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Grid connection method of gravity energy storage generator motor based on voltage index sensitivity analysis

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Abstract

The basic requirements for the grid connection of the generator motor of the gravity energy storage system are: the phase sequence, frequency, amplitude, and phase of the voltage at the generator end and the grid end must be consistent. However, in actual working conditions, there will always be errors in the voltage indicators of the generator and grid terminals, resulting in transient impulse currents. In addition, due to the difference between gravity energy storage systems and conventional power generation units, frequent switching between charging and discharging operating conditions is required according to the needs of the power grid. Each switching requires the completion of the generator motor startup and grid connection. If there is always a significant error in the voltage indicators between the generator and grid terminals during frequent grid connection, stable transient surge currents will be generated. Without human intervention, long-term operation will bring hidden dangers to the safety of the grid connected system, leading to a series of consequences such as equipment aging and even damage. In response to the above issues, this article establishes a gravity energy storage power generation/motor grid connection model. Through simulation analysis, the variation law of the weight of the impact of different terminal voltage indicators on the grid connected transient impulse current is summarized. A grid connection method for gravity energy storage systems based on sensitivity analysis of voltage grid connection indicators is proposed. Through simulation verification, this method can significantly reduce the grid connected transient impulse current while improving the success rate of grid connection, The correctness and practicality of the proposed method have been fully verified.

Keywords: Gravity energy storage, Motor grid connection, Transient impulse current, Data processing, Indicator optimization

Introduction

The electrical power system is one of the indispensable infrastructures in modern society for production and daily life. With the rapid development of the social economy, the demand for the reliability of the electrical power system has been increasing. In order to ensure the safe and stable operation of the electrical power system, backup power sources are an essential part of it (Chen et al. 2019). Gravity energy storage, as a physical energy storage method, is characterized by its inherent safety, flexible site selection, zero self-discharge rate, large energy storage capacity, and high discharge depth, and has attracted increasing attention in recent years (Li et al. 2021). Moreover, in the current context of increasing demand in the energy storage market and global decarbonization, gravity energy storage, which can rival pumped hydro storage, has enormous development prospects, with a significant global market potential over the next decade (Xia et al. 2022; Liu et al. 2023a).

Gravity energy storage is a mechanical energy storage system, and its energy storage media can be either water or solid materials. It achieves energy storage by raising and lowering energy storage media based on a significant height difference, which is used in the charging and discharging processes. The fundamental principle of gravity energy storage is to store gravitational potential energy by lifting heavy objects when surplus electricity is available and releasing these heavy objects to drive generators for electricity generation when needed (Song et al. 2022). Water-based gravity energy storage is easier to establish near natural water sources due to its dependence on terrain and water availability. Tong et al. (Tong et al. 2023) introduces gravity energy storage based on solid materials, mainly involving high-density materials such as metal, cement or gravel, and relying on mountains, underground shafts or artificial buildings to lift and lower heavy objects.

Although the demand for energy storage continues to grow, scalable energy storage technologies like pumped hydro storage and chemical batteries face significant challenges in terms of scalability, levelized cost, safety, and environmental risks (Haider et al. 2020). Therefore, in the context of global decarbonization, gravity energy storage, with its high safety and environmental friendliness, becomes one of the most promising energy storage technologies. Additionally, for regions like the "Three-North" areas in China with abundant wind and solar resources but limited water resources, solid-material-based gravity energy storage systems are an optimal choice. Berrada and Loudiyi (2016) analyzed the related problems of gravity energy storage modeling and material selection through finite element analysis. The safety and sustainability of materials and the low construction cost make the gravity energy storage technology based on solid materials promising to develop into a large-scale, low-cost and safe power system energy storage solution.

Gravity energy storage grid integration technology refers to connecting gravity energy storage systems distributed at different locations with other electrical facilities to form a large-scale power grid, enabling the exchange and sharing of electrical power. This integration is a crucial aspect of the operation of gravity energy storage systems (AlZohbi 2023). When integrating gravity energy storage into the grid, it is essential to ensure that the generator/motor end voltage of the gravity energy storage system matches the grid voltage in terms of phase sequence, phase angle, amplitude, and frequency to ensure the safety and stability of the entire system after synchronization. Guo et al. and Dovgalyuk et al. (2022, 2021) introduced the method and operation characteristics of flywheel energy storage connected to the grid via converter, and made a detailed analysis of the application prospect of gravity energy storage system. Due to the different startup and grid connection modes of the gravity energy storage generator/motor, as well as the deviation of the control system, in the actual gravity energy storage system, there is always a certain degree of error between the generator terminal and the grid terminal voltage, resulting in the impact of transient impulse current on the power quality and stability of the grid power supply. Furthermore, since gravity energy storage system generator/motor units differ from conventional generator units, they need to switch frequently between charging and discharging modes according to grid demand. If there is a significant error in voltage indicators at both the machine end and grid end during frequent synchronization, stable transient surge currents may occur. Without intervention and control, this could pose a safety risk to the grid system and lead to a series of problems, including equipment aging and damage, during long-term operation.

To address these issues, this paper proposes a grid connection method for gravity energy storage power generation motors based on voltage index sensitivity analysis. Through simulation verification, this method improves the success rate of grid integration for gravity energy storage generators/motors, achieves precise processing of synchronization indicator data, effectively suppresses transient surge currents during synchronization, and enhances the power quality of the grid supply.

