Research on Simulated Inertia Coordination Control Strategy of VSG Based on Energy Storage

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Abstract. With the development of new energy and micro grid, inverter plays an important role as the interface of distributed new energy to realize power conversion. However, the introduction of various power electronic components not only enhances the response speed and flexibility of the micro grid, but also greatly reduces the overall inertia of the system. VSG control technology is introduced in this paper. At the same time, through the in-depth analysis of energy storage system, the inertial parameters of energy storage system are deduced. The VSG control and the energy storage system inertial parameters are matched to increase the system inertia and damping. Aiming at the power response part of multi-machine system, the inertial parameters of multi-machine system are controlled uniformly, which makes the whole system achieve good power response and distribution. At last, a simulation model was set up by MATLAB for verification and analysis.

Introduction

With the development of new energy sources, various distributed power generation and distributed energy storage are continuously connected to the power system. However, a large number of distributed systems with power electronic devices as interfaces improve the system's rapid response and flexibility, while also reducing the overall inertia of the power system. The reduction of the overall inertia of the system has a major impact on the frequency stability and power fluctuations of the grid, and it is easy to cause system power oscillations and frequency deviations. Therefore, scholars of various countries have conducted extensive research on the control strategy of converter and off-grid. The classic control strategy of the inverter mainly includes PQ control, Vf control and droop control, and the improved control strategy based on this. In recent years, some scholars have proposed a virtual synchronous generator control strategy, which has aroused widespread concern and research. The so-called virtual synchronous generator control refers to the mechanical and electromagnetic characteristics of synchronous generator introduced into the converter control strategy by taking advantage of the rapidity of power electronic interface converter. Finally, the power electronic converter also has the excellent characteristics of synchronous generator, which provides voltage and frequency support for the system. Reference [1-2] mainly studied the principle of virtual synchronous generator control technology and its parameter characteristics, and analyzed and verified the off-grid mode and grid-connected mode. Reference [4-7] mainly improves the stability of the virtual synchronous generator control. In the improvement of system inertia, most of the energy storage elements such as inductance and capacitance of DG are adopted, and DC voltage source is adopted at DC side. Reference [8-10] introduced energy storage units in the control of virtual synchronous generator to improve the system inertia, and only analyzed the power and energy demand of the control system for the energy storage system. Reference [11] analyzed the inertial nature of energy storage system and verified its conclusions by combining with single-machine VSG system. But the problem of multi-machine system is not considered. Reference [12-14] analyzed the power distribution of multi-machine VSG control system and simplified the
treatment of dc side. In view of the above problems, this paper combines the inertia parameters of the energy storage system with the inertia parameters of the virtual synchronous generator control system. Through the analysis of the multi-machine system, the coordinated control of the multi-machine simulated inertia is achieved.

Inertial Analysis of Energy Storage System

Nature of Inertial Characteristics

In physics, it is pointed out that inertia is the property of a body to maintain static or uniform motion in a straight line, and is the inherent property of an object, which is manifested as the degree of resistance of the object to its movement state. Let an object moving in a straight line have a mass of \( m \) and a velocity of \( v \). It is known from Newton's second law:

\[
f_d - f_L = f_d - kv = m \frac{dv}{dt}
\]

(1)

Where, \( f_d \) is the traction force, \( f_L \) is the resistance (\( f_L = kv \), \( k \) is the damping coefficient). Solving the first-order linear ordinary differential equation, the velocity \( v \) of the object is:

\[
v = \frac{f_d}{k} + (v_0 - \frac{f_d}{k})e^{-\frac{kt}{m}}
\]

(2)

Where, \( t \) is the time when the object moves. The starting time is \( t=0 \). \( v_0 \) is the initial velocity of the object. It can be seen from the analysis of equation (2) that, due to the existence of exponential function, the object velocity cannot be abrupt at the moment of sudden change of traction, but continues to transition to the steady-state value. It is because of the inertia of the object itself that the velocity cannot be mutated, and the process of velocity change is affected by the inertial mass.

So mass is a measure of inertia. Which is:

\[
J_{z-eq} = m
\]

(3)

Similarly, for a rotating object, it is learned by physics:

\[
J_{x-eq} = mr^2
\]

(4)

Where, \( J_{z-eq} \) is the moment of inertia of a linear moving object, and \( J_{x-eq} \) is the moment of inertia of a rotating moving object.

