Research on dynamic simulation technology and fault characteristics of Pumped Storage Power Station

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Abstract. The fault equivalent circuit model of the pumped storage unit is established, the key electrical parameters of the generator motor of the pumped storage power station are analyzed, and the short-circuit fault characteristics of the generator motor of the pumped storage power station are studied. Based on the typical connection mode of pumped storage power station, a dynamic model test platform including dynamic model pumped storage unit, excitation system, frequency conversion starting device and its control system is established. The dynamic model tests of metal or transition resistance short circuit fault, stator ground fault and stator turn to turn short circuit are carried out.

1. Introduction

With the rapid economic growth, wide application of distributed generation, and gradual increase of large-capacity inter-regional networking projects, pumped storage power stations which can better cope with large-scale load changes will have a more rapid development. In the next few years, the State Grid Corporation will start the construction of pumped storage power station in an all-round way. The connection of pumped storage power plants will have a great impact on the voltage stability, power quality and power supply reliability of power grid [1, 2].

Pumped storage power station is to solve the contradiction between supply and demand between peak and trough of power grid [3, 4, 5]. It is a way of indirect storage of electric energy. It uses excess electricity in the second half of the night to drive pumps, pumping water from the lower reservoir to the upper reservoir for storage, and then releasing the water into the lower reservoir during the next day or in the first half of the night to generate electricity. In the whole operation process, although part of the energy will be lost during the conversion, the use of pumped storage power stations is still cheaper and more effective than the construction of additional coal-fired power generation equipment to meet peak power consumption and the situation of pressure and shutdown at low valleys. Besides, Pumped Storage Power Station can also take on dynamic functions such as frequency modulation, phase modulation and accident reserve. Therefore, pumped storage power station is not only the power point, but also the power user, and becomes an important tool for the operation and management of the power grid, and is the pillar to ensure the safety, economy and stable production of the power grid[6, 7]. In this paper, the dynamic simulation technology and fault characteristics of Pumped Storage Power Station is analyzed. The analysis of the fault characteristics and the study of the dynamic simulation method will provide a strong theoretical basis for its safe and reliable operation in the future[8, 9].

The study of the change of the fault short-circuit current of the generator motor in pumped storage power station is of great significance to the analysis of the influence of the pumped storage unit on the
system when the fault occurs, and to the determination of the sensitivity of the related protection of the pumped storage unit, as well as to the provision of the setting basis for the related protection.

The research on the dynamic simulation technology of pumped storage power station can provide a research platform for the impact of pumped storage power station on power system and relay protection device, and also provide a test platform for the test of protection device of generator motor transformer unit.

2. Fault characteristics analysis of pumped storage units

2.1. Preliminary analysis

No matter synchronous motor or synchronous generator, the short-circuit current provided by the generator or system is only related to the reactance, time constant and short-circuit fault location of the motor. The typical parameters of 300MW Generator Motor and 300mva conventional generator supplied by a motor factory are shown in Table 1, which only lists the relevant parameters affecting the fault characteristics of synchronous units.

| parameters                  | Direct axis short circuit transient time constant | Direct axis short circuit subtransient time constant | Quadrature axis short circuit transient time constant | Quadrature axis short circuit subtransient time constant | Quadrature axis synchronous transient reactance | Direct axis synchronous transient reactance | Direct axis subtransient reactance X''d |
|-----------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| generator motor             | 3.59                                          | 0.17                                          | 0.18                                          | 70.82                                          | 107.81                                         | 72.27                                          | 20.14%                                         |
| conventional generator      | 1.13                                          | 0.035                                         | 0.035                                         | 38.11                                          | 204.5                                          | 194.6                                          | 19.95%                                         |

Comparing the key parameters of generator motor and conventional generator:

1. The quadrature axis transient reactance $X'_q$ of generator motor is much larger than that of conventional generator, and the direct axis synchronous reactance $X_d$ and quadrature axis synchronous reactance $X_q$ are much smaller than that of conventional generator;

2. The time constant of Q or D axis short circuit subtransient of generator motor is much larger than that of conventional generator.