Problems of gravity energy storage system directly connected to the grid

Composition of gravity energy storage system

Taking the tower crane gravity energy storage system (T-GESS) as an example, the main components, operation mode and physical and electrical characteristics of the tower crane gravity energy storage system are briefly analyzed. The operation mode of gravity energy storage system is described as follows:

As shown in Fig. 1, the main components of the vertical gravity energy storage system include the tower crane jib, electric generator, stacked mass energy reservoir, control center, support tower, cables, and more. When there is surplus electrical energy in the grid, the control center operates the tower crane jib to precisely lift the mass located at

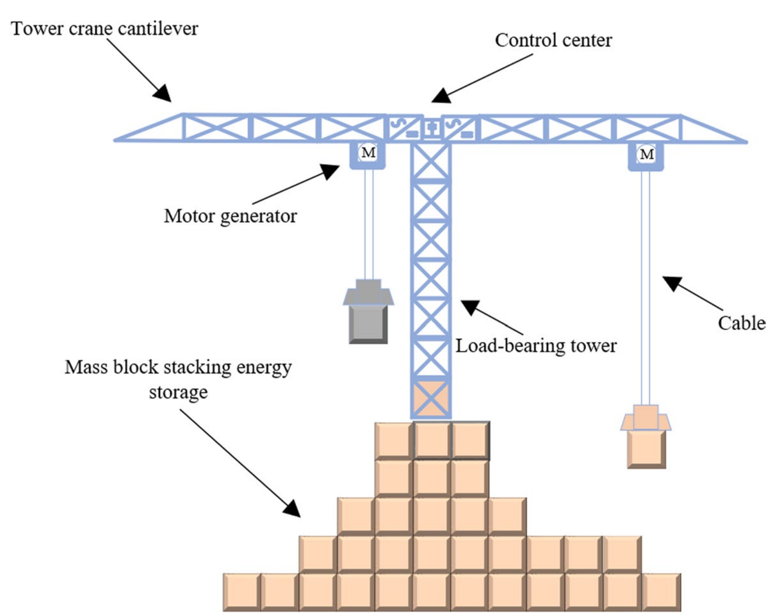

Fig. 1 Vertical gravity energy storage system

a lower position and stack it on top of the masses at a higher position. As the height of the stacked mass increases, the gravitational potential energy stored in it also increases. Meanwhile, the electric motor used to move the mass consumes excess electrical energy from the grid, converting electrical energy into gravitational potential energy. When there is an energy deficit in the grid, the masses are lowered to a lower position via the cables, driving the electric generator to produce electricity. This conversion utilizes the stored gravitational potential energy to feed energy back into the grid, compensating for the energy shortfall in the grid.

Gravity energy storage system also has the following physical characteristics.

The output power of the system is positively correlated with the number of mass blocks in online operation. However, due to the discrete distribution of mass blocks, the output power adjustment achieved in this way is stepped. In addition, when the mass block enters the track, the sudden increase of the rail force will bring impact to the mechanical structure of the system, resulting in vibration and noise. Furthermore, the impulse current generated by sudden power change will have adverse effects on the force and temperature rise of electrical components.

On the other hand, the output power of the system in the power generation state is also positively related to the running speed of the mass block, and the stepless adjustment can be achieved instead of the step adjustment. However, for the gravity energy storage using synchronous motor, the adjustment of the running speed of the mass block depends on the high-performance transmission device, which is relatively difficult to achieve. For the gravity energy storage using doubly-fed induction motor, the rotor side converter can be controlled by stator field oriented vector control to control the motor speed, and then adjust the running speed of the mass block.

The electrical characteristics of gravity energy storage system are mainly reflected in the system power, the energy storage capacity of the vertical gravity energy storage system is:

$$E_T = \eta_T \sum_{i=1}^{n} m_i g h_i \tag{1}$$

where E_T is the energy storage capacity of the system; η_T is the output efficiency of the system; m is the mass of the mass block; h is the effective height of the mass block.

The average output power of the energy storage system can be expressed as:

$$\overline{P}_x = \frac{Ex}{Tx} \tag{2}$$

where $\overline{P}_x$ is the average output power of energy storage system x, and E_x is the energy storage capacity of energy storage system x; T_x is the discharge time of energy storage system x.

The output instantaneous power of a single mass block is:

$$P_x = \frac{dEx}{dt} \tag{3}$$

Furthermore, the instantaneous output power of a single object can also be defined from a kinematic perspective for SGES systems:

$$Px = mgv \tag{4}$$

where m is the mass of weight; v is the vertical speed of the weight.

At present, the main grid-connected methods of vertical gravity energy storage system power generation/motor are grid-connected by converter, direct grid-connected and heavy drag motor start to complete grid-connected. Considering the cost of the converter and the special construction mode of vertical gravity energy storage system, the synchronous generation/motor grid-connected mode described in this paper is direct grid-connected, and the starting mode is driven by mass block. It effectively reduces the operating cost of the vertical gravity energy storage system, improves the reliability of the entire system and the power supply quality, and lays a foundation for the application and large-scale promotion of the vertical gravity energy storage system (Venugopal et al. 2023).

Key problems of power generation/motor grid-connection

The gravity energy storage system uses synchronous motor directly connected to the grid, which can provide inertial support for the system, while the synchronous motor startup has various forms. According to the structure of the gravity energy storage system, the mass block is directly dragged to achieve startup, which has the most obvious economic effect. However, the mass block is dragged to start the synchronous motor, and the motor speed cannot be accurately controlled. Therefore, when the synchronous generation/motor is connected to the grid, the grid-connected index, that is, the phase, amplitude and frequency of the outlet voltage of the machine end are not accurate or the single element does not meet the grid-connected index standard, which will cause voltage fluctuations in the grid, power transmission instability, harmonic pollution, etc., affecting the reliability of the grid operation and the quality of power supply. In addition, when grid-connected, compared with conventional generator sets, the gravity energy storage system needs to switch frequently between charge and discharge operating conditions according to the demand of the grid, and each switching process involves the start and grid-connected of the generation/motor. At this time, continuous and stable impulse current will be generated due to multiple grid-connected, posing a threat to the safe operation of the grid-connected system.

