Application of Virtual Synchronous Generator in Solar Power Generation

Jianjun Su¹, Wenbo Li¹, Hengjie Liu², Fanmin Meng², Long Wang³, Xueshan Han³

¹State Grid Shandong Electric Power Research Institute, China. ²State Grid Laiwu Power Supply Company, China. ³Key Laboratory of Power System Intelligent Dispatch and Control of Ministry of Education (Shandong University), Jinan, China.

Abstract. For the virtual synchronous control strategy of grid-connected inverters, the impact of the output response of the change of source is mainly analyzed, and the response time is calculated to lay a theoretical foundation for the system economic dispatch. First, the photovoltaic cell model is introduced, as well as the mathematical model and control strategy of the virtual synchronous generator. Then the optimal configuration of the source input is analyzed under different inertia and virtual damping conditions. The results show that the virtual inertia and damping coefficient of the inverter are closely related to the energy density and response time of the source input. Finally, a simple simulation model is given to observe the influence of the output change of the source on the response of the inverter output.

1. Introduction

With the large-scale consumption of new energy such as wind energy and photovoltaics, the system is facing a series of new challenges. The virtual synchronization technology is a major technological innovation and has been received significant attention at home and abroad recently.

An adaptive inertial control strategy is proposed that selects different rotor inertias based on the acceleration and slip of the virtual synchronous machine and verifies the state of its negative inertia[1]. A strategy adjusting the voltage and reactive power by adding excitation links is introduced[2]. In the literature[3], on the basis of the predecessors, the synchronverter scheme is proposed. The equivalent structural is analyzed and mathematical equations of the inverter and the synchronous generator are compared and analyzed. The control strategy inherited and developed and summarized the correlation of the virtual synchronous machine theory. In Literature[4], by detecting the frequency change rate in the transient process, the functional relationship of the frequency drop coefficient of the VSG droop is established, and the droop coefficient is adjusted according to the change of the frequency to reduce the frequency deviation in the transient process. Literature [5] studies the relationship between the magnitude and frequency of virtual inertia and gives a quantitative selection method of virtual inertia. Based on the small-signal model, the design principles of relevant parameters are proposed, and the adaptive control of virtual inertia is studied.

This article will be based on the above introduction, first we gives the photovoltaic cell model, introduces the basic principle of the virtual synchronous generator; then we gives the second-order model of the virtual synchronous machine, and analyzes its response time; Finally, we gives the simulation results, changes Irradiation and other sources of input to verify the system output response time.
2. Photovoltaic model
The output current of the photovoltaic cell according to the KCL law is:

\[ I = I_{ph} = I_{sc} - I_s - I_d \]

\[ I_{ph} = I_{sc} \left( \frac{S}{1000} + K_0 (T - T_{ref}) \right) \]

\[ K_0 = \frac{I_{sc(T2)} - I_{sc(T1)}}{T_2 - T_1} \]

\[ I_d = I_0 (e^{\frac{q(E_q + IR)}{T_{ref}}} - 1) \]

\[ I_0 = I_{do} \left( \frac{T}{T_{ref}} \right)^3 e^{\frac{qE_q}{ak(T_{ref} - 1/T)}} \]

\[ I_r = \frac{(U + IR)}{R_{sh}} \]

Formula (1)~(6) is the mathematical model of single diode photovoltaic cell. Where, \( I_{sc} \) for the short-circuit current, A; \( I_{do} \) for the diode reverse current, A; \( S \) for the irradiation intensity, W/m²; \( T \) for the battery surface temperature, K; \( \alpha \) for the diode quality factor; \( q \) for the electronic power, \( 1.602 \times 10^{-19} \); \( E_q \); \( k \) for the Boltzmann constant, \( 1.38 \times 10^{-23} \); for the Boltzmann constant, J/K; \( E_s \) With energy constants, eV.

Photovoltaic cells form a photovoltaic array through series and parallel connection. The relationship between output voltage and current is as follows:

\[ I = N_p I_{ph} - N_p I_s \left\{ \exp \left[ \frac{q}{akT} \left( \frac{U}{N_s} + \frac{IR}{N_p} \right) \right] - 1 \right\} - \frac{N_p}{R_{sh}} \left( \frac{U}{N_s} + \frac{IR}{N_p} \right) \]

Where, \( N_p \) represents the number of batteries in series and \( N_{sh} \) represents the number of parallel batteries.

3. VSG model
Taking the VSG's terminal connection point as the common coupling point, the renewable energy can be equivalent to the traditional prime mover, the energy storage unit can be equivalent to the traditional steam engine, and the grid-connected inverter can be equivalent to the traditional synchronous generator.

Traditional synchronous generators include second-order, third-order, fifth-order, and seventh-order mathematical models. Here, only the simplest second-order electromechanical model analysis is considered. The key to the second-order model is the rotor motion equation and the electromagnetic equation.