2.2. Analysis of steady state short circuit current

2.2.1. Fault equivalent circuit of generator motor

The fault equivalent circuit of synchronous generator and generator motor is shown in Figure 1. In the figure, the short-circuit point $f_1$ is at the generator end of the generator motor, and the short-circuit point $f_2$ is at the high-voltage side of the main transformer.

![Figure 1. Fault equivalent circuit of synchronous generator and generator motor.](image)

2.2.2. Sensitivity check

According to figure 1, when the minimum two-phase short circuit occurs at the generator end:

$$I_{d,\text{min}} = 0.866 \times \frac{1}{X''_d} \times I_{gn} \quad (1)$$

Where: $X''_d$ is the direct axis subtransient reactance with the rated capacity of the generator motor as the reference capacity; $I_{gn}$ is the rated current of the generator motor.
For the parameters of $X''_d$, 20.14% for generator motor and 19.96% for conventional generator. It is known from equation (1) that under typical parameters, the short-circuit current is basically the same when the two-phase short circuit is the minimum at the generator end. For the same fixed value, the complete differential protection of conventional generator should be slightly sensitive.

2.3 Analysis of transient short circuit current

When the stator winding of generator or generator motor is suddenly three-phase short circuit, the starting value of stator armature current is closely related to the time of short circuit. When the rotor position angle $\gamma = 0$, the flux of phase $a$ at the moment of fault is the maximum value, which is the maximum non periodic current generated by the protection of the stator armature loop flux.

According to the theory of motor transition process, the current of phase $a$ is:

$$i_a = \frac{1}{2} E \left( \frac{1}{X''_q} + \frac{1}{X''_d} \right) (1 - \cos t) + \frac{1}{2} E \left( \frac{1}{X''_q} - \frac{1}{X''_d} \right) (\cos 2t - \cos t)$$

(2)

Where: $E$ is the potential in the generator, $t$ for the time.

For the hidden pole machine $X''_d \approx X''_q$. Therefore, the above formula can be simplified as:

$$i_a = \frac{E}{X''_d} (1 - \cos t)$$

(3)

For 50Hz power system, when $t = 0.01$s, the maximum A-phase current is about $2 / X''_d$. Therefore, for the generator, the maximum value of A-phase current after fault is about 10.02; for the generator, the maximum value of A-phase current after fault is about 9.93. In other words, the short-circuit current of generator motor and generator is about the same.

2.4 Analysis of transient process

For the time constant of Q or D axis short circuit subtransient, the generator motor is much larger than the conventional motor. Therefore, for the conventional generator, the current of rotor damping winding and excitation winding caused by fault starts to decay from the occurrence of fault, the current of damping winding decays very fast, and the process of generator motor is much slower. However, the RMS values of the transient currents is about the same.

The damping winding is no longer effective in the transient process, and the speed of the stator fundamental current transient process will depend on the direct axis short-circuit transient time constant. Therefore, the fault transient current of generator motor is almost the same as that of conventional generator, but the attenuation speed of generator motor is much slower.

When the aperiodic component of the excitation current caused by the fault decays to zero, the armature current decays to the steady-state value is $E / \sqrt{X_d}$. The effective value for generator motor is 0.65, and for the generator is 0.35. So the steady-state current of the generator motor is 1.9 times of that of the generator.