The problems of vertical gravity energy storage system that uses synchronous generation/motor driven by heavy blocks for grid-connection are summarized as follows:

1. When the gravity energy storage motor is connected to the grid, the phase, amplitude and frequency of the motor outlet voltage and the grid voltage are inconsistent or the error is large, and the grid connection cannot be successfully completed.
2. The gravity energy storage system needs to switch frequently between charge and discharge operating conditions according to the demand of the power grid, so that the synchronous generation/motor needs to be frequently connected to the grid, so as to further improve the success rate of grid-connection to ensure that the synchronous motor can be successfully connected to the grid.
3. The gravity energy storage system needs to switch frequently between charge and discharge operating conditions according to the demand of the grid, resulting in syn-

chronous generation/frequent grid-connection of the motor. Multiple grid-connection will produce continuous and stable impulse current. If no adjustment is made at this time, it will pose a threat to the safety of the grid-connection system and seriously affect the power quality of the grid supply.

The meaning of sensitivity

When comprehensively analyzing the impact of different indicators of gravity energy storage synchronous power generation/motor terminal voltage on grid connected impulse current, it is necessary to separately analyze the impact of terminal voltage phase, amplitude, and frequency on the impulse current. The meaning of the voltage index sensitivity specified in this paper is: the sensitivity of the voltage index represents the ability to generate transient impulse current when there is an error between the voltage index of the synchronous generator/motor end and the network end. When the error of the voltage index is the same, the greater the transient impulse current, the higher the sensitivity of the voltage index. On the contrary, the lower the sensitivity.

Proposal of the optimal matching scheme for index weights

This paper proposes a grid connection method for gravity energy storage power generation motors based on voltage index sensitivity analysis. The feature of this method is to ensure that the phase, amplitude and frequency of synchronous power generation/motor outlet voltage meet the broadest grid-connected standards and improve the success rate of grid-connected. The errors of grid-connected index data are reduced constantly, and the accurate processing of grid-connected index data is finally realized. The basic principle and implementation process are as follows:

1. Based on the grid-connected model of vertical gravity energy storage system established, the change law of impulse current generated under different terminal voltage phase, amplitude and frequency parameters was analyzed; According to the analysis results, reasonable weights are assigned to the index parameters of the grid-connected process according to the impact on the system and the engineering experience.
2. Select the observed values of grid-connected index data, apply least square method to process and fit the data, optimize the data model, and reduce the prediction error to the greatest extent.
3. The grid-connected index data were selected three times, and the multiple linear regression method was adopted to obtain the optimal grid-connected data set of terminal voltage, so as to minimize the impulse current generated by gravity energy storage after multiple grid-connected, and improve the power quality of grid power supply.

The grid-connected model of vertical gravity energy storage system is established

Analysis of influence mechanism of grid-connected index

When the phase, amplitude and frequency of the output voltage of the synchronous motor are inconsistent with the power grid, the specific effects are as follows.

Amplitude: When the synchronous motor is connected to the grid, its electromagnetic field must be synchronized with the grid electromagnetic field, that is, the frequency of the two is the same, and the phase difference is zero. When the grid voltage applies the electromagnetic force to the synchronous motor, if the voltage is too low, the motor will not be able to output enough torque to maintain synchronization, and the speed of the motor will be reduced, or even out of sync. When the voltage is too high, the motor may not be able to withstand excessive voltage, which will cause the motor to be damaged or burned out (Tong et al. 2021).

Phase: The synchronous motor and the grid must maintain phase synchronization, otherwise the motor will be out of sync and unable to output active power. The larger the phase difference, the more active work is lost. Under normal operation, the electrical power output of the synchronous motor is equal to the mechanical power input, and if the phase difference changes, the active power output of the motor will be reduced, thereby reducing the overall efficiency (Dhar and Chakraborty 2022).

Frequency: The synchronous motor and the power grid must keep the frequency synchronized, otherwise the motor will not be able to maintain the synchronous state. The greater the frequency deviation, the greater the change in motor speed, thus affecting the normal operation of the motor. When the power grid frequency is high, the speed of the motor will increase, it is easy to overload, and may even be damaged or burned out. When the grid frequency is low, the motor speed will be reduced and may not be able to meet the load requirements (Al-Hilfi et al. 2022).

In summary, there is a close relationship between the voltage amplitude, phase and frequency of the synchronous motor outlet voltage, and it is necessary to meet the power generation/motor operation specifications to ensure the safe and efficient operation of the motor and the entire vertical gravity energy storage system.

