Study on cause analysis and detection method of inter-turn short circuit fault of large turbine generator rotor

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Abstract
Short circuit between turns of the rotor winding of large turbogenerator is one of the common faults which adversely affect the safe operation of generator, the bad effects include overheating of the short circuit point, thermal bending, intensified vibration of the rotor, magnetization of the large shaft, etc. In this paper, the characteristics of inter-turn short circuit fault of rotor insulation structure are analyzed, and the optimal diagnosis method for generator running state and shutdown state is obtained with examples.

Key words : generator, rotor, inter-turn, short circuit

1. Introduction

The inter-turn short circuit fault of rotor winding is a common fault in generator operation. It is estimated that no less than 50% of the turbine generators in service in North America have interturn short circuit faults[1]. After a decade of rapid development from 2008 to 2018 in China, domestic thermal power has made brilliant achievements, but there are also some hidden dangers in the reliability of generator equipment.

Researchers across the world have conducted a large number of studies on the diagnosis methods of insulation failure between turns of excitation windings[2~4]. Traditional methods, such as DC resistance method[5] and AC impedance method[6], have rich practical experience, but their effectiveness is poor. New test methods include RSO method[7], detection coil waveform method, stator circulation analysis method[8], and axial voltage method [9], among which RSO method has gradually become a necessary item for overhaul. Detection coil waveform method is limited by sensors and is used less frequently, while stator circulation and axial voltage method are mainly concentrated in theoretical and simulation research stages.

The principle of various detection methods will be discussed in the following part of this paper, and the appropriate diagnosis method will be selected according to the equipment state to realize the accurate judgment of the insulation state between turns of the excitation windings of large turbo-generator.

2. Analysis of rotor insulation

A two Pole rotor body milling along the circumference has a number of axial grooves, which are used to arrange excitation windings, each groove winding around the direction of the large axis rotation arrangement of many twists, between the radon and the arrangement of epoxy glass plate insulation. The cooling design of the rotor winding grooves of large turbine generators with 600MW and above capacity class is show as below.

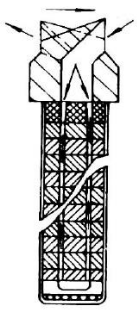

Fig.1 Schematic diagram of rotor ventilation structure

The inner part of the rotor winding and inter-shaft insulation design has two vents, the overall composition of the internal hydrogen cooling duct. For in-slot windings, the general inter-tunnel failure occurs mostly near the cooling duct or at the inter-tunnel insulation stitching region, see Figure 2. The reason is that the installation or maintenance causes the generator internal metal foreign material, in operation with the cooling hydrogen in the air duct distribution, if there is a difference between the size of the insulation duct and winding duct size, the foreign body will stay there, the rotor heat cycle increased the number of wear, resulting in the failure of the insulation between the turns.

Fig.2 Failure spot close to the vents

End windings are more exposed to foreign bodies than in-groove windings. On the one hand, the end winding support is relatively small, while the straight-line winding thermal stress, centrifugal force and additional thermal stress during the inlet run. On the other hand, the end winding manufacturing process will also bring hidden dangers, end winding needs to be shaped and bent, which inevitably causes the problem of gap cooperation between multi-twisting windings, especially in the area of straight line and over-angle, copper wire thickness is uneven leading to insulation wear in the operation. Taken together, it can be seen that the insulation operating environment between the ends is more demanding, easy to become a frequent area of short-circuit failure between the two, see Figures 3 and 4.