3.1. Electromagnetic equation
The electromagnetic equation of a virtual synchronous generator is

\[ L \frac{di_{abc}}{dt} = e_{abc} - u_{abc} - Ri_{abc} \]

Where, \( L \) represents the synchronous inductance of the synchronous generator, H; \( R \) represents the synchronous resistance of the synchronous generator, \( \Omega \); \( e_{abc} \) represents the internal potential, \( V \); \( u_{abc} \) represents the terminal voltage of the synchronous generator, \( V \).

The virtual synchronous generator's virtual potential consists of three parts. \( E_0 \) is the no-load voltage of the virtual synchronous generator; the second is the reactive power regulation part \( E_r \), expressed as
\[ \Delta E_a = k_q (Q_{ref} - Q) \]

Where, \( k_q \) represents the reactive power adjustment coefficient; \( Q_{ref} \) is the reactive power instruction of the grid-connected inverter; \( Q \) is the instantaneous reactive power value output by the machine.

\( \Delta E_a \) is the output voltage of the terminal voltage regulator unit, which is equivalent to the excitation regulator or automatic voltage regulator of the synchronous generator, which can be simplified as a proportional element.

\[ \Delta E_a = k_u (U_{ref} - U) \]

Where, \( k_u \) indicates the voltage adjustment coefficient; \( U_{ref} \) and \( U \) are the command value and the real value that represent the effective value of the terminal voltage.

The analogy of the inverter filter to the virtual impedance of the synchronous generator has some problems. The parameter design of the filter needs to consider factors such as reactive power, voltage drop and the like, and at the same time, parameter drift occurs, which is related to the parameter design in the control model. There is some error.

3.2. Mechanical equation

The mechanical equation of the virtual synchronous generator is

\[
J \frac{d\omega}{dt} = T_m - T_e - T_d = T_m - D(\omega - \omega_0)
\]

Where, \( J \) represents the moment of inertia, \( kgm^2 \); the mechanical angular velocity of the synchronous generator \( \omega \) is equal to the electrical angular velocity; \( \omega_0 \) is the synchronous angular velocity of the power grid, \( rad/s \); \( T_m, T_e, T_d \) are the mechanical torque, electromagnetic torque, and damping torque of the synchronous generator, respectively; \( D \) is the damping coefficient, \( Nms/rad \).

The electromagnetic torque of a virtual synchronous generator \( T_e \) can be calculated from the virtual synchronous generator voltage and current

\[
T_e = P_e / \omega = (e_i a + e_i b + e_i c) / \omega
\]

Where, \( e \) indicates the air gap electromotive force, \( V \); \( i \) represents the output current, \( A \); \( P_e \) represents the output electromagnetic power of the virtual synchronous generator.

3.3. Inertia and damping

The moment of inertia of a synchronous generator is a physical quantity, and inertial time constant \( H \) is generally used to measure the inertia of synchronous generators of different sizes and power levels. \( H \) is defined as

\[
H = J \omega_0^2 / S_n
\]

Where, \( S_n \) represents the rated capacity of the synchronous generator; \( H \) represents the time that the synchronous generator is at nominal torque from no-load start to the rated speed. Based on the concept of the inertial time constant, the second-order model of the synchronous generator is obtained from the above equation:

\[
\begin{cases}
\dot{\delta} = \omega_0 \omega_r \\
H \dot{\omega}_r = T_m - T_e - D_p \omega_r = P_{ref} - P_e - D_p \omega_r
\end{cases}
\]
the system asterisk indicates the standard system, \( \omega_0 = (\omega - \omega^*_0) / \omega^*_0 \) indicates the speed difference; the torque reference value is \( T_m = S_n / \omega^*_0 \). In addition, \( D_p = D \omega^*_0 / S_n \), the relationship between power and speed is \( P^* = T^* \omega^* \).

In general, due to the physical conditions of the synchronous generator, the inertial time constant of different generator sets different in several seconds. The inertial time constant of the virtual synchronous generator is a function related to the virtual inertia. It has the characteristics of flexible and variable, and it has the advantages of the adjustment range that the traditional synchronous machine does not have. It can realize the adjustment of different time scales. The problem is that the choice of inertial time constant and the dynamic response time of the virtual synchronous generator DC power supply should match. For example, the inertia time constant of the wind turbine is second level, and the dynamic time constant of the photovoltaic cell is millisecond level. The dynamic constant of the energy storage battery varies due to different properties.