Establishment of grid connection model

The grid-connected model of synchronous motor of vertical gravity energy storage system is established, as shown in Fig. 2. The principle diagram of direct grid-connection of synchronous motor driven by mass block is shown in Fig. 4. In this paper, the rated power of GESS motor, its rated power is 6500 kW, rated current is 397.1 A, rated excitation is set, rated power factor is 0.9, and stator voltage level is 10.5 kV. Connected to the 10.5 kV power grid, the rated frequency of the power grid is 50 Hz, and the grid-connection mode is direct grid-connection. The simulation model is established, as shown in Fig. 5. The simulation parameters that need to be changed are the phase, amplitude and frequency parameters of the terminal voltage of the synchronous motor. The grid-connected module can play the purpose of controlling a single variable, that is, when the frequency is different, the point of the voltage phase and amplitude of the machine end and the network end should be selected for closing the grid-connected. When the phase is different, it is necessary to select the point with the same voltage frequency and

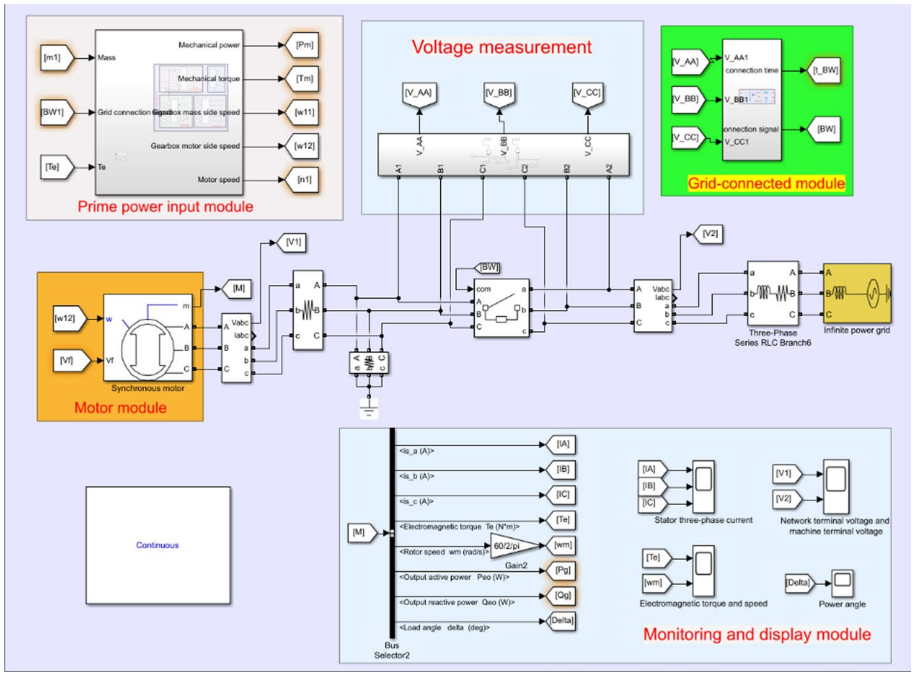

Fig. 2 Grid-connected model of gravity energy storage

Table 1 Parameter settings of synchronous motor in vertical gravity energy storage system

Parameter name	Parameter value
Rated capacity Sn	7222
Rated power Pn	6500
Rated power factor	0.9
Stator rated voltageUn (kV)	10.5
Rated capacity currentIn (A)	397.1
Rated speed nN (r/min)	600

amplitude at the machine end and the network end for closing and connecting the grid. When the amplitude is different, it is necessary to select the point with the same voltage phase and frequency at the machine end and the network end for closing and connecting the grid.

The motor used in the grid-connected vertical gravity energy storage system is a synchronous motor, and the parameter Settings of the synchronous motor are shown in Table 1.

Priority analysis of the impact of grid connection indicators on system impact

Simulation analysis of different grid connection index models

When the motor of the gravity energy storage system needs to achieve frequent grid connection, there will be errors in the phase, amplitude, frequency, and power grid of the terminal voltage during each grid connection, resulting in a continuous and stable surge current that affects the quality of power supply and the safety of the grid connection system. Select a synchronous motor as shown in Table 1, adjust the phase, amplitude, and frequency of the terminal voltage near the existing grid connection specifications, and analyze its impact current situation through simulation as follows:

The phase adjustment range is $0° \pm 15°$, and the simulation results of different phases within this range are shown in Fig. 3.

The amplitude adjustment range is $1 \pm 5\%$ times the rated voltage. The simulation results of different amplitudes within this range are shown in Fig. 4.

The frequency adjustment range is 50 ± 0.5 Hz, and the simulation results are shown in Fig. 5.

According to the analysis of simulation results under different conditions of phase, amplitude, and frequency in Figs. 1, 2, 3, 4, 5, it can be concluded that:

1. The maximum/minimum impulse current generation time and minimum impulse current value are basically the same when different grid connection indicators fluctuate, and both occur at the time of grid connection and closing.

