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ORIGINAL ARTICLE

Transient Stability Simulation Analysis of Multi Node Power Network with Variable Speed Pumped Storage Units

Chong Zhao[1] · Longze Wang[1] · Yiyi Ma[1] · Pengfei Xiang[1] · Siyu Jiang[1] · Weidong Chen[2] · Yan Zhang[3,4] · Meicheng Li[1]

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Abstract

The output characteristics of variable speed pumped storage are different from conventional hydropower and constant speed pumped storage units. The continuous increase of installed capacity of variable speed pumped storage, poses a severe challenge to the safe and stable operation of the local power grid. Proposed in this paper is a kind suitable for multi-node containing variable speed pump machine storage unit electric power network transient stability method, considering the variable speed pumped storage units by the end of the instantaneous failure prone to sudden drop transient power, the power network with more nodes each busbar voltage stable operation as the goal, according to the regional power grid data under typical operation modes, Based on the power system analysis software package, an electromechanical simulation model of the 7-node power grid with variable speed pumped storage unit was established. The influence on the transient stability of a 7-node power grid is analyzed by removing variable speed pumped-storage units and three-phase short-circuit faults. The transient stability of the power grid can be maintained under the conditions of removing variable speed pumped-storage units and three-phase short-circuit faults, but some bus voltages are higher than the specified voltage upper limit. The reactive power compensation device is installed to improve the voltage stability of the power grid system, which can prevent the overvoltage accident caused by the fault of the communication system, achieve the purpose of multi-node power network stability, and improve the safety and stability of the regional power system when the fault occurs.

Keywords Variable speed pumped storage · Reactive power compensation · Simulation analysis · Transient stability

✉ Meicheng Li
mcli@ncepu.edu.cn

Chong Zhao
zc-beijing@163.com

Longze Wang
51102710@ncepu.edu.cn

Yiyi Ma
120212211018@ncepu.edu.cn

Pengfei Xiang
956476050@qq.com

Siyu Jiang
120202211047@ncepu.edu.cn

Weidong Chen
2990540050@qq.com

Yan Zhang
zhangyan8698@ncepu.edu.cn

1 State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, School of New Energy, North China Electric Power University, Beijing 102206, China

2 School of Electrical Engineering, Shenyang University of Technology, Shenyang 110044, China

3 School of Economics and Management, North China Electric Power University, Beijing 102206, China

4 Beijing Key Laboratory of New Energy and Low-Carbon Development, Beijing 102206, China

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1 Introduction

The variable-speed pumped-storage power station can be used as a way of indirectly storing electric energy. It is a hydropower station formed to properly handle the contradiction between supply and demand between the trough and the peak of the power grid. The hydropower station has dynamic functions such as emergency backup, phase modulation, and frequency modulation. In the power grid, the strong support to ensure the stable, safe, and economical operation of the power grid is the reason for the official completion of the pumped storage power station. The pumped storage power station can play a key and core role in an all-around way during this process. The pumped storage power station is suitable for smoothing the output fluctuation of renewable energy power generation, and can fully reflect the characteristics of a fast ramp rate and strong peak-shaving ability. The advantage of the variable speed unit is that the speed of the unit can be adjusted. To take advantage of the above, it is necessary to select the optimal speed of the unit according to the requirements to realize the efficient operation of the unit. The choice of rotational speed when the unit is operating in the pump condition is related to factors such as the optimal operating range (water head) of the unit's pump condition [1–3], the frequency regulation of the power system, and the active power regulation of the power system. Through the research on multi-objective control strategies, it is concluded that the choice of rotational speed when the unit is operating in the power generation condition is related to factors such as the optimal operating range, safe operating range, power system frequency regulation, and power system active power regulation of the unit's power generation condition. In reference [4–6], this multi-objective control strategy for optimal rotational speed generation is studied.

Both Europe and Japan have carried out in-depth work on the research and application of variable-speed pumped storage units. Japan accounts for 76.26% of the world's total capacity of variable speed units and is the country that has carried out the largest number of studies on continuous variable speed AC excitation energy storage units. In addition to Japan, Germany accounts for 18.33% [7–9]. Since the 1990s, the basic role of Japan's pumped storage power station has changed from peak shaving and valley filling to a power grid dispatch management tool. To improve the power quality and ensure the smooth and safe operation of the power system, the Japanese side produced seven variable speed units with an installed capacity of 1711.5 MVA in the 1990s. By the end of 2010, 10 continuous-speed AC excitation pumped-storage units had been installed in 7 power stations, with a total capacity of 2746.5 MVA. Among these 10 units, the two 395 MVA units installed in this power station had the largest single-unit capacity. At the same time, two 576–624 r/min, 360 MVA variable speed units were installed in Xiaowanchuan pumped-storage power station, and now they are officially put into operation at the highest speed. The 3rd and 4th units of the Geyechuan Pumped Storage Power Station will be put into operation in 2017. The unit uses a 475 MVA 480–520 r/min variable speed unit and will become the world's largest variable speed unit in the future. In addition to Japan, Germany located in Europe is an important distribution area for the application of variable speed units. In 2004, the German Jingu Pumped Storage Power Station put into use two 331 MVA variable speed units. The lignite-fired power plant can operate under the optimum working condition through the adjustable load performance of the speed-adjusted unit through the pump working condition, and the overall economic benefit of the power grid can reach the optimum. Slovenia equipped its AVCE-pumped storage power station with 195 MVA variable speed units in 2009 [10–13].

Transient stability of a power system generally refers to the ability of each synchronous generator to maintain synchronous operation and transition to a new or return to the original operating state when the power system suffers from large disturbances such as a short circuit of transmission lines. Transient instability can be manifested as first pendulum instability or subsequent swing instability for large systems. The time range of transient stability research is generally 3–5 s after the disturbance, and the large system considers the interconnected mode oscillation can continue to 10–20 s [14, 15].