Fig.3 Failure spot aroud the corner

Fig.4 Displacement of the inter-turn insulation

During generator operation, the rotor insulation is subject to electrical, thermal, mechanical stress and environmental factors. The thermal effect of the current in the winding leads to the generation of thermal stress, and the change of the motor load causes the change of the winding temperature. Due to the different expansion coefficients of the copper conductor and the inter-turn insulation material, after many thermal cycles, the bond between the inter-turn insulation and the conductor will be destroyed, especially when a large area of thermal power plants participate in peak shaving operation, the load will be fast in a short time The change greatly increases the thermal stress on the rotor insulation. The mechanical stress on the rotor is mainly the centrifugal force borne by the insulating structure in the high-speed rotating rotor. Environmental factors refer to a series of surrounding conditions that cause the generator to fail, such as excessive hydrogen humidity, winding condensation, generator oil, foreign matter or conductive particles, dust, etc. Each of these factors affects the insulation strength of the rotor in different ways. In most cases, multiple factors work together to

eventually cause the insulation failure between the rotor turns.

3. Analysis of detection methods

3.1 Diagnosis method of shutdown state

3.1.1 DC resistance

For generators with a capacity range from 600MW to 1000MW, the typical DC resistance value of the rotor at 20℃ is 60mΩ to 100mΩ. According to the current common rotor design, the rotor winding structure is generally 32 grooves,16 sets of windings, in an extreme case No.1 winding 4, No.2 to No.8 winding 7. A total of 106. For a common short circuit between the crucifists, the DC resistance is theoretically reduced by 0.94%in terms of loss of 1 winding.

The electric power industry standard of China stipulates that the difference between the measured DC group in the cold state and the first (handover or overhaul) measured result is generally no more than 2%. For the rotor of a generator with a capacity of 300MW, the number of turns tends to be more. For a generator rotor with an inter-turn short circuit fault, it cannot be distinguished by the DC resistance test alone.

3.1.2 AC impedance test

The rotor winding AC impedance test wiring is shown in Figure 5, using a regulator to apply an ALTER voltage of different amplitudes between the rotor's positive and negative poles and to record the total active loss and equivalent impedance of the rotor. According to the theoretical analysis, when a short circuit occurs between the turns, it is equivalent to a secondary side short circuit of a self-coupled transformer, and the short-circuit current is N(N is the total number of revolutions) times the excitation winding current, whose strong degaussing effect will increase the magnetic resistance of the circuit, the external manifestation is that the AC impedance decreases and the power loss increases.

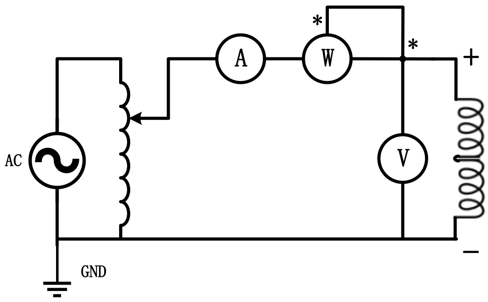

Fig.5 Diagram of the AC impedance test

The effectiveness of the AC impedance method must be based on the same test conditions, such as test voltage, rotor position (inside or outside the chamber), speed, interference with the surrounding magnetic field, etc., the above conditions are consistent, the resistance and power loss of previous tests can be compared vertically.

The AC impedance result should be judged to be a fault if one of the following conditions occurs:

a) The impedance is reduced by more than 10% compared to factory or historical data;

b) Increase by more than 10% compared to factory or historical data;

c) When the AC impedance is reduced by more than 8% compared to factory data or historical data, and the loss increases by more than 8%compared to factory data or historicaldata;

d) When more than 5% of the AC impedance or loss value of the same voltage mutates at adjacent speeds during the rotor boost and descent.

Through the above criteria, it can be seen that the AC impedance or power loss limit is large, field operation is only based on the AC impedance method of a single experimental results, it is difficult to determine whether there is a short circuit between the crucibles.

3.1.3 Polar voltage balance method

The pole voltage balance method is based on the AC impedance method and utilizes the symmetry of the rotor structure. The test results greatly eliminate the interference caused by the test conditions on the AC impedance method. There is no need for longitudinal comparison, just by comparing the voltage of the positive pole and the inter-electrode connecting line, and the negative pole and the inter-electrode connecting line voltage, a conclusion can be drawn, and the inter-turn short-circuit fault is located at which pole.

