the use of energy, new energy units usually use the control method of tracking maximum power without providing effective backup, so they do not have the primary frequency modulation capability similar to synchronous machines when the system frequency changes. With the increasing proportion of DC power supply, the inertia and primary frequency modulation ability of synchronous power grid are declining, which brings risks to the frequency stability and recovery ability of the system under the impact of high power gap. Frequency problem is particularly prominent in the receiving power grid. In 2015, a bipolar blockade occurred in an UHVDC feeding into East China, resulting in an instantaneous loss of power of 5400MW, and in the lowest frequency of the system falling to 49.56Hz, which is the first time to fall below 49.8Hz and the frequency exceeding the limit for hundreds of seconds in nearly 10 years. It sounds an alarm for the frequency safety of power system under the new situation. Simulated synchronous machine rotor motion equation and primary frequency modulation are introduced into the network controller to make
the new energy unit have the external characteristics of synchronous generator unit such as inertia, damping, frequency modulation and voltage regulation, so as to improve the operation adaptability and safety and stability level of high proportion of new energy connected to the grid. This kind of control method can be collectively called "virtual synchronous generator (VSG) control. State Grid Corporation is vigorously promoting the application of VSG in power system. It will build the world's largest VSG demonstration project in Zhangbei Fengguang Storage and Transportation Base. At present, it mainly pays attention to the two functions of primary frequency modulation and inertia support. However, the current research on VSG inertia support and primary frequency modulation pays more attention to its own control strategy and response characteristics as well as its response in micro-grid and local grid. There is no relevant literature on the inertia support of VSG and the effect of primary frequency modulation on grid frequency under the scenario of power system access. Moreover, from the current process of formulating relevant standards, there are still some inconsistencies and unclear understandings between academia and industry on the functional positioning of VSG inertia support and primary frequency modulation and their specific applications in power system. In view of the above problems, the inertia support function and its physical significance of VSG are analyzed in depth at first, and the expression of inertia support power of VSG is deduced. Then, the functional requirements and physical significance of VSG primary frequency modulation are analyzed, and the location distinction between VSG inertia support function and primary frequency modulation function is discriminated in detail. Then, the inertia support function of VSG is established. The electromechanical transient simulation model supporting and primary frequency modulation function is presented. The effect of different control functions of VSG on the dynamic change of system frequency and the response characteristics of VSG in the process of large-scale receiving-end power grid frequency accidents are simulated and analyzed. Finally, the demand of VSG control function for large-scale receiving-end power grid is further clarified by combining theoretical analysis and simulation results.

2. Function and Physical Significance of VSG Inertia Support

2.1. Inertia Response of Synchronizer

The inertia support function of VSG is also called inertia response, but this paper emphasizes "support" because the inertia response of VSG is generally concerned with the function that the active power output by virtual synchronous generator responds to the frequency change rate of the system in the course of system frequency change (current source VSG can only simulate this function), but in fact, the overall inertia of synchronous generator is the only function that can be simulated by current source VSG. The response includes the following two aspects: 1. The response of the rotor state variables (power angle and frequency) to unbalanced torque. The frequency variation of the power grid is often caused by the impact of power imbalance (input and output power imbalance). In this process, all synchronous machines in the network will feel the effect of unbalanced power. Under the effect of unbalanced power (torque), the state variables of synchronous machines will be changed. The response can be described by the equation of motion of the rotor shown in equation (1).

\[
\begin{align*}
\frac{d\delta}{dt} &= (\omega - 1)\omega_0 \\
\frac{d\omega}{dt} &= \frac{T_m - T_e}{T_j} \approx \frac{P_m - P_e}{T_j}
\end{align*}
\]

(1)

In the formula, \( t \) is the time; \( \omega_0 \) is the rated angular velocity of the system; \( T_j \) is the inertia time constant of the rotor; \( \delta \) is the power angle of the rotor; \( \omega \) is the angular velocity of the rotor; \( T_m, T_e \), \( P_m \), and \( P_e \) are the mechanical torque, electromagnetic torque, mechanical power and electromagnetic power of the rotor, respectively. Except \( t \), \( \omega_0 \) and \( T_j \) are the nominal values, the others are all
standard unitary values. When the system frequency changes, the speed of each generator in the network basically changes synchronously. In this process, the kinetic energy of the generator rotor also changes accordingly. Assuming that the mechanical input power applied to the rotor remains unchanged, the variation of the rotor kinetic energy will be injected into the grid in the form of the electromagnetic power of the generator, which is the inertia support power. The following emphasis is put on pushing forward. The expression of inertia support power.