In literature, Lung et al. [16] derived the mathematical model of a doubly-fed variable speed pumped storage unit by using the improved induction motor model of wound rotor AC excitation and the theory of magnetic field oriented control, and verified the correctness of the proposed model by comparing the simulation results with practical examples. About, Teshager et al. [17] proposed a detailed dynamic model of rigid and elastic dynamics suitable for pumped storage. In the power generation condition, the system adopts the conventional modeling method of hydraulic turbine, and in the pump condition, the pump head curve is used to model the system. The simulation results show that the rigid model is suitable for studying the transient dynamics of the system. The elastic model is suitable for the study of long-term dynamics. The operation characteristics and control strategies of variable speed pumping and storage units have also been actively explored in China. According to the two different working conditions of the unit, the control strategies of unit efficiency optimization, primary frequency modulation, and combined control of speed regulation and excitation are proposed in the literature [16], and the control strategies of variable speed pumping and storage unit are simply explored. Literature [18] studies the mathematical model of a pumped storage power station and AC exciter unit and verifies the control strategy of the grid side and rotor side under different working conditions by simulation, and the results prove the applicability of the control strategy. Literature [19] studies an optimization method to determine the optimal combined daily operation strategy of pumped storage. Improved economic returns and reduced active power fluctuations due to the intermittency of wind energy resources. In reference [7], Shu Zhengyu et al. proposed the use of pumped storage to solve the emergency low-frequency problem caused by large-scale wind power grid connection, and selected different pumping strategies for pumping storage units according to dynamic frequency characteristics. The equivalent single-machine model of the power grid is established, and the simulation curves under different permeability are verified and analyzed by PSASP software. The results show that the large-scale wind turbine permeability affects the frequency of the power grid, and then affects the cutting pump selection scheme, and the proposed optimization scheme is better than the unoptimized one. Above research, the emphasis is focused on the speed of the pumped storage unit itself characteristic research, and variable speed pumped storage units with the new energy joint operation of the unit. This paper innovatively puts the number of variable speed pump energy storage units in many nodes in the network to analyze its variable speed pumped storage units under extreme conditions, such as cutting machine, and voltage stability of three-phase short-circuit fault time. Then, the voltage stability of each node is analyzed, and the reactive power compensation device is innovatively proposed to improve the stability of the multi-node network with a variable speed pumped storage unit.

In this paper [20], a method and system for evaluating the transient stability of the power grid are proposed. The node energy is obtained by bringing the pre-obtained node data into the preset energy-saving model. The stability of the node is determined according to the node energy and the preset judgment index; The transient stability of the power grid is evaluated based on the stability of the nodes. The method provided in this question provides technical support for accurately providing a power system transient. Complement the prior art's technical defects. In Article [20], the transient stability of the power grid is assessed directly through node energy, which is difficult to measure directly and difficult to use in practice. In this paper [21], the power grid transient stability evaluation method based on energy function is proposed. The power grid transient stability evaluation method based on energy function is used to collect data by a wide area measurement system and establish the transient energy function model. The system data in the transient process was collected, and the transient energy function model was constructed to obtain the energy sum of n generators in the system. According to the energy change trajectory of the secondary disturbance process, the quantitative index model of transient stability based on the secondary disturbance is constructed. Construct the energy margin index and judge Ts(t) according to the energy margin index. With the help of the wide-area measurement system parameters online access and the calculation of the energy function itself advantages, can improve the calculation speed, simplifying the calculation process, further improve the direct method in the application of power system, aiming at the shortcomings of the existing technology, provide with variable speed pumped storage units of regional power network transient research plan, previous studies only consider basic variable speed pumped storage unit itself, Or only the multi-node power network itself is considered, and the transient characteristics of the multi-node power network with variable speed pumped storage unit are not systematically analyzed. Moreover, the reactive power compensation device is innovatively introduced in this paper, which greatly improves the stability of the power system.

Based on the power system analysis software package (PSASP), an electromechanical simulation model of a 7-node power grid with variable speed pumped storage units is established. We analyzed the influence on the transient stability of a 7-node power grid by removing variable speed pumped-storage units, three-phase short-circuits faults, and short-circuit faults. The transient stability of the power grid can be maintained under the conditions of removing variable speed pumped-storage units and three-phase short-circuit faults, but some bus voltages are higher than the specified voltage upper limit. In addition, the reactive power compensation device is installed to improve the voltage stability of the power grid system.

2 Calculation Analysis of Power System Transient Stability

The main indicators of whether the power system can continue to maintain stable operation after a large disturbance are: first, whether the relative angular swing between units is gradually attenuated; second, whether the voltage level in local areas is within an acceptable range. Usually, there are two possible outcomes in the transient process after a large disturbance: one is that the relative angle between the rotors of the generators changes with time in a swaying state, the oscillation amplitude gradually decays, and the relative speed between the units finally decays. When it is zero, the voltage of each node gradually rises to a value close to the normal value, and the system returns to the operating state before the disturbance, or transitions to a new operating state. In this operating state [22–25], all generators still keep running synchronously. In this outcome, the power system is transiently stable. Another outcome is that the relative angle between the rotors of some generators increases with time during the transient process, causing the generators to lose synchronization between them or the voltage in the local area to be low for a long time. In this outcome, the power system is transiently unstable, or the power system loses transient stability. After the generator is out of synchronization, a strong oscillation of power and voltage will be generated in the system, which will force some generators and loads to be cut off, and even lead to the decoupling or disintegration of the system in severe cases. Article [26, 27] improves the stability of converter system from the perspective of photovoltaic, which has a good reference value for this paper.

To ensure the safety and stability of the power system, transient stability calculation and analysis are needed in the process of system planning, design and operation. Power system transient stability calculation is to determine the purpose of the system is a big interference (such as short-circuit fault occurs, the instantaneous load larger mutation, removal of the large capacity of power generation, transmission and substation equipment, etc.), the system each generator is to maintain synchronization operation and based on a complete analysis of system transient stability. Its main application scope includes: post-analysis of complex and serious accidents, reproducing the dynamic response of the system after the accident, understanding the cause of stability failure, and studying the correct anti-accident measures; In the planning and design stage, the ability of the system to withstand extreme serious failures, that is, serious failures beyond the normal design standards, is assessed to reduce the frequency of such serious failures and prevent the occurrence of malignant accidents; Analyze and evaluate the transient voltage stability of power system [7, 28]; From the point of view of system failure capacity, such as N-1, N-2 accidents, fault critical cutting time and transmission power limit of the system, the configuration of dynamic components and their influence on transient stability is considered, such as electrical braking, rapid adjustment valve, cutting machine, single-phase reclosing and so on. Especially with the development of large-capacity long-distance transmission and large network interconnection and the operation of new components, the study and calculation of the transient stability of power systems is a crucial topic [28].

As mentioned above, transient stability is to study the synchronous operation stability of a system subjected to large disturbances. Transient stability calculation mathematical model including the mathematical description of a grid (network equation) and generator, excitation regulators, speed regulators, power system stabilizers, loads, reactive power compensation, dc transmissions, and relay protection devices such as primary equipment and secondary dynamic characteristics of the mathematical description of the (differential/difference equations), and a variety of possible perturbation method and measure of stability simulation, etc. Therefore, the mathematical model of PSASP transient stability calculation (ST) can be divided into the following three parts: the mathematical model of the power grid, namely, the network equation. The mathematical model of generator, load, and other primary equipment and secondary automatic device, namely differential equation.