3.1.4 RSO test

RSO (repeated pulse method) is a diagnosis technology for inter-turn short circuit of generator rotor proposed by British expert J.W. Wood based on wave process theory. It can be used for early detection and fault location of inter-turn short circuit of generator rotor, and it does not need to install equipment inside turbine generator.

Fig.6 shows the lossless transmission line distribution parameter model of wave process theory. When the switch of DC power supply E is turned on, the power supply charges the capacitor, and an electric field is set up around the wire. The capacitor near the power supply is immediately charged and discharged to the adjacent capacitor. Because of the inductance, the capacitor at a distance takes some time apart to be charged, which means that voltage waves travel along the path at a certain speed.

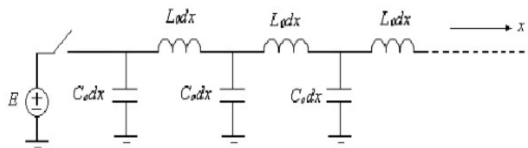

Fig.6 A model of lossless transmission line

At the same time, as the line's capacitance is charged and discharged, the current builds up a magnetic field around the wire. Current waves travel along the road at the same speed. The propagation process of voltage wave and current wave along the wire is actually the propagation process of electromagnetic wave along the road, referred to as wave process. When traveling waves move along a wire, reflection and refraction phenomena occur at connection points of different wave impedances or at connection points of several parameter impedances (see Fig.7). The degree of reflection and refraction of traveling waves can be expressed by reflection coefficient and refraction coefficient. Based on the theoretical calculation of lossless transmission line wave, the relation between voltage wave and current wave and the calculation formula of traveling wave refraction and reflection are obtained, Fromula（1）~（5）is listed below.

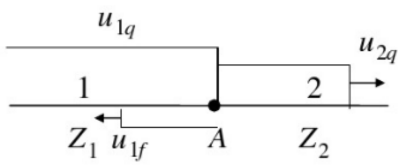

Fig.7 Reflection and refraction of electromagnetic wave

$$u_{1q} = i_{1q}Z_1 \qquad (1)$$

$$u_{1f} = -i_{1f}Z_1 = \alpha_u u_{1q} \qquad (2)$$

$$u_{2q} = i_{2q}Z_2 = \beta_u u_{1q} \qquad (3)$$

$$\alpha_u = \frac{Z_2 - Z_1}{Z_1 + Z_2} \qquad (4)$$

$$\beta_u = \frac{2Z_2}{Z_1 + Z_2} \qquad (5)$$

The wave process in a rotating motor winding is similar to the wave process in a transmission line,and the RSO pulse test is based on the wave process theory in the winding, using the symmetry of the rotor winding (the windings of the two poles are almost identical at each pole) to apply square waves or pulses between the rotor winding and the ground, alternating at certain frequencies at both ends of the winding (see Figure 8). If there is no fault then measured two exactly the same waveform, the reverse indicates that there is a fault, because of the location and degree of short circuit between the two, the moment and degree of reflection, refraction of the wave is not the same, so the corresponding waveform signal measured must contain the information of the short circuit fault between the ripples.

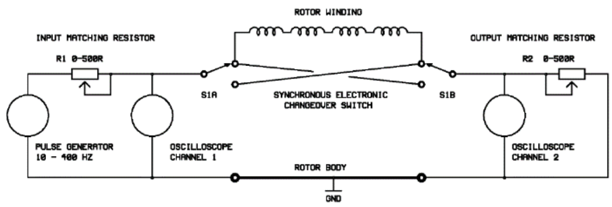

Fig.8 Diagram of the RSO test

There are two main types of excitation applied to the rotor by the RSO test equipment, one is square wave and the other is pulse. The turbine generator rotors, which are properly insulated between the crucibries, apply two excitation waveforms, as shown in Figures 9 and 10. Both waveforms are applied between the rotor winding and the large axis and have similar steep forward waveform rise segments, the pre-wave time depending on the on rate of the electronic switch, typically around 1 s. The difference is that the overall waveform amplitude of the horizontal segment after the square wave has risen is the same, such as somewhere there is a defect in the insulation, impedance mutation, the difference between the two polar waveforms is based on the same benchmark worth it, convenient for horizontal comparison of different rotors. The pulse method begins to decay and decrease after the waveform passes up the edge, if there is a defect in the insulation somewhere, the impedance mutates, and the reference value of the difference between the two polar waveforms at different locations is different. Therefore, the RSO test uses square-wave output waveforms for better consistency and facilitates lateral comparison of different rotors.