2.2. Expression of inertia support power for synchronous machine

When the system runs normally at the rated frequency, the kinetic energy \( W_k \) of the synchronous machine rotor rotating at the rated speed \( \Omega_N \) (i.e. synchronous speed) is as follows:

\[
W_k = \frac{1}{2} J \Omega_N^2
\]  

(2)

In the formula: \( J \) is the moment of inertia of the rotor, in \( \text{kg} \cdot \text{m}^2 \); \( \Omega_N \) is the rated mechanical angular velocity of the rotor.

According to the physical meaning of the generator rotor inertia time constant \( T_J \), \( T_J \) accelerates the rotor from the standstill state (mechanical angular velocity \( \Omega = 0 \)) to the rated state (mechanical angular velocity \( \Omega = \Omega_N \)), i.e. the time it takes for the rotor to accelerate from the standstill state to the rated state (mechanical angular velocity \( \Omega = \Omega_N \)).

\[
W_k = \int_0^{\bar{t}} T_J \Omega(t) \, dt = \int_0^{\bar{t}} \Omega(t) \, dt
\]

\[
= \frac{T_J}{2} \Omega_N^2 T_J = \frac{P_N}{2} \Omega_N^2
\]

(3)

\( P_N \) is the rated power of synchronizer. According to formula (3), the inertia time constant \( T_J \) of the rotor is as follows:

\[
T_J = \frac{2W_k}{P_N} = \frac{J \Omega_N^2}{P_N}
\]  

(4)

When the pole logarithm of the generator is 1 (e.g. turbo generator), the mechanical angular velocity of the rotor is \( \Omega \) equal to the angular velocity \( \omega \), and:

\[
T_J = \frac{J \omega_0^2}{P_N}
\]

(5)

For synchronous machines, when the rotational speed changes, the kinetic energy of the rotor changes, and the energy released or absorbed increases or decreases as the output electromagnetic power.

The rotational speed of the rotor at zero time be the rated rotational speed \( \omega_0 \), while at time \( t \), the change of the kinetic energy of the rotor, that is, the cumulative energy change of the output electromagnetic power at \( 0 \sim t \) time:

\[
\Delta E(t) = \frac{1}{2} J \left( \omega_0^2 - (\omega(t))^2 \right)
\]

(6)

The electromagnetic power output at time \( t \) is the differential of the energy.
\[ P_e(t) = \frac{d\Delta E(t)}{dt} = \frac{1}{2} J (0 - 2\omega(t)) \frac{d\omega(t)}{dt} \]
\[ = -J \omega(t) \frac{d\omega(t)}{dt} = -4\pi f(t) \frac{df(t)}{dt} \]

(7)

In formula \( f(t) \) is the instantaneous frequency of the system.

From Formula (5):

\[ J = \frac{P_N T_J}{\omega_0^2} = \frac{P_N T_J}{4\pi f_0^2} \]

(8)

In the formula: \( f_0 \) is the rated frequency of the system.

The formula (8) is substituted for formula (7), that is, the instantaneous electromagnetic power output by the change of rotor kinetic energy is expressed as follows:

\[ P_e(t) = -\frac{P_N T_J}{4\pi f_0^2} f(t) \frac{df(t)}{dt} = -\frac{P_N T_J}{f_0^2} f(t) \frac{df(t)}{dt} \]

(9)

Since the relative value of the frequency variation of the system is not too large (the absolute value exceeds 0.8Hz may cause the action of low frequency load shedding, while the relative value is only 1.6%), Therefore \( f(t) \approx f_0 \) the equation (9) can be simplified as follows:

\[ P_e(t) \approx -\frac{T_J}{f_0} \frac{df(t)}{dt} P_N \]

(10)

Formula (9) and Formula (10) are expressions of electromagnetic power released or absorbed by synchronous machine due to the change of rotor kinetic energy in the process of system frequency change, i.e. expressions of inertia support power needed to be simulated by VSG. This formula has been written into the State Grid Corporation's enterprise standard on VSG technical requirements and test methods (submission for approval).