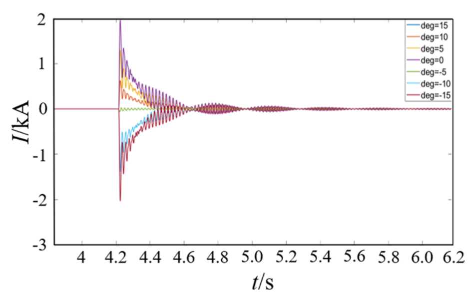

Fig. 3 Impulse current with different phase differences

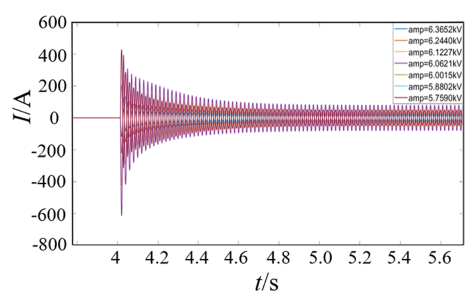

Fig. 4 Impulse current with different amplitude differences

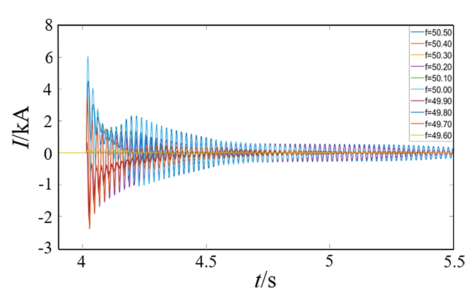

Fig. 5 Impulse current with different frequency

2. The maximum impulse currents generated during the adjustment process of phase, amplitude, and frequency are −2.09 kA, −0.63 kA, and 6.04 kA, respectively, which are 5.26 times, 1.89 times, and 15.21 times the rated current of the motor. Therefore, it can be preliminarily determined that under the same deviation ratio, the sensitivity of phase, amplitude, and frequency is amplitude > phase > frequency. Thus, the weight of the impact of different grid connection indicators on the system can be obtained as frequency > phase > amplitude.
3. During the simulation process, the absolute value of the impulse current generated at the time of grid connection and closing increases with the increase of the difference between the machine terminal voltage index and the grid terminal voltage. The maximum forward impulse current at the time of grid connection and closing is greater than the maximum reverse impulse current.

Indicator weight allocation and allocation method

Although the phase, amplitude, and frequency of the terminal voltage of gravity energy storage synchronous power generation/motor grid connection can generate transient impulse currents when there is an error between the phase, amplitude, and frequency of the terminal voltage and the grid end, it is found through the above simulation analysis that the magnitude of the impulse currents generated by the three is not equal under the same other conditions. Therefore, the phase, amplitude, and it is obviously unreasonable to equivalently analyze the transient impulse current generated by frequency allocation with the same weight.

According to the analysis in section A, when gravity energy storage power generation/electric motor is connected to the grid, the phase, amplitude, and frequency of the generator terminal voltage are different from the grid terminal. The sensitivity of the three factors on the transient impact current of the grid connection is amplitude > phase > frequency. That is, if the same transient impact current value is reached, the change in frequency is the smallest, the change in phase is the second, and the change in amplitude is the largest.

In order to allocate accurate and reasonable weights for the phase, amplitude, and frequency of the terminal voltage of gravity energy storage power generation/electric motor, a relatively reasonable allocation method is also introduced: first, set the transient impulse current threshold to 2 kA, and then only set reasonable model simulation parameters. Set the phase, amplitude, and frequency of the terminal voltage to be different from the grid terminal, but the resulting transient impulse current amplitude is 2 kA, as shown in Fig. 6, The final changes in the phase, amplitude, and frequency of the terminal voltage are 30°, 17.538 kV, and 0.026 Hz, respectively. From this, the ratio of the phase, amplitude, and frequency weights of the terminal voltage under this synchronous motor parameter setting can be obtained.

However, in practical engineering applications, due to factors such as different motor parameters and deviations in control methods, the above weight allocation results may not be applicable to all gravity energy storage synchronous power generation/motors. It is necessary to use the above method to obtain more accurate weight allocation results based on specific motor types and motor parameters. To ensure the universality of this

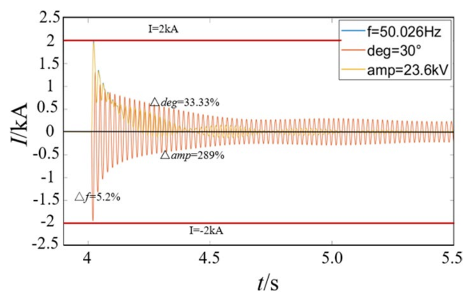

Fig. 6 Different voltage indicators under the same impulse current, this variable

article, the weights of the phase, amplitude, and frequency of the terminal voltage are represented by P_1, P_2, and P_3, respectively. The weighting conditions for grid connection are:

$$\omega = \frac{f}{P1} + \frac{\varphi}{P2} + \frac{V}{P3} \tag{5}$$

In the equation, ω is the weighted grid connection decision condition, f, ϕ, V represents the frequency, phase, and amplitude of the terminal voltage, with units of Hz, degrees, and kV. The corresponding weights assigned to P_1, P_2, and P_3 respectively.

Obviously, when the phase, amplitude, and frequency of the output voltage of the synchronous motor are completely consistent with the infinite grid, it is the optimal grid connection condition for grid connection, that is, the optimal grid connection time. At this point, the weighted grid connection conditions are recorded as ω_0. The phase, amplitude, and frequency of the voltage between the power grid and synchronous generator/motor terminals are ϕ_0, V_0, f_0, then there are:

$$\omega_0 = \frac{f_0}{P1} + \frac{\varphi_0}{P2} + \frac{V_0}{P3} \tag{6}$$

The most basic requirement for meeting the weighted grid connection conditions is that the weighted values do not exceed the optimal grid connection conditions $\omega_0 \pm 10\%$. That is:

$$|\omega - \omega_0| \leq 10\%\omega_0 \tag{7}$$

Due to the fact that the above adjustment range for voltage phase, amplitude, and frequency is based on existing standards, it can be considered that the above adjustment range includes all errors between the outlet voltage of the synchronous motor and the grid voltage during actual grid connection.

The above adjustments are also equivalent to appropriately relaxing the grid connection standards, making the gravity energy storage system synchronous power generation/motor more able to meet the requirements of impulse current under frequent grid connection, improving the success rate of grid connection, but not reducing the impulse current of grid connection. Through the weighted indicators of grid connection, only the gravity energy storage system synchronous power generation/motor can meet the broadest grid connection index limit and complete the grid connection process, However, for gravity energy storage systems that require frequent switching between charging and discharging operating conditions, gravity energy storage synchronous generators/motors also need to be connected to the grid multiple times. The impact current generated will have a lasting and stable impact on the grid as the number of grid connections accumulates. If not intervened in a timely manner, the power quality of the grid's power supply will be continuously or largely affected by the impact current, seriously affecting the stability of gravity energy storage and even the entire power system power supply.