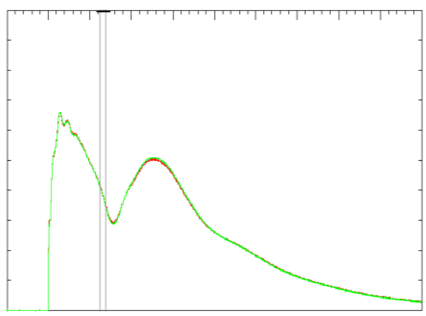

Fig.9 Typical waveform using pulses

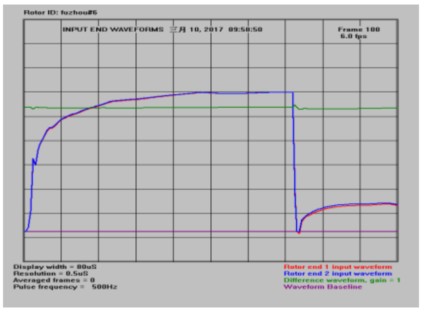

Fig.10 Typical waveform using square wave

3.1.5 Other methods

The coil voltage method and the inter-twisting voltage distribution method, when the rotor applies voltage with the help of a probe, one by one to measure the voltage between each coil and the corresponding pole or between all adjacent windings. Finally, according to the voltage distribution, the location of the short circuit fault point between the two systems is determined.

In view of the potential hazards of short-circuit failure between rotors and the uncertainty of the timing of these hazards, the general power station professionals for the rotor inter-circuit short-circuit fault repair strategy is that no matter where the short-circuit fault is located, should be thoroughly dealt with as soon as possible, treatment options include return-to-plant repair or on-site repair. Therefore, considering the effectiveness of coil voltage method and inter-twisting voltage distribution method for fault location, it can be combined with other test methods when conditions are available.

3.2 Diagnosis method of running status

3.2.1 Detecting coil waveform method

This detection method is suitable for generators with flux probes such as detection coils installed in the generator stator chamber (see Figure 11),because each rotor groove produces leakage flux on the rotor surface, when the generator is running, each rotor slot is sensing voltage when it passes through the probe, which is shown as the leakage flux of each groove produces a peak of the induction voltage on the detection coil. Each peak represents the size of the leakage flux around a rotor slot. If there is a short circuit between the turns of a coil, the wave peak corresponding to the two grooves associated with it will be reduced because the number of amps in the two grooves is smaller, and therefore the leakage flux is less, so the voltage induced in the flux probe is reduced. Since the leak flux is only one of three components in the air gap flux (the other two are the armature reaction flux generated by the rotor main flux and stator current), the highest detection sensitivity for the leak flux requires measurement when both components are approximately zero. The main limitation of this experiment in the past was that measurements under different load conditions had to be carried out from the empty load to the full load range, and the adjustment load caused the total magnetic pass-through zero to occur for each pair of poles.

Fig.11 Layout of the probe coil

The method of detecting coil waveforms is as follows.

$$U_{\mathrm{j}} = \frac{|U_{1j}-U_{2j}|}{\max(U_{1j},\ U_{2j})} \times 100\% \qquad (6)$$

$$U_{\sigma j} = \frac{1}{N} \times k \qquad (7)$$

U_{1j}: Voltage of coil No.j of the first pole, V; U_{2j}: Voltage of coil No.j of the second pole, V; N: number of grooves measured by rotor ; k: shortcircuit index; U_j: Coil feature value No.j; $U_{\sigma j}$- Coil Limit of No.j.