Energy Storage System Inertia

Inertia is an intrinsic property of an object, and each object has inertia. The energy storage system also has its inertia as a storage unit of electrical energy, and the electrical energy is generally stored by electric field energy or magnetic field energy. In this paper, the general battery storage energy is taken as an example for analysis. The principle is to store electric energy through electric field energy. The energy storage system is equivalent to a capacitor \( C \), the initial voltage is \( u_0 \), and its charging and discharging circuit is as follows:

![Figure 1. Energy storage system equivalent diagram.](image)

Where, \( u_s \) is the voltage step signal and \( R \) is the circuit resistance. Then the equation for the voltage \( u \) across the capacitor is:
\[
C \frac{du}{dt} + \frac{1}{R} u = \frac{1}{R} u_s
\] 

According to the first-order response expression, the variation of the voltage \(u\) across the capacitor with time is known:

\[
u = u_s + (u_0 - u_s) e^{-\frac{1}{RC} t}
\]

Comparing equation (2), it can be found that the capacitance voltage \(u\) and the velocity \(v\) have the same property, and the capacitance is a determining factor of the speed of change. The linear motion object velocity, the rotational motion object angular velocity, and the capacitance voltage variation characteristics are compared and analyzed, and they have the same characteristic equation. Therefore, for an energy storage system in which the capacitor is a storage medium, the capacitance is a measure of the magnitude of its inertia. Therefore, for a capacitive energy storage system, such as an energy storage battery, the inertia is the equivalent capacitance \(C_{eq}\) under the rated condition, as shown in equation 7.

\[
C_{eq} = \frac{2S_{CN}}{U_{CN}^2} = \frac{2I_{CN}T_{CN}}{U_{CN}}
\]

Where, \(S_{CN}\) is the rated capacity of capacitive energy storage system, \(U_{CN}\) is rated voltage, \(I_{CN}\) is rated current, and \(T_{CN}\) is rated charge-discharge time.

Similarly, according to the law of conservation of energy, the equivalent rotational inertia \(J_{c_{eq}}\) of energy storage system can be obtained. Because the energy of the actual energy storage system is changing, the effect of SOC and charge-discharge rate of the energy storage system on its equivalent rotational inertia must be considered. In the actual control system, SOC is usually set within a reasonable working range to meet the energy demand of the equivalent rotational inertia of the energy storage system. Therefore, the charge-discharge rate can only be considered. Namely, the equivalent rotational inertia of the energy storage system is:

\[
J_{c_{eq}} = C_{eq} \frac{U_{CN}^2}{\omega^2} C_{max}
\]

Where, \(C_{max}\) is the maximum charge-discharge rate of energy storage battery, and \(\omega\) is the rated angular frequency of the energy storage system access system.

**Multi-Machine Analysis of VSG**

**Principle of VSG Control**

The virtual synchronous generator control is mainly to introduce the principle of synchronous motor in the inverter control loop, so that the inverter presents the characteristics of the synchronous machine. The overall control structure of the virtual synchronous generator is shown in Figure 2.

![Figure 2. Overall control structure of virtual synchronization machine.](image-url)
The main circuit of the system consists of energy storage battery, voltage type three-phase bridge inverter, LC filter circuit and load. In the control loop, the output voltage and current of the main circuit are first collected, and the modulation signal is produced by the virtual synchronous generator control strategy. Finally, the three-phase inverter is controlled by the SPWM to generate a switching signal.

On the control strategy of virtual synchronous generator, this paper adopts the classical second-order model of synchronous generator for modeling, and its electrical and mechanical equations are as follows:

\[
\begin{align*}
J \frac{d(\omega - \omega_N)}{dt} &= \frac{P_m}{\omega} - \frac{P_e}{\omega} - D(\omega - \omega_N) \\
\dot{E} &= \dot{U} + \dot{I}(r_a + jx_a)
\end{align*}
\]  

where, \( J \) is the moment of inertia, \( \omega \) is the electrical angular velocity, \( \omega_N \) is the rated angular velocity, \( P_m \) is the mechanical power, \( P_e \) is the electromagnetic power, \( D \) is the constant damping coefficient, \( \dot{E} \) is the excitation electromotive force, \( \dot{U} \) is the stator terminal voltage, \( \dot{I} \) is the armature current, \( r_a \) is the stator armature resistance, and \( x_a \) is the synchronous reactance. The specific control block diagram is shown in figure 3.