3 Model Establishment of Variable Speed Pumped Storage Unit

The variable speed pumping storage unit adopts the doubly-fed motor excited by AC. The principle of the variable speed pumping storage unit is similar to that of the ordinary constant speed pumping storage unit, but the difference lies in the rotor structure and excitation system of the generator motor. Different from conventional synchronous and asynchronous motors, the variable speed pumping storage unit rotor side is connected with ac frequency conversion excitation power, which can realize the decoupling control of the unit speed and power. The variable speed pumping storage unit is equipped with three-phase AC excitation windings in the rotor slot, and the excitation system of the variable speed pumping storage unit is replaced by the ac frequency conversion device instead of the common SCR DC rectification device of the conventional constant speed unit. The pump turbine has its mechanical governor, which is the prime mover or load of the system, the impeller forward rotation of the turbine to drive the generator, and the reverse rotation of the motor to drive the pump rotation. The control device is used to generate power and speed-given signals to control the converter and guide vane respectively. In the normal operation of the variable speed pumping storage unit, the excitation winding in the rotor slot will also generate a rotating magnetic field relative to the rotor through the three-phase ALTERNATING current. Because the stator magnetic field frequency needs to be kept at 50 Hz, the variable speed pumping storage unit can run at a constant frequency only by adjusting the frequency of the input rotor excitation current when the rotor rotation frequency changes. According to the energy conversion law, the speed of the stator magnetic field is the sum of the mechanical speed of the rotor and the rotating speed of the rotor magnetic field. At this time, the relative speed of the rotating magnetic field of the rotor is proportional to the frequency of the excitation current, as shown in Formula (1–3). In summary, the purpose of VSCF can be achieved by adjusting FR. The specific formula is as follows:

$$f_1 = f_2 + f_{\mathrm{r}} \tag{1}$$

$$n_1 = n_2 + n_r \tag{2}$$

$$n_r = 60 f_r / p \tag{3}$$

where f_1 is the stator magnetic field frequency, which is 50 Hz; f_2 is the rotor rotation frequency; f_r is the frequency of rotor excitation current; N1 is the speed of stator magnetic field; n_2 is the mechanical speed of rotor; n_r is the rotating magnetic field speed of the rotor; p is the polar logarithm of the motor.

The reversible pump turbine is the most commonly used unit in pumped storage power stations and can be used as the core equipment of electromechanical energy conversion in variable speed units. The reversible pump turbine in the traditional pumped storage works on the active guide vane in the power generation mode and the fixed guide vane in the electric mode. It can be regarded as a fixed load in the system, so the operation efficiency of the normal speed-pumped storage power station is low and the speed regulation range is small. The reversible pump turbine in a variable-speed pumped-storage unit can adjust the opening and speed of the guide vane according to the actual situation, so it has a high energy utilization rate and large power adjustment range.

Variable speed pumped storage system by variable speed unit, pump-turbine governing system, circuit breaker parts, such as variable speed pump storage unit USES is the doubly-fed motor, the wind generator, and doubly-fed type mathematical model, the research theory has been relatively mature, the face of doubly-fed motor, speed control system and the mathematical model of pump-turbine analysis and research.

Doubly-fed motors, also known as ac excitation asynchronous motors with synchronous characteristics, are famous for their ability to feed both stator and rotor to the grid. Different from a traditional induction motor, a doubly-fed motor has independent excitation winding, and adjustable power factor, and the speed does not change with the load, which is a relatively superior performance of the motor.

The dynamic mathematical model of a doubly-fed motor is very complicated because of the mutual inductance in the three-phase coordinate system. The equation can be simplified by using a two-phase rotating coordinate system with two-phase winding orthogonal so that mutual inductance is 0. The positive direction selection of stator windings and rotor windings conforms to motor conventions. In the two-phase rotating coordinate system, the voltage, current and flux chains of the stator and rotor of the doubly-fed motor should be changed to the d-q coordinate system, with subscripts "s" to represent the amounts of stator and "r" to represent the amounts of the rotor. Subscripts "d" and "q" are used to represent the d-axis and q-axis components respectively. The doubly-fed motor includes a voltage equation, flux equation, torque equation, motion equation, and power equation. The mathematical models in the two-phase step rotation dq0 coordinate system are as follows:

(1) Voltage equation

$$\begin{cases} \mathrm{u}_{sd} = R_s i_{sd} + p\psi_{sd} - \omega_1 \psi_{\mathrm{sq}} \\ \mathrm{u}_{sq} = R_s i_{sq} + p\psi_{sq} + \omega_1 \psi_{\mathrm{sd}} \\ \mathrm{u}_{rd} = R_r i_{rd} + p\psi_{rd} - \omega_s \psi_{rq} \\ \mathrm{u}_{rq} = R_r i_{rq} + p\psi_{rq} + \omega_s \psi_{rd} \end{cases} \tag{4}$$

(2) Flux equation

$$\begin{bmatrix} \psi_{\mathrm{sd}} \\ \psi_{sq} \\ \psi_{rd} \\ \psi_{rq} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{\mathrm{sd}} \\ i_{sq} \\ i_{rd} \\ i_{rq} \end{bmatrix} \tag{5}$$

(3) Torque equation

$$T_{\mathrm{e}} = p_n L_m (i_{sq} i_{rd} - i_{sd} i_{rq}) \tag{6}$$

(4) Equation of motion

$$2H_M \frac{\mathrm{d}\omega_r}{dt} = T_w - T_e - D_M \omega_r \tag{7}$$

(5) Power equation

$$\begin{cases} \mathrm{P}_s = \frac{3}{2}(\mathrm{u}_{sd} i_{sd} + \mathrm{u}_{sq} i_{sq}) \\ \mathrm{Q}_s = \frac{3}{2}(\mathrm{u}_{sq} i_{sd} - \mathrm{u}_{sd} i_{sq}) \end{cases} \tag{8}$$

wherein ω1 is the synchronous angular velocity, whose value is equal to the coordinate system speed ω dqS. ω S is the slip angular velocity, which is the speed of the dq0 coordinate system relative to the motor rotor, and its formula is. P is the differential operator. ls and Lr are the self-inductance of the stator and rotor respectively, and Lm is the mutual inductance of the stator and rotor. Pn is the polar logarithm of the motor, HM is the inertia time constant and DM is the damping coefficient.

A pump turbine is a very important part of variable-speed pumping and storage system. Its mathematical model generally adopts the ideal rigid water hammer model. To approach the actual results, the dynamic characteristics of the pump-turbine can be modified by the flow correction coefficient Ky. The model describes the relationship between the output mechanical moment MT of the turbine and the guide blade opening G, and the formula is as follows:

$$\mathrm{m}_t = \frac{1 - \mathrm{k_y} T_w s}{1 + 0.5\mathrm{k_y} T_w s} G \tag{9}$$

where is the water flow inertia time constant, represents the characteristic time of the flow inertia in the pipeline underrated working conditions, generally ranging from 0.5 to 4 s, s is the Laplace transform operator.