The selection of short-circuit index directly affects the judgment of short-circuit fault, and through the research and research of on-line monitoring equipment to detect coil waveforms at home and abroad, the setting is as follows:

a) DL/T 1525-2016《The Guidelines for Short-circuit Troubleshooting between The Rotors of cylindrical-rotor Synchronous Generators》, k is set to 0.45;

b) The standard of judgment provided by the IRIS power RFA type device , k is set to 0.6;

c) The standard of judgment provided by the

Generator Tech(Model9610) device, k is set to 0.75;

d) Domestic Guangzhou HAOzhi ROM type, Shanghai Sree RMM-RSM type, Harbin Guoli Electric FZGL-20 type and other generator rotor short circuit online device, the current alarm value is set according to industry standards.

3.2.2 Operation parameter comparison method

The operating parameter comparison method has low sensitivity in diagnosing inter-turn short circuits, and an accurate judgment can be made only when multiple inter-turn insulation fails.

4. Diagnosis case

4.1 Generator overview

Generator model QFSN-600-2-220, rated capacity/rated power of 667MVA/600MW,rated power factor 0.9,rated voltage 22kV,rated excitation voltage 431V,rated excitation current 4366A,11th year 2010 The month is officially put into operation. The generator rotor has a total of 32 wire grooves, each large tooth corresponding to a set of windings, each of which consists of 8 sets of concentric coils of different sizes, each with the number of turns of 4,7,7,7,7,7,7,7.

4.2 Fault diagnosis process

4.2.1 RSO test

Figure 12 shows the input voltage waveform measured from both ends by applying repeated square waves at both ends of the rotor (red for rotor pole 1 corresponds to the collector ring, blue for rotor pole 2 corresponds to the collector ring, and green for the two waveform subtraction curves), the two waveforms begin to separate at 14.2μs (one-way propagation time 15.6μs), the green curve produces a spike at the same location. The reason why the two waveforms cannot fully coincide is not a short circuit between the turns, but also a slight difference in the waveform due to poor contact between the ground end of the device and the rotor shaft.

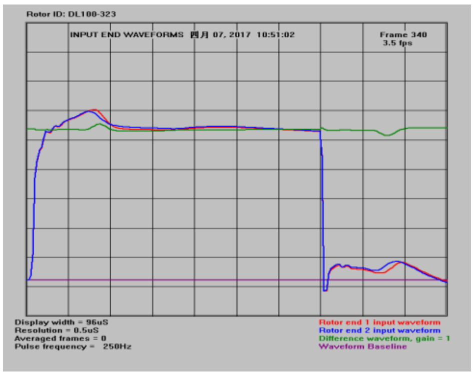

Fig.12 Result of the RSO test

The fault point distance from rotor pole 2 collector ring distance of about 45.5% of the total length of the rotor, 50% position is the position of the inter-pole cable, that is, the point of failure is located in the pole 2 8th set winding

4.2.2 Detection coil waveform method

The detection graph and data of the detection coil waveform method are shown as Fig.13 and Table 1.

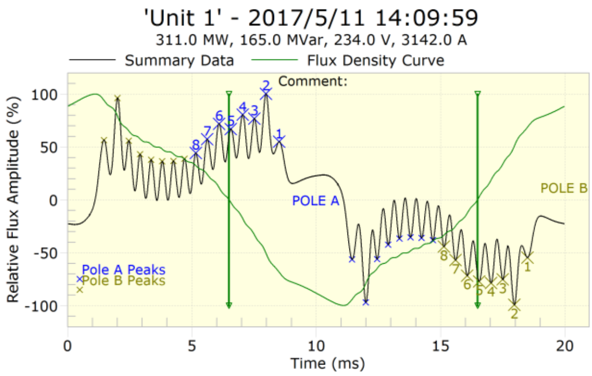

Fig.13 Flux peaks corresponding to each slot

Table 1 Result of the rotor flux test

Coil	Pole-1	Pole-2	Feature value	limit
1	55.2	-54.9	0.47%	15%
2	99.9	-99	0.88%	8%
3	83.2	-81.2	2.41%	8%
4	86.7	-85.5	1.42%	8%
5	78.5	-79.5	1.18%	8%
6	67.1	-66	1.68%	8%
7	49.4	-49.1	0.49%	8%
8	33.9	-40.1	15.18%	8%