To further address the above issues, the adjustment range for the phase, amplitude, and frequency of the terminal voltage mentioned above is obviously not accurate enough. It is necessary to further reduce the error between the phase, amplitude, and frequency of the terminal voltage during grid connection and the grid voltage in order to effectively suppress the magnitude of the impulse current. This article proposes a grid connection method for gravity energy storage systems based on sensitivity analysis of voltage grid connection indicators. Through simulation verification, this method improves the success rate of gravity energy storage power generation/motor grid connection, achieves optimization of grid connection indicator data, effectively suppresses transient surge current during grid connection, and improves the power quality of power supply in the grid.

Data model optimization

Before the optimization of gravity energy storage synchronous power generation/motor end voltage index, it is necessary to optimize the data model of the phase, amplitude and frequency data obtained in advance during the operation of the motor, eliminate the bad data, and avoid the data error on the overall index optimization effect.

According to the power quality fluctuation range of grid-connected specifications and the practical engineering application experience, the grid-connected index data range conforming to the grid-connected weighted index is obtained, and the terminal voltage phase data set $\phi = \{\phi_1, \phi_2, \phi_3 \ldots \phi_i\}$, machine end voltage amplitude data set $V = \{V_1, V_2, V_3 \ldots V_i\}$, terminal voltage frequency data set $f = \{f_1, f_2, f_3 \ldots f_i\}$. Since the above data are all observed values, the least square method (Liu et al. 2023b) is introduced here to reduce the error of the data set, optimize the data model, and ensure the high accuracy and strong robustness of the data model. Suppose that the fitting function adopted is:

$$\hat{y}(x_i) = a\phi(x_i) + b \tag{8}$$

where x_i (i = 1, 2,..., n) is the i th data in the data set, and n is the total number of data in the data set; ϕ (x_i) is the scoring data obtained by data fitting with assigned weights; $\widehat{y}(x_i)$ is the data obtained through the least squares operation.

Assuming the real data is $Y(x_i)$, the problem is transformed into solving unknown parameters a and b, so that the mean square error of (x_i) and $Y(x_i)$ is minimized, that is:

$$\left(a^*, b^*\right) = \frac{1}{2}\text{argmin}\sum_{i=1}^{n}\left[\hat{y}(x_i) - Y(x_i)\right]^2 = \frac{1}{2}\text{argmin}\sum_{i=1}^{n}\left[Y(x_i) - a\phi(x_i) - b\right]^2 \tag{9}$$

By taking the partial derivatives of a and b separately, we can obtain:

$$\frac{\partial}{\partial a}\left[\frac{1}{2}\sum_{i=1}^{n}\left[Y(x_i)-a\phi(x_i)-b\right]^2\right]=\sum_{i=1}^{n}\left[a\phi^2(x_i)-Y(x_i)\phi(x_i)+b\phi(x_i)\right] \tag{10}$$

$$\frac{\partial}{\partial b}\left[\frac{1}{2}\sum_{i=1}^{n}\left[Y(x_i)-a\phi(x_i)-b\right]^2\right]=\sum_{i=1}^{n}\left[a\phi(x_i)-Y(x_i)+b\right] \tag{11}$$

By setting the values of the above two equations to zero, the optimal solutions for a and b can be obtained as follows:

$$\begin{aligned} a^* &= \frac{n\sum_{i=1}^{n}\phi(x_i)Y(x_i)-\sum_{i=1}^{n}\phi(x_i)\sum_{i=1}^{n}Y(x_i)}{n\sum_{i=1}^{n}\left[\phi(x_i)\right]^2-\left[\sum_{i=1}^{n}\phi(x_i)\right]^2} \\ b^* &= \frac{1}{n}\sum_{i=1}^{n}\left[Y(x_i)-a^*\phi(x_i)\right] \end{aligned} \tag{12}$$

Substituting the obtained a^* and b^* into Eq. (12) yields:

$$\hat{y}(x_i)=a^*\phi(x_i)+b^* \tag{13}$$

Set the terminal voltage phase data $\varphi=\{\varphi_1, \varphi_2, \varphi_3 \ldots \varphi_i\}$, amplitude data set $V=\{V_1, V_2, V_3 \ldots V_i\}$, frequency data set $f=\{f_1, f_2, f_3 \ldots f_i\}$ is substituted into the above formula respectively to obtain a more accurate data set of φ, V and f.

$$\begin{aligned} \widehat{\varphi_i} &= a^*\phi(\varphi_i)+b^* \\ \widehat{V_i} &= a^*\phi(V_i)+b^* \\ \widehat{f_i} &= a^*\phi(f_i)+b^* \end{aligned} \tag{14}$$

The fitted data set is denoted as:

$$\begin{aligned} \hat{\varphi} &= \left\{\hat{\varphi}_1,\hat{\varphi}_2,\hat{\varphi}_3\ldots\hat{\varphi}_i\right\} \\ \hat{V} &= \left\{\hat{V}_1,\hat{V}_2,\hat{V}_3\ldots\hat{V}_i\right\} \\ \hat{f} &= \left\{\hat{f}_1,\hat{f}_2,\hat{f}_3\ldots\hat{f}_i\right\} \end{aligned} \tag{15}$$

Optimal matching of deviation grid connection indicators

Optimal selection of voltage index data

Three sets of data are generated in the same coordinate system, generating three curves:

Terminal voltage phase φ: The corresponding data set is (φ_1, φ_2, φ_3... φ_i);
Terminal voltage amplitude V: The corresponding data set is (V_1, V_2, V_3... V_i);
Terminal voltage frequency f: The corresponding data set is (f_1, f_2, f_3... f_i);

During the process of synchronous power generation/motor startup driven by the mass block and reaching the rated excitation of the motor, the frequency, phase, and amplitude of the terminal voltage must change to the standard value together with time t. Therefore, the abscissa of the three curves all use the same coordinate axis to ensure the synchronization of the three sets of data.