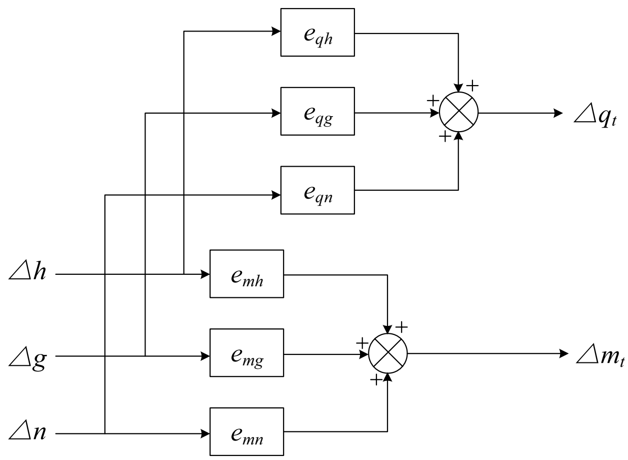

Fig. 1 Transfer function diagram of pump-turbine

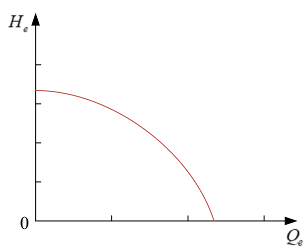

Fig. 2 Schematic diagram of head and water flow characteristic curve

In the case of small fluctuation, the turbine transfer function can be expressed by the following formula

$$\begin{aligned} \Delta \mathrm{m}_t &= e_{mg}\Delta g + e_{mn}\Delta n + e_{mh}\Delta h \\ \Delta q_t &= e_{qg}\Delta g + e_{qn}\Delta n + e_{qh}\Delta h \end{aligned} \tag{10}$$

where $\mathrm{e_{mg}}$, $\mathrm{e_{mn}}$, $\mathrm{e_{mh}}$, $\mathrm{e_{mh}}$, $\mathrm{e_{qn}}$ and $\mathrm{e_{qh}}$ are transfer functions of mechanical torque and water flow on guide vane opening, speed and head respectively. For ideal pump-turbine, $e_{mg}=1$, $e_{mn}=1$, $e_{mh}=1.5Q$, $e_{mh}=1$, $e_{qn}=0.5Q$, $eqh=0$. These coefficients are static characteristic coefficients of the pump-turbine, so they are only suitable for small fluctuations. Figure 1 is the transfer function diagram of the pump-turbine.

Speed control system mainly includes a governor and electro-hydraulic servo system. First of all, generally by changing the speed to adjust the input power of the pump-turbine, the specific implementation method is to use a PID governor, that is, with a proportional integral–differential link of the controller, the PID controller through the speed deviation constantly adjust and control to achieve the goal, relatively high reliability (Fig. 2).

Because the hydraulic link sometimes moves too fast under the condition of fluctuation so that the amplitude exceeds the full stroke position, it is necessary to consider the follow-up system, which is connected to the governor. The relay is the main controlled device of the electro-hydraulic servo system. The control of the main pressure distribution valve can be represented by integral links. Once the piston of the main pressure distribution valve deviates from the middle position, the relay begins to move with the piston and is proportional to the offset value. The dead zone includes the mechanical transmission dead zone, the main pressure distribution valve lap volume dead zone, etc., used to deal with the error value. The rate-limiting function of the follow-up system is the limiting amplitude fluctuation limit, and the saturation link is used to represent the working stroke of the relay, and its range is from full on to full off. The whole governor and electro-hydraulic servo model have high reliability.

Because variable speed pumping and storage unit is the focus of this paper, variable speed pumping and storage unit play a major role in regulating the power delivery capacity of the combined system, it is necessary to study the power regulation capacity of variable speed pumping and storage unit. According to the power of wind turbines deficiency and excess power, variable speed pump storage unit operation in power generation and pumping conditions respectively, for two kinds of working conditions affect the ability of the variable speed pump storage power unit static factor analysis respectively, find the key factors affecting the mechanical power output, it is important to note that in this case, the influence on the power active power.

1. Power generation conditions

The mechanical energy of a variable-speed pumping storage unit is converted into electrical energy through a water turbine. For different water heads, the speed and output power of the water turbine can be approximately expressed by a linear relation

$$\omega_r = -0.05 + 1.25\left(P_m - 0.8\right) - 0.25(h - 0.8) \tag{11}$$

After simplification, we get:

$$P_m = 0.8\omega_{\mathrm{r}} + 0.2h + 0.68 \tag{12}$$

Under different water heads, the guide vane opening and output power of the turbine can also be approximated by the following linear relationship:

$$P_m = G + \mathrm{h} - 0.8 \tag{13}$$

It can be seen from the approximate relationship that the output mechanical power of the hydraulic turbine is related to head, speed, and guide vane opening, and the relationship is a linear increase. According to the textbook, the mechanical power of the turbine also meets the following relations:

$$P_g = \rho g H_g Q_g \eta_g \tag{14}$$

where ρ is the density of water (kg/m3), g is the gravitational acceleration (m/s^2), Hm, Q_m, η_m water head (m), water flow (m^3/s) turbine efficiency respectively. Where, there is a coupling relationship between the water flow and the opening of the head and the guide vane, and there is a formula: G is the opening of the guide vane (mm).

When the variable speed pumping and storage unit is operating under electric conditions, the pumping process of electrical energy being converted to mechanical energy is mainly completed by the water pump. At this time, the output power of the water pump meets the following relationship:

$$P_e = \frac{\rho g H_e Q_e}{\eta_e} \tag{15}$$

Only H_e represents the pump head and η_e pump operating efficiency, and subscript E represents an electric working condition. Wherein, the pump head is related to rotational speed and water flow, and its specific formula can be expressed as follows, where a_0, a_1, and a_2 are constants.

$$H_e = a_0\omega_r^2 + a_1\omega_r Q_e + a_2 Q_e^2 \tag{16}$$

The above formula can be fitted to a descending conic.

4 Transient Stability Analysis of Variable Speed Pumping Storage Connected to the Power Grid

4.1 Model Overview

Figure 3 shows the single-line diagram of the CEPRI 7-node system. The system consists of 5 generators, 4 transformers, 4 ac lines, 1 DC line, 1 load, and 1 shunt reactor.

The multi-node grid electromechanical simulation model includes the first thermal power unit, the second thermal power unit, the first transformer T2W9, the second transformer T2W10, the third transformer T2W11, the fourth transformer T2W12, and the reactor. In the attached Fig. 1, G1 is the first 18 kV bus, G2 is the second 18 kV bus, B2-220 is the 220 kV bus, S1 is the 220 kV bus, B1-500 is a 500 kV bus, B3-500 is the 500 kV bus, B4-500 is 500 kV bus.