3. Study on dynamic simulation technology of Pumped Storage Power Station

3.1. Dynamic model system for Pumped Storage Power Station

The dynamic simulation system of pumped storage unit including SFC and excitation system is established. SFC is used to start the pumped storage unit, and the synchronization device captures the grid connection mode. After the grid connection, SFC exits. In the pumped storage unit, DC power generation or motor is used to simulate water pump or turbine, DC generator state is used to simulate water pump pumping load with resistance load, and DC motor operation state is used to simulate water turbine to drive synchronous generator for power generation. The main parameters of the laboratory pumped storage unit model are shown in table 2.
Table 2. Main parameters of pumped storage unit.

| parameter s                                      | Rated capacity | Rated voltage | Rated current | Rated speed | Direct axis transient reactance $X'_d$ | Quadrature axis subtransient reactance $X''_q$ | Direct axis subtransient reactance $X''_d$ |
|-------------------------------------------------|----------------|---------------|---------------|-------------|----------------------------------------|-----------------------------------------------|---------------------------------------------|
| Dynamic simulation unit                          | 3.59           | 0.17          | 0.18          | 70.82       | 107.81                                 | 72.27                                         | 20.14%                                      |
| Actual unit on site                              | 1.13           | 0.035         | 0.035         | 38.11       | 204.5                                  | 194.6                                         | 19.95%                                      |

Main wiring diagram of dynamic model test system of Pumped Storage Power Station is as Figure 2.

![Diagram](image_url)

Figure 2. Main wiring diagram of dynamic model test system of Pumped Storage Power Station.

The pumped storage unit is a protected equipment. The transformation ratio of the current transformers TA76 and TA77 at the head and end of the pumped storage unit is 20 / 5, and the analog transformation ratio is 12500 / 5; the transformation ratio of the current transformers TA28 at the high voltage side of the step-up transformer and the current transformers TA17, TA18 and TA71 in the series is 10 / 1, and the analog transformation ratio is 1000 / 1. During the test, five fault points are set in and out of the protected equipment area, and their numbers are FD11, FD16, FD49, FD50 and FD51.
respectively. Each fault point can simulate various types of metal or transit resistance short-circuit fault. In addition, it can also simulate the fault tests such as stator grounding and stator turn to turn short circuit.

3.2. Dynamic simulation test of Pumped Storage Power Station

3.2.1. Metallic failure test

The faults of FD11 and FD16 point are simulated, which the metallic instantaneous faults of single-phase grounding, two-phase grounding, two-phase grounding, three-phase short-circuit and three-phase short-circuit grounding occur respectively. Among them, the short circuit waveform for a phase of FD11 is shown in Figure 3.

![Figure 3. metallic instantaneous faults of single-phase grounding.](image)

3.2.2 Developmental and transformative fault testing

60ms after single-phase ground fault occurs at AN of FD11, single-phase ground fault occurs at BN of FD16. The short circuit waveform is shown in Figure 4.

![Figure 4. Developmental and transformative fault waveform.](image)

3.2.3. One point ground fault of stator

Simulating the single-phase grounding metal fault of FD48 at the low voltage side of transformer, FD49 at the generator end and FD50 at the neutral point of generator motor. Among them, simulate the one-point grounding fault of an at the generator end of the generator motor, and the short-circuit waveform is shown in Figure 5.

![Figure 5. one point ground fault of stator.](image)
3.2.4. Turn to turn fault of stator
FD51 with different turn ratio is set in the stator loop winding of generator to simulate the inter turn fault of generator. The inter turn range is from 2.5% to 12.5%. Simulate 2.5% turn to turn fault of generator motor, and the short circuit waveform is shown in Figure 6.

Figure 6. turn to turn fault of stator.

4. Conclusion
(1) The maximum value of A-phase current after fault of generator motor is equivalent to that of generator, and the decay speed of fault super transient current and non periodic component is much slower, when three-phase short-circuit fault occurs at the generator end.
(2) The effective value of stator transient current after generator motor fault is equal to that of generator, but the attenuation speed is much slower than that of generator, when three-phase short-circuit fault occurs at generator end.
(3) The fault steady-state current of the generator motor is about 1.9 times that of the generator, when the three-phase short circuit fault occurs at the generator end.
(4) The dynamic simulation test system of pumped storage unit can simulate the fault characteristics of pumped storage unit, and can be used to test the action characteristics of relay protection device.

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