It can be seen from formula (10) that the inertia support power of a synchronous machine is proportional to the inverse of the differential value of the system frequency (i.e. the frequency change rate), so it can be regarded as the differential feedback control of the system frequency. For the drastic change curve of a power grid frequency shown in figure 1, if the \( T_J = 8s \) of a synchronous machine in the power grid, the inertia support power output of the synchronous machine is obtained according to formula (9). The calibration power unification curve is shown in Fig. 2.

Fig. 1: Frequency changing curve of power system
As can be seen from Figure 2, the inertia support power is the largest at the initial moment when the frequency of the power grid drops rapidly. For the drastic change of the frequency shown in Figure 1, the maximum inertia support power can reach about 13% of the rated power of the machine. When the power grid frequency reaches the lowest point, the inertia support power is negative (during the frequency rise) and zero (after the frequency is stable). It is worth pointing out that, for the sake of equipment safety, if the inertia support power does not want to jump instantaneously, the first-order inertia link can be added to the equation (10) for buffer adjustment, as detailed in sections 4.1 and 4.2 below. The value of the first-order inertia link time constant must be coordinated with the virtual inertia time constant, and can pass through the time domain when the frequency curve of the system is given. True tuning buffer effect.

3. Function and Physical Significance of VSG Primary Frequency Modulation

3.1. VSG Primary Frequency Modulation Function Requirements
When the system frequency deviation is greater than (+0.03Hz) and the active power output of VSG is greater than 20% PN, VSG should be able to adjust the active output according to the frequency deviation and participate in primary frequency regulation of power grid. The specific requirements for VSG to participate in primary frequency regulation are as follows.

1) When the system frequency decreases, VSG should increase the active output, and the maximum value of active output can be increased by at least 10% PN.

2) When the system frequency rises, VSG should reduce active power output. The maximum reduction of active power output is at least 20% PN. When the output is reduced to 20% PN, the active power output of VSG can no longer be adjusted downward.

3) Considering the coordination with traditional units, the active frequency modulation coefficient $K_f$ of VSG (defined in Appendix A) is recommended to be 10-20.

4) Although the speed of VSG regulation can be faster, considering the coordination with traditional units, it should be recommended that VSG and the main indicators of primary frequency regulation performance of traditional units should be basically consistent, that is, the starting time of primary frequency regulation (the time to reach 10% target load) should not be more than 3s, the response time to reach 90% target load should not be more than 12s, and the adjustment of 95% target load should be achieved. The time should be no more than 30s. The primary frequency modulation power is proportional to the opposite number of the deviation value of the system frequency, so it can be regarded as the proportional feedback control of the system frequency.
3.2. Physical Significance of VSG Primary Frequency Modulation

The primary frequency modulation function of VSG is essentially the active-frequency droop control of VSG, which realizes the adaptive regulation of active output of VSG with the frequency variation of power grid system, and makes corresponding contributions to the new power balance point of power grid. It is worth pointing out that the system frequency of power grid is an important operating index reflecting the overall power gain and loss of AC network. The system frequency remains unchanged; the system frequency decreases when the power gap occurs in the power grid (e.g. when the generator drops off); when the power surplus occurs in the power grid (e.g. the sudden withdrawal of the large user load), the system frequency increases. For the voltage source VSG, the output electromagnetic power is not the target controlled quantity, so as for the real synchronous machine, the primary frequency modulation is realized by changing the input power command of the prime mover. For the current source VSG, the output current and electromagnetic power are the direct target controlled variables, so the primary frequency modulation can be realized by directly adding the primary frequency modulation power instructions on the electromagnetic power instructions, and the speed can be faster.

4. Simulation and Analysis of the Function of VSG on System Frequency and Its Response Characteristics in the Process of Power System Frequency Accident

4.1. Electromechanical Transient Modeling of VSG Inertia Support Function and Primary Frequency Modulation Function

As described in Section 1, the rigorous mathematical expression of inertia support function of VSG is shown in Formula (9) - Formula (10). However, as shown in Figure 2, for the virtual inertia time constant of 8s, the instantaneous output of inertia support power may reach more than 10% of the rated power at the moment when the system frequency drops sharply, and the instantaneous unbalanced torque may produce to the relevant components of fan equipment. Large torque impact is not conducive to the safe and stable operation of the fan. Therefore, when designing the inertia support control function of the fan, a first-order inertia link with a time constant of \( T \) (adjustable) is usually added after equation (10) to buffer it. The transfer function is shown in Fig. 3.