The first thermal power unit T1 is connected to the first 18 kV bus G1. The first 18 kV bus G1 is connected to bus B1-500 through the middle of the first transformer T2W9. Bus B1-500 is connected to bus B4-500 through two alternating current lines, and bus B3-500 is connected to bus B4-500 through two alternating current lines. The middle of bus S1 and bus B3-500 is connected through the fourth transformer T2W12, the middle of bus B2-220 and bus B1-500 is connected through the third transformer T2W11, the middle of bus B2-220 and bus B3-500 is connected through a DC line, Bus B2-220 is connected to the second 18 kV bus G2 through the second transformer T2W10 in the middle, where the second thermal power unit T2 is connected to the second 18 kV bus G2, and the first thermal power unit T3 is connected to the bus B2-220 (not shown in the attached picture), and the variable speed pumped storage unit V1 is connected to the bus S1. The load is connected to bus B2-220 and the reactor is connected in parallel to bus B4-500 (Table 1).

4.2 Effect of Cutting Machine Disturbance on Transient Stability of the System

Transient stability of a power system generally refers to the ability of synchronous generators to maintain synchronous operation and transition to the new or return to the original operating state when the power system is subjected to a large disturbance. The main indicators of whether the power system can maintain stable operation after large disturbance are

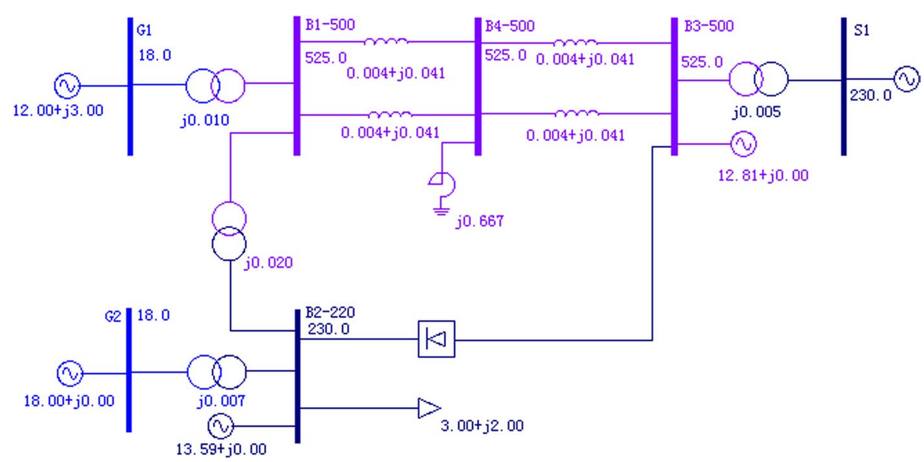

Fig. 3 Single-line diagram of CEPRI 7-node system

Table 1 Simulation parameters

Bus name	Reference voltage (kV)	Upper voltage limit (kV)	Lower voltage limit (kV)	Bus type
B1-500	525	550	490	AC
B2-220	230	230	200	AC
B3-500	525	550	490	AC
B4-500	525	550	490	AC
G1	18	18	15	AC
G2	18	18	15	AC
S1	230	230	200	AC

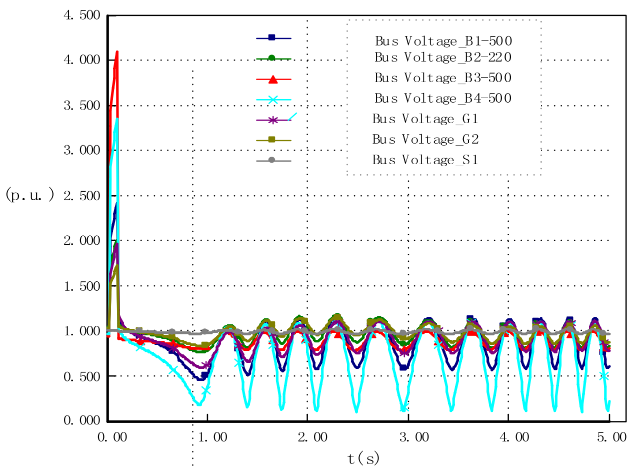

Fig. 4 Voltage fluctuation of each bus after cutting machine

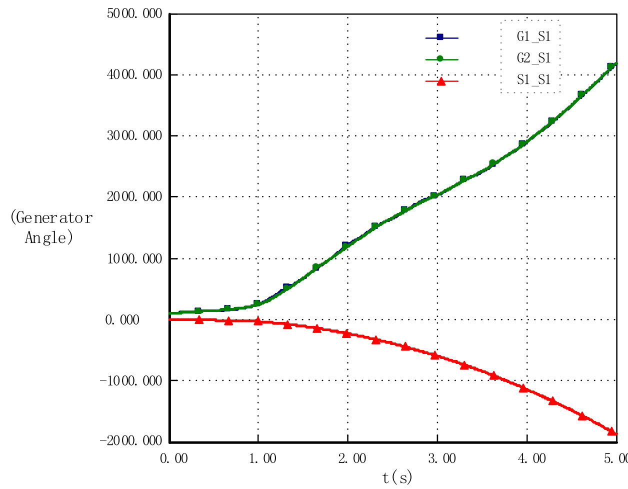

Fig. 5 The cutting machine disturbs the generator relative work Angle curve

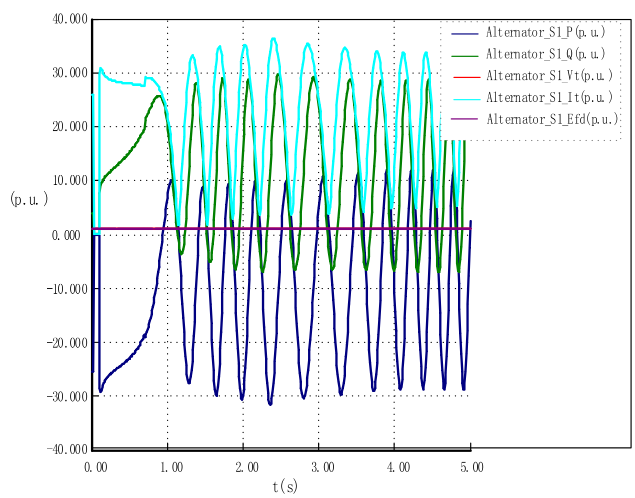

Fig. 6 Power, voltage, voltage, and current of bus policy of post-cutting variable speed pumped storage unit

as follows: first, whether the relative angular swing between each unit gradually attenuates; the criterion of power Angle stability is whether the relative power Angle difference of the generator is greater than 180°; when the power Angle difference is less than 180°, the transient power Angle is stable; otherwise, the system is unstable; The second is whether the voltage level in local areas is within the acceptable range. The criterion of transient voltage stability is that the central point voltage is not less than 0.8 pU and the duration is not more than 1 s after the system is disturbed, and the amplitude of voltage oscillation gradually decreases until it disappears.

The connection of variable speed pumped storage unit indirectly affects the stability of the power Angle of the system. Variable speed pumped storage units contain a large number of power electronic equipment, and the reactive power support capacity is weak during the disturbance, which has a great influence on the transient voltage stability of the system (Figs. 4, 5, 6 and 7).