Extract three sets of data for the first time: based on the frequency range $f_0 \le f_i$ (terminal voltage frequency) $\le f_p$, the terminal voltage frequency data (f_1, f_2, f_3… f_i), and terminal voltage phase data (ϕ_1, ϕ_2, ϕ_3…ϕ_i). Intercept frequency data (f_j… f_k) and phase data from the amplitude data of terminal voltage (V_1, V_2, V_3… V_i) within the same time range(ϕ_j… ϕ_k), amplitude data (V_j… V_k);

Select three sets of data for the second time: based on the phase range $\phi_j \le \phi_i$ (terminal voltage phase) $\le \phi_k$. From the first extracted terminal voltage frequency data (f_j… f_k), terminal voltage phase data (ϕ_j… ϕ_k) Extract frequency data (f_{jm}… f_{kn}) and phase data from the voltage amplitude data (V_j… V_k) of the terminal again within the same time range (ϕ_{jm}… ϕ_{kn}), amplitude data (V_{jm}… V_{kn});

Select three sets of data for the third time: based on the amplitude range $V_0 \le V_i$ (terminal voltage amplitude) $\le V_p$, extract the terminal voltage frequency data (f_{jm}… f_{kn}) and terminal voltage phase data from the second time(ϕ_{jm} … ϕ_{kn}), terminal voltage amplitude data (V_{jm}… V_{kn}), extracting frequency data (f_{jmo}… f_{knp}) and phase data within the same time range again (ϕ_{jmo}… ϕ_{knp}), amplitude data (V_{jmo}… V_{knp}).

Comprehensive judgment of grid connection

The comprehensive judgment of grid connection is based on the multiple linear regression algorithm, and the dependent variable is set as the data set Y, which is a critical value when three sets of data indicators can just complete the grid connection (Farjana et al. 2021). Analyze three sets of independent variables again: terminal voltage frequency data (f_{jmo}… f_{knp}), terminal voltage phase data (ϕ_{jmo}… ϕ_{knp}), the amplitude data of terminal voltage ($V_{jmo\ldots}$ V_{knp}), and its impact on the dependent variable Y.

$$Y = \beta_0 + \beta_1 f + \beta_2 \varphi + \beta_3 V + \varepsilon \tag{16}$$

where, Y represents the dataset of three sets of indicators that can just complete the grid connection, β_0 is the intercept; β_i is the regression coefficient, where i = 1,2,3, ε Is the residual. The regression coefficient is calculated using the least squares method.

$$\beta = (X^T X)^{-1} X^T Y \tag{17}$$

Among them, X is:

$$X = \begin{bmatrix} 1 & f_{jmo} & \varphi_{jmo} & V_{jmo} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ 1 & f_{knp} & \varphi_{knp} & V_{knp} \end{bmatrix} \tag{18}$$

where, $\beta = [\beta_1, \beta_2, \beta_3]^T$; $Y = [y_{jmo}, \ldots y_{knp}]$ T, which is the response variable of the data. Finally, the corresponding set of three selected data grid connection indicators Y was obtained. The optimal and precise processing of data has been achieved.

Example analysis

The phase, amplitude and frequency data of terminal voltage of synchronous motor with rated voltage of 10.5 kV before and after grid connection were obtained through simulation analysis. The precise data were obtained after least square processing, as shown in Table 2.

The red data in Table 2 is the "optimal" data that can complete the grid connection, and the data set is shown in the dashed box. Selecting the red data as the adjustment direction of the terminal voltage during the grid connection can generate the minimum

Table 2 Terminal voltage data after data processing

t (s)	*f* (Hz)	*deg* (°)	*amp* (V)
4	48.56	-17.07	430.28
4.5	48.97	-13.82	466.33
5	49.23	-10.56	499.84
5.5	49.53	-6.06	541.24
6	49.79	-2.27	582.95
6.5	49.92	1.31	600.09
7	50.05	3.64	633.87
7.5	50.19	6.83	629.72
8	50.35	14.25	656.32
8.5	50.48	18.37	682.77
9	50.78	19.28	698.46
9.5	51.17	14.19	719.07
10	51.23	16.80	676.52
10.5	50.75	11.24	634.28
11	50.43	16.06	647.54
11.5	50.82	10.87	611.25
12	49.93	18.25	601.08
12.5	49.49	14.32	649.82
13	49.89	7.28	613.88

impulse current. Yellow data is a "better" data set. Yellow data meet the required frequency range, but the phase and amplitude are not optimal data. Choosing yellow can produce a small impulse current. The blue data is "good" data, which can only ensure that the motor can be successfully connected to the grid, but the selection of blue data will produce a large impact current. Finally, after three times of selection and ternary linear regression, the data set of frequency, phase and amplitude of the terminal voltage can be obtained as follows:

$$f = \{49.79, 49.89, 49.92, 50.05, 50.19\};$$

$$\Phi = \{-2.27, 1.31, 3.64, 6.83, 7.28\};$$

$$\mathrm{V} = \{582.95, 600.09, 633.87, 629.72, 613.88\};$$

From the data sets of phase, amplitude and frequency of the terminal voltage of the above three sets of synchronous generators/motors, the terminal voltage data of any group corresponding to the same time t were selected, and the impulse current simulation analysis and verification were carried out. Here, four sets of data were selected for simulation, and the impulse current simulation results were shown in Fig. 7. It can be seen that under the comprehensive error, The maximum impact current value of synchronous generation/motor grid-connected time has been reduced to about 200 A, which is about 0.5 times of the rated current value of synchronous generation/motor (rated current value is 397.1 A), which meets the requirements of the impact current when synchronous generation/motor grid-connected closing of vertical gravity energy storage system. The continuous and stable shock caused by synchronous generation/motor of vertical gravity energy storage system in the case of frequent grid connection is successfully suppressed.