![Fig. 3 Transfer function of inertia support control of VSG for wind turbines](image)

Modeling of primary frequency regulation function is relatively simple, but it is worth pointing out that if energy storage is not considered, the premise of primary frequency regulation capability of fan is that the output of fan is reserved. The fan usually runs in the mode of maximum power point tracking (MPPT), that is, no reserve; and only at high wind speed, in order to prevent fan speed from breaking through the maximum speed limit, it has to be closed into constant. In power operation interval, it can be considered that there is a natural reserve of output; otherwise, in MPPT operation interval and constant speed operation interval of fan corresponding to low and middle wind speed, the maximum power tracking capability must be sacrificed by active propeller collection to obtain the reserve of output, otherwise there is no reserve.

4.2. Simulation and Analysis of the Function and Response Characteristic of VSG Different Control Functions on Frequency Change in Power Shortage Accidents of Power System

The electromechanical transient simulation model of VSG inertia support function and primary frequency modulation function is established in PSASP. Taking a large receiving-end power grid as an example, the regional power grid starts up about 208GW in a certain way. Considering the low frequency change rate of the system in the regional power grid, in order to observe the more significant inertia support power of VSG, the larger virtual inertia time constant TJ is 55s, and the
first-order inertia loop is taken as an example. The time-saving constant is 5.5s, and the primary frequency modulation coefficient Kf is 10. In the case of all real synchronizers and 12 000 MW doubly-fed fans in the regional power grid, the bipolar blockade occurs when the fault is set to a UHVDC, and the loss of 8 000 MW external power is about 3.58%. The simulation results show that the frequency variation curves of the system in the two cases are as shown in Figure 4.

![Fig.4 System frequency curve under serious active power shortage contingency in a large power grid](image)

As can be seen from Figure 4, in the case of pure synchronous machine system, the lowest point of the system frequency curve of the receiving end power grid is 49.59 Hz; in the case of the receiving end power grid with 12 000 MW doubly-fed fan system, the lowest point of the system frequency curve of the receiving end power grid is 49.53 Hz, which decreases by 0.06 Hz. Because the ordinary doubly-fed fan does not have inertia support and primary frequency modulation capability, the dynamic frequency curve of the system is the same. If the 12 000 MW fan is further transformed into VSG, Fig. 5 shows how to improve the frequency dynamic characteristics of power grid system under the same power gap impact, when the inertia support function of VSG and primary frequency modulation function are put into operation separately and jointly, respectively.

![Fig.5 Comparison among dynamic frequency curves corresponding to different control functions of VSG under serious active power shortage contingency in a large power grid](image)
From Fig. 5, it can be seen that the frequency dynamic characteristics of pure synchronous system are the best and the lowest frequency is the highest; the frequency dynamic characteristics of the system are the worst and the lowest frequency is the lowest in the case of ordinary doubly-fed fan with 12000MW; when the 12000MW fan is transformed into VSG and the inertia support control and primary frequency modulation control functions are put into operation, the frequency dynamic characteristics of the system are greatly improved, which is close to the original pure. Synchronizer system; if only the primary frequency modulation function is used, the frequency dynamic characteristics of the system will be greatly improved, which is very close to the original pure synchronous system; but if only the inertia support control function is used, the frequency dynamic characteristics of the system will be improved only before reaching the lowest frequency point, that is to say, the frequency change rate of the system will be delayed and the arrival of the lowest frequency point will be delayed. However, in the recovery process after the lowest frequency point, the frequency recovery characteristics of the system are deteriorated. Fig. 6 shows the electromagnetic power and mechanical power response of VSG when only inertia support control function is put into use. From Fig. 6, it can be seen that when only inertia support control function is put into use, VSG detects that the frequency of the system falls behind rapidly and generates electromagnetic power to realize inertia support. However, due to the absence of primary frequency modulation function (the fan is not reserved), the mechanical input power of the prime mover side of the fan cannot be increased. Under the forced action of inertia support electromagnetic power, the speed of the wind wheel will decrease rapidly, and because of the deviation from the optimal speed, the input mechanical power will also decrease, so the short-term electromagnetic power inertia support will have to be terminated, and even further reduction is needed. Low output electromagnetic power (lower than the power before the start of inertia support) is needed to avoid stall of the fan. Overall, the output energy needed to be reduced during the recovery process is higher than the output energy generated during the inertia support period (about 1.5-2.5 times of the support energy), and the power recovery time is longer than the power support time, which is why only inertia control is put into Figure 5. The reason for the deterioration of the frequency recovery characteristics of the system after the lowest point.