![Figure 3. Architecture of VSG control strategy.](image)

As can be seen from figure 3, the control strategy of the inverter introduces the characteristics of synchronous machine's rotation inertia \( J \) and large damping. Matching it with the equivalent rotational inertia of energy storage system can not only reduce the resource waste caused by over-allocation of energy storage system capacity, but also optimize system control to achieve good response. The equivalent moment of inertia of the whole system is mainly determined by the equivalent moment of inertia of the energy storage body and the inverter system. It is known from reference [11] that the overall inertia of the system depends on the minimum of the two.

**Analysis of VSG Multi-Machine Parallel**

For the parallel operation of multi-machine system, under the premise of the matching of single-machine VSG control and energy storage inertia parameters, this paper takes two-machine system as an example for analysis. Figure 4 shows the parallel connection diagram of two VSGs.

![Figure 4. VSG multi-machine parallel diagram.](image)

The fluctuation (or change) of the load power will result in the change of the system frequency. When the power generation units in the system are completely consistent, the system divides the power and changes the same frequency. However, in practice, each distributed unit always has different capacity levels and differences, which inevitably leads to a difference in frequency
response speed, and thus the frequency fluctuation is too large or oscillates. In this paper, the energy storage is used to increase the inertia of the system, and the inertia of the energy storage and the inertia parameters of the VSG control are combined. Through the reasonable inertial parameter matching between multiple machines, the frequency response of distributed power sources with different capacities is achieved, and the transient stability of the system is enhanced.

According to the mechanical equation in equation (9), when the system is stable, the difference between $\omega$ and $\omega_n$ is small, and the difference is ignored. There are:

$$2H \frac{d\omega}{dt} = P_m - P_e$$

(10)

Where, $H = J\omega_s^2/(2pS_n)$, $p$ is the number of poles of the virtual synchronous generator, and $S_n$ is the rated capacity of the virtual synchronous generator.

![Figure 5. VSG frequency characteristic curve.](image)

Before and after the disturbance occurs, the system works at two points A and C respectively, including:

$$2H \frac{d\omega}{dt} = P_{mA} - P_{eA}$$

(11)

$$2H \frac{d\omega}{dt} = P_{mC} - P_{eC}$$

(12)

Combined with the VSG active adjustment link.

$$\Delta \omega = -D_p \Delta P$$

(13)

When the system load power changes, that is, $P_{eA}$ changes to $P_{eC}$, and at this time, $P_{mA}$ and $P_{mC}$ do not change, so

$$P_{eC} = P_{eA} + \Delta P = P_{mA} + \Delta P$$

(14)

The simultaneous (11) and (14) are:

$$2H \frac{\Delta \omega}{\Delta t} = -\Delta P$$

(15)

From equation (13) and equation (15):

$$\Delta t = 2HD_p$$

(16)

Therefore, when the multi-machine VSGs are operated in parallel. To make all VSG inverters have the same transition time, the inertial time constant $H$ and droop coefficient $D_P$ of each VSG inverter are configured inversely.

**Verification Analysis**

According to the above analysis, in order to verify the control effect between multi-machine energy
storage simulation inertia, two VSG control simulation models based on energy storage system are built in MATLAB/Simulink. In order to make the two VSGs have the same time, the inertia time constant $H$ and the droop coefficient $D_P$ are arranged in inverse ratio. The energy storage system takes the battery as an example, and its rated parameter configuration and VSG inertia parameters are consistent. The capacity of the two VSG systems is equal to 10kW respectively. The VSG virtual moment of inertia $J$ is $0.5 \text{kg} \cdot \text{m}^2$, the energy storage system voltage is 800V, and the capacity is 30Ah. The system starts from $t=0$, and starts to supply power to the load. When $t=2s$, the load side increases 4kW disturbance. The system frequency and power curve are shown in Figure 6.

![System frequency curve](image1)

![System power curve](image2)

Figure 6. System frequency and power curve.

As can be seen from the system frequency curve, the system frequency quickly reaches steady state. When $t=2s$, the active power of the system increases, the frequency decreases, and the two units of VSG1 and VSG2 are synchronized. The frequency of the two units is only slightly deviated in a small range, almost completely coincident, and the error can be ignored. At the same time, the frequency slowly changes to a steady state value due to system inertia support. In the same way, the system's active power is equally divided. The two units share 2kW active power when load power increases.

**Conclusion**

In this paper, energy storage is introduced into the system to solve the problem of reducing inertia and affecting system stability caused by a large number of new energy access systems. Combining the inertia of energy storage system and the inertia of VSG control system, the simulation verification is carried out by analyzing the power distribution of multi-machine system and taking the inertial coordination control of system as the target. The results show that the overall inertia of the system is obvious and the VSG power is reasonably distributed and coordinated.

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**References**