In the multi-node network of a multi-node electrical and mechanical simulation model of a multi-node power grid, the connection between variable speed pumped storage unit V1 and bus S1 is cut off. Under the condition that variable speed pumped storage unit V1 is cut off, The bus voltages of bus B1-500, bus B2-220, bus B3-500, bus B4-500 the first 18 kV bus G1, the second 18 kV bus G2, and bus S1 in the multi-node network of the multi-node electrical and mechanical simulation model of the multi-node power grid are collected and connected to the first 18 kV bus G1 and the second 18 kV bus G2. The relative power angles of the first thermal power unit station T1, the second thermal power unit station T1, and the variable speed pumped storage unit V1 on bus S1 are collected. The port active power S1_P0 of the variable speed pumped storage unit and the port reactive power S1_Q0 of the variable speed pumped storage unit are collected. The port voltage S1_Vt0 of the variable speed pumped storage unit

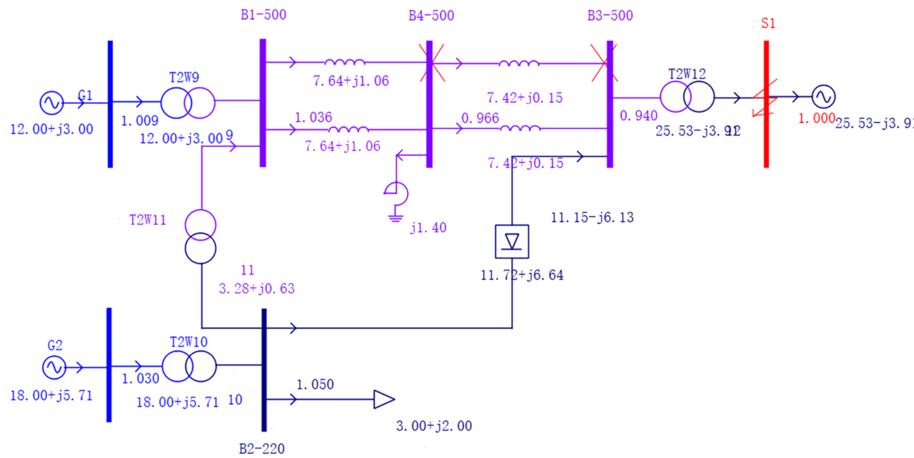

Fig. 7 Location diagram of the short-circuit fault in the multi-node network

and port current S1_It0 of the variable speed pumped storage unit are analyzed in the power system analysis comprehensive program database.

Set S1 as the pumped-storage power station and other buses are connected as the thermal power station. Observe the changes in the voltage of each bus in the multi-node network, the relative power Angle of each station, and the changes in the active power, reactive power, and voltage and current of the pumped-storage power station itself after the pumped-storage power station is removed. The value is the standard unit value. It can be seen that the voltage of each node in the multi-node network fluctuates greatly when the machine is switched off. The relative power Angle also gradually increases, and the active power, reactive power, voltage, and current of the bus connection with the variable speed pumped storage energy all fluctuate greatly.

4.3 Influence of short circuit fault on transient stability of the system

It can be seen from Fig. 8, 9 and 10 that the bus voltage drops to different degrees when faults occur, and the bus voltage that is closer to the electrical point of fault is more affected, and the bus voltage can return to a stable state after faults are removed. During the three-phase short-circuit fault, the maximum power Angle difference of each unit is greater than 180°, and the power Angle curve between each unit shows that the oscillation amplitude decreases with time, and the system is transient unstable.

4. Weak links between power grid stability and improvement measures

   4.1 Influence of short circuit fault on transient stability of the system

   4.2 Improvement measures

The three-phase short-circuit fault power grid system has the problem of over-limit voltage. A reactive power compensation device is adopted to improve the stability of the system. The measures are as follows:

2 × 2.5 mvar inductive reactive power compensation device is installed at bus S1;

Bus B3-500 is equipped with inductive reactive power compensation device 3 Mvar;

A 2 × 1.5 mvar inductive reactive power compensation device is installed at bus B4-500.

When a reactive power compensation device is added, the relative power Angle curve of the three-phase short-circuit fault power grid system is shown in Fig. 11. The voltage fluctuation of each bus is shown in Fig. 12. The bus policy power, voltage, and voltage current of variable speed pumped storage unit are shown in Fig. 13 after a short circuit fault increases reactive power compensation.

According to "Standard voltage (GB/T 156-2007), 220 kV bus of the power plant and 500 kV substation: under normal operation mode, the allowable voltage deviation is

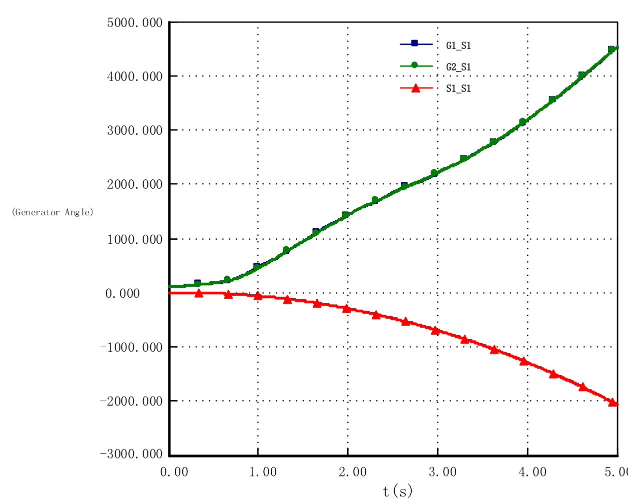

Fig. 8 Relative power Angle curve of short-circuit fault generator

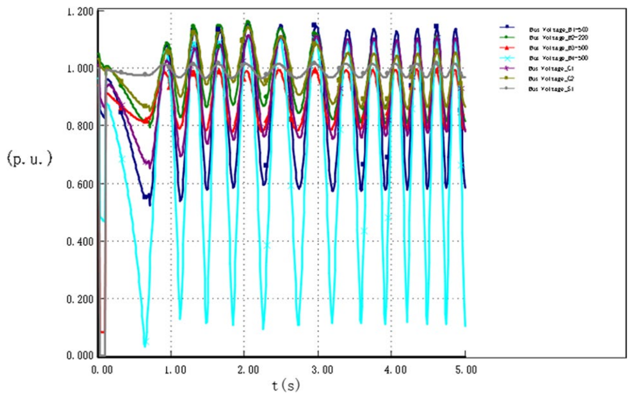

Fig. 9 Voltage fluctuation of each bus after short circuit fault

0 ~ + 10% of the rated voltage of the system; The operation mode of the accident is − 5% to + 10% of the rated voltage of the system. Maintain periodic stability, can keep balance with the original load value, cut the variable speed pumped storage unit V1 condition, all parameters can be restored to the stable range.