According to the single-machine infinite-bus system, the output of active power and reactive power of a virtual synchronous generator can be expressed as:

\[
\begin{align*}
P^*_e &= \frac{EU}{Z}\cos(\alpha - \delta) - \frac{U^2}{Z}\cos\alpha \\
Q^*_e &= \frac{EU}{Z}\sin(\alpha - \delta) - \frac{U^2}{Z}\sin\alpha
\end{align*}
\]

Where, the impedance \( Z \) of the filter inductor and the impedance angle \( \alpha \) are:

\[
\begin{align*}
Z &= \sqrt{(\omega L)^2 + R^2} \\
\alpha &= \tan^{-1}\left(\frac{\omega L}{R}\right)
\end{align*}
\]

According to the second-order virtual synchronous generator model obtained by analogy, the small-signal analysis model of the virtual synchronous generator can be obtained by referring to the small-signal model analysis method of the conventional synchronous generator. From the foregoing, we can see that the second-order electromechanical model adopted in this paper can be used to derive the second-order transfer function of the input and output power response characteristics of a virtual synchronous generator:

\[
G(s) = \frac{P^*_e}{P^*_m} = \frac{\omega_0 S_E / H}{s^2 + (D_p / H)s + \omega_0 S_E / H}
\]

Where, \( S_E \) is the standard value of the synchronous power,

\[
S_E = \frac{\partial P^*_e}{\partial \delta} = \frac{E_U}{S_n Z} \sin(\alpha - \delta)
\]

Where, \( E_s \) and \( \delta \) are the stable operation equilibrium points related to the active power and reactive power obtained by the power equation derivation. Since the filter inductance parameters are known and the grid voltage \( U \) is constant, the solution can be solved

\[
\begin{align*}
\delta &= \alpha - \tan^{-1}\left(\frac{Q_{ref} + U^2 \sin \alpha / Z}{P_{ref} + U^2 \sin \alpha / Z}\right) \\
E_s &= \frac{Q_{ref} Z + U^2 \sin \alpha}{U \sin(\alpha - \delta)}
\end{align*}
\]

It can be seen that in the case of a given active power command, \( S_E \) is a constant, which the natural oscillation angle frequency and damping coefficient of the second-order model can be derived.
4. Simulation
In MATLAB/Simulink, a simulation model for photovoltaic cells directly connected to the VSG is built. The simulation parameters are shown in the table. The simulation process is as follows: 0.3s simulated cloud shelter, lighting is reduced from 1000 $W/m^2$ to 350 $W/m^2$, temperature is maintained at 40°C; 1.4s is simulated in the evening, light and temperature are simultaneously decreased, light is reduced from 1000 $W/m^2$ to 800 $W/m^2$, temperature is decreased from 40°C to 35°C, 1.8s light fell to 200 $W/m^2$, the temperature dropped to 30 °C.

\[
\begin{align*}
\omega_n &= \sqrt{\omega_0 S_E / H} \\
\xi &= 0.5 D \sqrt{1 / (\omega_0 S_E H)}
\end{align*}
\]
It is not difficult to find from the figure that the input light and temperature changes, the uncertainty of photovoltaic output is simulated, and the dynamic tracking response at the output end of the photovoltaic cell exhibits certain volatility, and the voltage tracking effect is slightly different. The power tracking effect basically conforms to the light curve. Simulation results show that the tracking time is around 0.1. Observed from the VSG output terminal, taking the DC input as a reference, its power tracking effect is good, and the response time is about 0.01s.

5. Conclusion
From an engineering point of view, the current photovoltaic application scenario is basically a direct grid-connected storage without energy storage. In the foreseeable future, because the cost of energy storage batteries is high, photovoltaic batteries directly connected to the virtual synchronous control inverter are the most possible options. It is necessary to study the inverter tracking effect of photovoltaic directly connected to the virtual control. From the perspective of the dynamic time, the time range of the scheduling given by the uncertainty output at the source is analyzed, and the time reference value of the dynamic scheduling is given.

In the next step, we will continue to use the second-order model to analyze the changes in the input of the step at the source, the voltage response range and the power response range of the system, and then provide the constraint range of the real-time scheduling of the inverter.

References
[1] Alipoor, J., Y. Miura and T. Ise, 2015, Power System Stabilization Using Virtual Synchronous Generator With Alternating Moment of Inertia, IEEE Journal of Emerging and Selected Topics in Power Electronics. 3(2): 451-458.
[2] Chen, Y., et al., 2012, Comparison of methods for implementing virtual synchronous machine on inverters. Renewable Energy and Power Quality Journal, 734-739.
[3] Zhong, Q. and G. Weiss, 2011, Synchronverters: Inverters That Mimic Synchronous Generators. IEEE Transactions on Industrial Electronics. 58(4): 1259-1267.
[4] Soni, N., S. Doolla and M.C. Chandorkar, 2013, Improvement of Transient Response in Microgrids Using Virtual Inertia. IEEE Transactions on Power Delivery. 28(3): 1830-1838.
[5] Cheng Chong, Yang Huan, Zeng Zheng, et al, 2015, Rotor inertia adaptive control method of VSG, Automation of Electric Power Systems. 39(19):82-89(in Chinese)