The comparison between the proposed method and the prior art is shown in Table 3.

The cost composition of GESS needs to comprehensively consider the type of motor, mechanical structure and various losses, etc., the specific cost has not been calculated in detail, and the "cost" in the table only considers the motor starting mode, grid-connected mode, and the type of motor applied for preliminary estimation. Due to the existence of frequency converter, the cost of using frequency converter to connect to the grid is significantly higher than that of direct grid-connection, and the grid-connection method in

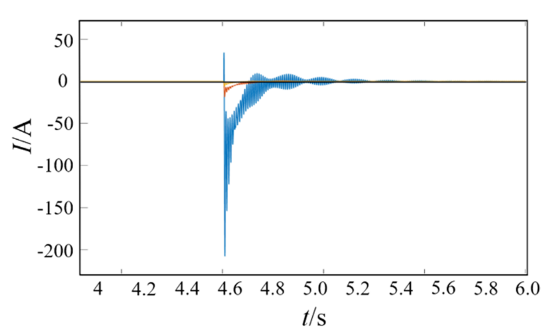

Fig. 7 Verification of simulation results of grid connected impulse currentafter accurate data

Table 3 Comparison of key indicators of different methods

	The grid-connected method of this paper	Direct grid connection	Connected to the grid by frequency converter
Cost	Low	Lower	High
Reliability	Higher	Normal	High
Success rate of grid connection	Higher	Normal	High
Scope of grid-connected application	Wide	Relatively wide	Narrow
Operating efficiency	Higher	Normal	High
Impulse current	Lesser	Larger	Small

All comparisons in the table are based on the gravity energy storage system under frequent grid-connection conditions

this paper also uses the mass block drive synchronous motor to start the grid-connection, so its cost is lower than the general synchronous motor direct grid-connection.

Because the grid-connected method in this paper is equivalent to the accurate end voltage index of synchronous motors during grid-connected, its reliability and success rate of grid-connected are higher than that of conventional direct grid-connected mode, especially under frequent grid-connected conditions, and its impulse current is lower than that of conventional direct grid-connected mode. The advantages of this grid-connected method are low cost and can provide system inertia and reactive power, and the success rate of grid-connected method is higher than that of conventional direct grid-connected method.

The grid-connected method in this paper is equivalent to relaxing the grid-connected conditions on the basis of the existing grid-connected standards of synchronous motors, so its grid-connected scope is higher than that of direct grid-connected and grid-connected by frequency converter.

In terms of operation efficiency, both the grid-connected method in this paper and the grid-connected method by frequency converter can ensure higher success rate and reliability of grid-connected, so their operation efficiency is higher than that of direct grid-connected synchronous motor.

Conclusions

As a new type of physical energy storage technology, gravity energy storage has broad application prospects in distributed power generation, smart grid, load peaking and frequency modulation, and renewable energy power generation. There are significant differences in grid-connected operation between the generator motor of gravity energy storage system and the traditional synchronous motor. Therefore, this paper proposes an optimal grid-connection control method for vertical gravity energy storage system based on weight allocation and data processing. The main conclusions are as follows:

1. By analyzing the influence mechanism of grid-connected conditions on grid-connected operation of gravity energy storage motors, it is obtained that the influence of grid-connected conditions on the system is frequency > phase > amplitude;
2. The weighted grid-connection conditions that can improve the grid-connection accuracy of gravity energy storage are obtained;

3. The data of grid-connected conditions of synchronous motors were fitted by least square method, and then the data of grid-connected conditions were selected three times according to their influence weights. Finally, the three selected sets of grid-connected conditions Y were obtained by multiple linear regression method. Y not only meets the initial weighted grid-connection conditions, but also makes the three groups of grid-connection data the optimal data set under the same working condition, and realizes the optimal control of grid-connection conditions of the vertical gravity energy storage system.

Prospect

The method proposed in this paper is explained based on a large amount of simulation data. Although it has been verified that the method in this paper can significantly reduce the grid-connected impulse current, the simulation data model in this paper is based on data detection.

In engineering practice, the continuously changing terminal voltage index data of synchronous motors cannot be obtained in advance through human prediction. In-depth research can also be conducted on the combination of model prediction and the method of this paper.

Regarding the grid connection accuracy of this method, the overall accuracy is significantly improved compared to the direct grid connection method of general synchronous motors, but it has not yet reached the accuracy when using a frequency converter to connect to the grid. If the machine terminal voltage index can be further optimized, it can getting closer to or even reaching the accuracy of the frequency converter connected to the grid is another direction that needs to be further studied in the future.

The study on the complete control strategy of this paper and the development of experimental equipment, application in field experimental verification and promotion of the grid connection method in this paper are work that needs to be done in the future.

Author contributions

Qingshan Wang: writing-original manuscript, Conceptualization, methodology Yan Li: writing-original manuscript, formal analysis Qun Zhang: data curation, writing—review and editing Darui He: writing—review and editing, validation All authors reviewed the manuscript.

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Availability of data and materials

The datasets generated or analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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