5 Conclusion

The purpose of this paper is to: Aim at the shortcomings of the existing technology, and provide variable speed pumped storage units of regional power network transient research plan, previous studies only consider basic variable speed pumped storage unit itself, or only consider the node power network itself, is not to contain the variable speed pumped

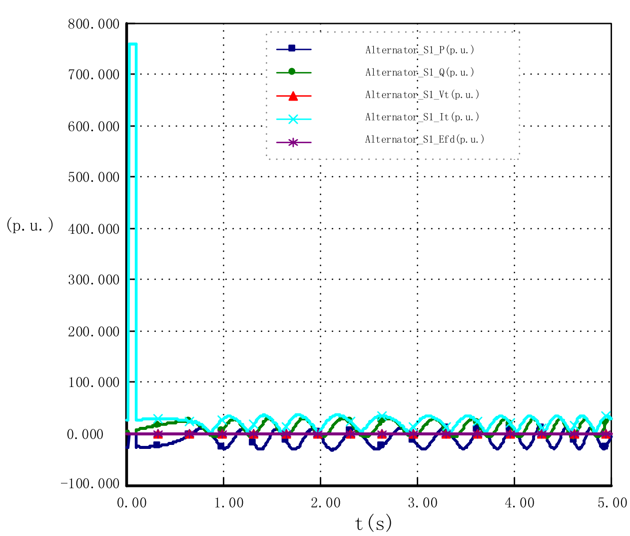

Fig. 10 Power, voltage, voltage, and current of bus policy of variable speed pumped storage unit after short circuit fault

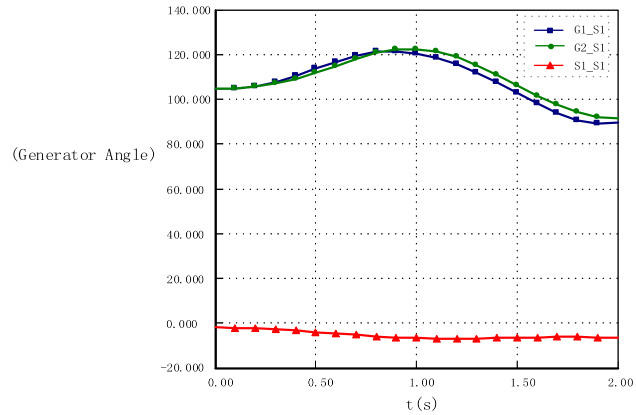

Fig. 11 After adding the reactive power compensation device, the relative power angle curve of the three-phase short-circuit fault power grid system

storage units multi-node system analysis, power network

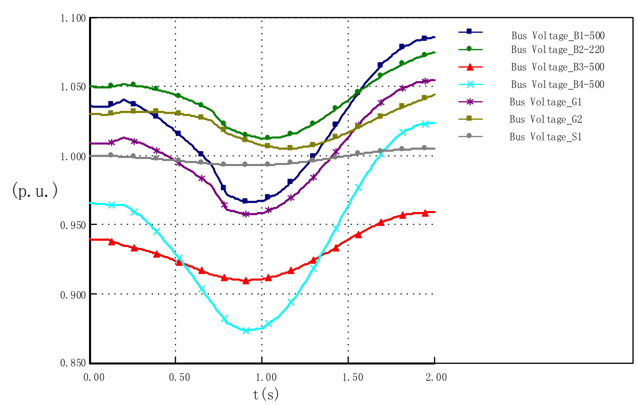

Fig. 12 The short circuit fault increases the voltage fluctuation of each bus after reactive power compensation

transient characteristics and the reactive power compensation device, introduced in this paper, the innovative, The

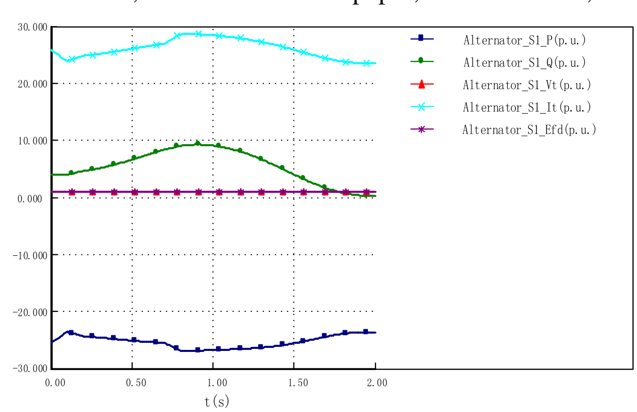

Fig. 13 Short circuit fault increases bus policy power, voltage, voltage, and current of variable speed pumped storage unit after reactive power compensation

influence of excised variable speed pumped storage unit and three-phase short-circuit fault on the transient stability of 7-node power grid is analyzed. The transient stability of the power grid can be maintained under the conditions of excised variable speed pumped storage unit and three-phase short-circuit fault, but some bus voltages are higher than the specified voltage upper limit. The reactive power compensation device is installed to improve the voltage stability of the power grid system, which can prevent the overvoltage accident caused by the fault of the communication system, achieve the purpose of multi-node power network stability, and improve the safety and stability of the regional power system when the fault occurs.

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Author Contributions CZ: Conceptualization, investigation, methodology, writing—original draft, writing—review and editing, project administration. LW: investigation, methodology, software. YM: writing—original draft, writing—review and editing, investigation. SJ: writing—review and editing, investigation. PX: writing—review and editing. YZ: funding acquisition, project administration, resources, supervision, validation. ML: conceptualization, funding acquisition, methodology, project administration, resources, supervision, validation.