![Graph showing mechanical and electromagnetic power response of VSG](image)

**Fig.6** Power response characteristic of VSG only with inertia support control under serious active power shortage contingency in a large power grid

From the above simulation analysis, it can be seen that the inertia support function of VSG is not obvious for the frequency dynamic characteristics of power system in serious power shortage accidents, but the primary frequency modulation function is more obvious. This is because, as described in Section 3, the main purpose of inertia support function is to gain time for primary frequency modulation, while in large receiving-end power grids, due to the number of synchronizers in the network. There is a large amount of inertia, so the frequency change rate is relatively small. The time to reach the lowest frequency point is about 15 seconds. There is enough time for primary
frequency modulation to play its role. Adding inertia support is just a icing on the cake, and too much inertia will make the frequency drop of the system smaller in the same time, thus affecting the primary frequency modulation power of the unit in the system. It is not conducive to the restoration of system frequency. Therefore, for large-scale receiving-end power grids, the primary frequency modulation capability of VSG is more needed than the time effect of inertia support. On the contrary, it can be imagined that in small and medium-sized power grids and micro-grids, where inertia is relatively lack of new energy, the frequency of the system may drop rapidly when power shortage occurs. If there is no additional inertia support, 1. Frequency collapse may occur before the secondary frequency modulation power can be tuned out. In this case, the demand for VSG inertia support function and primary frequency modulation function will be more urgent.

5. Conclusion
1) The main function of inertia support is to provide short-term power support which can respond to the frequency change rate of the system and prevent the system frequency from falling rapidly, thus gaining time for primary frequency modulation, but it can not effectively suppress the frequency drop depth.

2) The main function of primary frequency modulation is to provide continuous active power support which can respond to the frequency deviation of the system, so as to prevent the continuous frequency drop of the system, and work with the frequency effect of the load, so that the system can achieve a new balance at a lower frequency level.

3) In large-scale synchronous power grid, the system inertia is relatively abundant, the system frequency change rate is small, and the frequency change process is gentle. With the access of renewable energy, the deterioration of the system frequency dynamic characteristics caused by the decrease of primary frequency modulation capability is more serious than that caused by the decrease of system inertia; therefore, the system needs VSG to play a more important role than the short-term inertia support power. Continuous support of primary frequency modulation power.

References
[1] L Zhipeng, SHENG Wanxing, ZHONG Qingchang, et al. Virtual synchronous generator and its applications in micro-grid [J]. Proceedings of the CSEE, 2014, 34(16) : 2591 – 2603.
[2] DIPESH K, KALYAN C. A review of conventional and advanced MPPT algorithms for wind energy systems [J]. Renewable and Sustainable Energy Review s,2016 (55): 957–970.
[3] DREIDY M, MOKHLIS H, MEKHILEF S. Inertia response and frequency control techniques for renew able energy sources: are view [J]. Renew able and Sustainable Energy Review s,2017( 69) : 144 – 155.
[4] LI Heming, ZHANG Xiangyu, WANG Yi, et al. Virtual inertia control of DFIG based wind turbines based on the optimal power tracking [J]. Proceedings of the CSEE,2012, 33(7) : 32 – 39.
[5] LI Dong,ZHANG Jiangbin. Analysis on the primary frequency modulation characteristics of the permanent magnet direct drive wind turbine generator [J].Qinghai Electric Pow er, 2016, 35( 1) : 36–42.
[6] MORREN J,DE HAAN S W H,KLING W L, et al. Wind turbines emulating inertia and supporting primary frequency control [J].IEEE Transactions on Power System, 2006, 21( 1) : 433–434.
[7] Wang Y, Xu L. Coordinated control of DFIG and FSIG-based wind farms under unbalanced grid conditions [J]. IEEE Transactions on Power Delivery, 2010, 25(1): 367-377.