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Declarations

Conflicts of interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Li Y, Jin Z, Wang Y, Yang R (2016) A robust sparse adaptive filtering algorithm with a correntropy induced metric constraint for broadband multi-path channel estimation. Entropy (Basel, Switzerland) 18:380
2. Xue S, Lu J, Sun Y, Wang S, Li B (2022) A reverse traveling wave differential protection scheme for DC lines in MMC–HVDC system with a metallic return. Int J Electr Power 135:107521
3. Zhang L, Harnefors L, Nee H-P (2010) Modeling and control of VSC–HVDC links connected to Island systems. IEEE Trans Power Syst 26(2):783–793
4. Li Z, Ping W, Zhu H, Chu Z, Li Y (2012) An improved pulse width modulation method for chopper-cell-based modular multilevel converters. IEEE Trans Power Electron 27:3472–3481
5. Liu Q, Zhang Y, Kong Y, Qianru W (2012) Improving VRSS-based vulnerability prioritization using analytic hierarchy process. J Syst Softw 85(8):1699
6. Saleh NA, Paşa S, Kayan, C et al (2019) Imine containing C_2-symmetric chiral half sandwich η6-p-cymene-Ru(II)-phosphinite complexes: investigation of their catalytic activity in the asymmetric transfer hydrogenation of ketones. J Mol Struct 1200:127146
7. Busca-Forces A, Marinescu C (2014) Pumped storage system for wind energy in variable operating conditions. In: International symposium on fundamentals of electrical engineering (ISFEE). IEEE, Bucharest, pp 1–6
8. Herrera-Viedma E, Chiclana F, Herrera F, Alonso S (2007) A group decision-making model with incomplete fuzzy preference relations based on additive consistency. IEEE Trans Syst Man Cybern Part B 37(1):176–189
9. Tolon FE, Karabuga A, Tolon M, Utlu Z (2019) Evaluation of thermodynamic analysis of solar energy systems integrated into sustainable buildings with artificial neural network: a case study. Procedia Comput Sci 158:91
10. Dan L, Qisong W, Yan Z, Liu Xin L, Jingyang SJ (2019) A study on quality assessment of the surface EEG signal based on fuzzy comprehensive evaluation method. Comput Assist Surg 24:167
11. Xuelin Y, Hongwei D, Ti Z, Yaguang Q (2019) A multistage fuzzy comprehensive evaluation of landslide hazards based on a cloud model. PLoS ONE 14(11):e0224312
12. Li X, Zhou D (2016) Research on a comprehensive evaluation of the financial innovation ability of the national-level new areas based on grey correlation. J Shanghai Jiaotong Univ (Sci) 21(2):204
13. Shim JW, Cho Y, Kim SJ et al (2013) Synergistic control of SMES and battery energy storage for enabling dispatchability of renewable energy sources. IEEE Trans Appl Supercond 23(3):5701205
14. Stefani A, Yazidi A, Rossi C et al (2008) Doubly fed induction machines diagnosis based on signature analysis of rotor modulating signals. IEEE Trans Ind Appl 44(6):1711–1721
15. Skinner B, Mancarella P, Vrakopoulou M, Hiskens I (2020) Incorporating new power system security paradigms into low-carbon electricity markets. Electr J 33:106837
16. Lung JK, Lu Y, Hung WL et al (2007) Modeling and dynamic simulations of doubly fed adjustable-speed pumped storage units. IEEE Trans Energy Convers 22(2):250–258
17. Teshager B, Han M, Meng Z et al (2017) Phasor model simulation of grid integrated variable speed pumped storage system. J Eng 2017:1002
18. Castronuovo ED, Lopes JAP (2004) On the optimization of the daily operation of a wind-hydro power plant. IEEE Trans Power Syst 19(3):1599–1606
19. Wierzejski M, Bogalecka E (1993) Control system of doubly-fed induction machine working as a generator. In: Proceedings of the international intelligent motion conference. Intertec International, INC
20. Shan C, Zihao Y, Ye L, Xianwang Z (2022) Power system transient stability assessment based on the multiple paralleled convolutional neural network and gated recurrent unit. Protect Control Mod Power Syst. https://doi.org/10.1186/s41601-022-00260-z
21. Kangkang W, Han D, Wei W, Tannan X, Ying C, Bo Z (2022) Power system transient security assessment based on multi-channel time series data mining. Energy Rep 8(S13):843
22. Rama Murthi M, Hogg BW (1971) Transient performance of doubly excited synchronous machine. Proc Inst Electr Eng 118(118):143–147
23. Zhou G, Han M, Filizadeh S, Cao X, Huang W (2021) Studies on the combination of RSFCLs and DCCBs in MMC-MTDC system protection. Int J Electr Power 125:106532

24. Mukherjee D, Chakraborty S, Ghosh S (2021) Power system state forecasting using machine learning techniques. Electr Eng 104:283–305
25. O'Dwyer C, Flynn D (2015) Using energy storage to manage high net load variability at sub-hourly time-scales. IEEE Trans Power Syst 30(4):2139–2148
26. Adak S (2021) Harmonics mitigation of stand-alone photovoltaic system using LC passive filter. J Electr Eng Technol 16:2389–2396. https://doi.org/10.1007/s42835-021-00777-7
27. Adak S, Cangi H, Eid B, Yilmaz AS (2020) A developed analytical expression for current harmonic distortion of the PV system's inverter in relation to the solar irradiance and temperature. Electr Eng 103:697
28. Muljadi E, Singh M, Gevorgian V et al (2015) Dynamic modeling of adjustable-speed pumped storage hydropower plant. Power Energy Society General Meeting, IEEE

Chong Zhao was born in Dalian, Liaoning, China, 1981. He received Master's degree in power systems and automation from Shenyang University of Technology in 2007. He is currently a PhD student at the School of New Energy, North China Electric Power University, conducting technical research in the direction of evaluating the coordination capability of variable speed unit pumped storage power plants in flexible and direct grids.

Longze Wang was born in Jiling, Jiling, China, 1988. He received his PhD in renewable and clean energy from North China Electric Power University in 2022. Now he is working as a postdoctoral lecturer in the School of New Energy at North China Electric Power University. His research interests are integrated energy microsystems and the efficient use of new energy power, etc.

Yiyi Ma was born in Lishui, Zhejiang, China, 1999. He received Bachelor's degree in new energy science and engineering from North China Electric Power University, Beijing, China in 2021. Now he is pursuing the Master's degree at the School of New Energy, North China Electric Power University. His research interests are integrated energy system and carbon emission accounting.

Pengfei Xiang was born in Enshi, Hubei, China, 1998. He received Bachelor's degree in Electrical and Information Engineering from Hunan University in 2020. He works for the West-to-East Gas Transmission Company of the National Official Website Group. Now he is pursuing the Master's degree at the School of New Energy, North China Electric Power University. His research interests are integrated energy microsystems and integrated energy system.

Siyu Jiang was born in Yili, Xinjiang, China, 1998. She is pursuing the engineering Master's degree in New Energy College of North China Electric Power University. Her current research interests include integrated energy system and blockchain.

Weidong Chen was born in Chaoyang, Liaoning, China, 1996. He is currently pursuing his PhD at the School of Electrical Engineering, Shenyang University of Technology. His main research interests are in the analysis of new energy grid connection characteristics, power control of flexible DC transmission systems, and transient stability analysis of power systems.

Yan Zhang was born in Heilongjiang, China, 1975. She received her PhD in Management from the School of Business, Renmin University of China. Now she is a professor at the School of Economics and Management of North China Electric Power University, a doctoral supervisor and the director of the Institute of New Energy Management and Assessment. Her research interests are environmental accounting, energy management and investment, carbon planning management, etc.

Meicheng Li was born in Heze, Shandong, China, 1973. He received his PhD in Materials Physics and Chemistry from the Harbin Institute of Technology in 2001.He is a second class professor and doctoral supervisor at North China Electric Power University. Now he is the Dean of the School of New Energy and the Director of the Research Centre for New Energy Materials and Photovoltaic Technology at North China Electric Power University. He is a permanent researcher in the State Key Laboratory of New Energy Power Systems. He is in charge of the first batch of "New Energy Materials and Devices" in the national strategic emerging industries. His research interests are solar cells and solar energy utilisation technologies, lithium/sodium ion batteries and energy storage technologies, micro-energy and smart energy systems, etc.