NOTE: The feature value and limit in the table are calculated according to formula (6)and(7)

4.2.3 Repair with disassembly

After the pull-out ring disintegrates, a short circuit between the coils of the pole 2 8th set is found, as shown in Figure 14. The insulation between the crucibles is partially damaged and the surface of the copper conductor is ablation at the corresponding position.

Fig.14 Failure spot

4.3 Test verification after repair

After cleaning the inter-thumps insulation, after repair RSO and detection coil waveform results are shown in Figures 15 and 16,the results show that the short-circuit fault between the crucibles has been eliminated, this test waveform can be used as the initial data, pending further tests for comparative analysis.

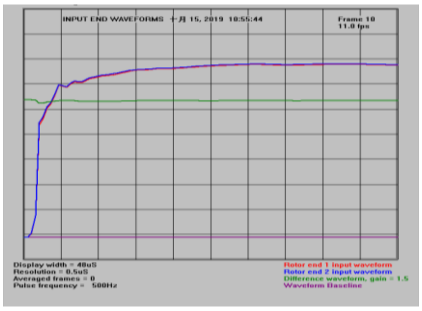

Fig.15 Result of the RSO test after repair

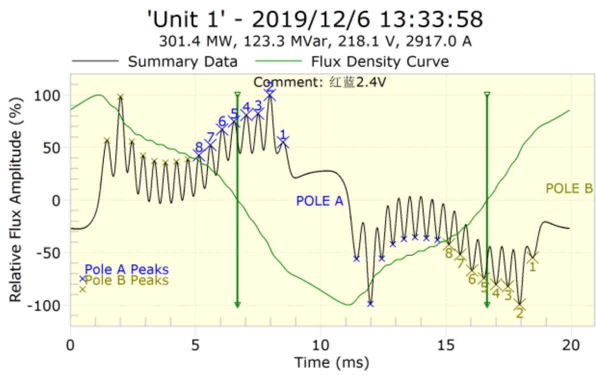

Fig.16 Flux peaks corresponding to each slot after repair

Table 2 Result of the rotor flux test after repair

Coil	Pole-1	Pole-2	Feature value	limit
1	54.9	-55	0.32%	15%
2	99.9	-99.5	0.44%	8%
3	82.2	-82.1	0.04%	8%
4	80.8	-80.6	0.33%	8%
5	74.5	-74.7	0.17%	8%
6	67.1	-67.0	0.13%	8%
7	52.2	-52.1	0.21%	8%
8	42.5	-42.4	0.19%	8%

NOTE：The feature value and limit in the table are calculated according to formula (6)and(7)

5. Conclusion

Short circuits between rotor windings threaten the safe operation of the equipment, and real-time on-line monitoring or periodic inspection of inter-rotor insulation is necessary. This paper analyzes and discusses various diagnostic methods, and verifies the validity of some methods in combination with examples, and draws the following conclusions:

(1) The reasons for the failure of the insulation between the turns of the generator rotor include the adhesion of foreign matter and oil stains, poor manufacturing technology, displacement of the insulation between the turns, and poor fixing of the end windings.

(2) The RSO method and the pole voltage balance method are sensitive and accurate in the diagnosis method of the insulation failure between the rotor turns in the shutdown state.

(3) In the diagnosis method of rotor inter-turn insulation failure in operating state, the detection coil waveform method is accurate and effective. It is recommended that the power plant be equipped with a detection coil sensor, which is carried out regularly during operation.

(4) Other methods, such as operating parameter comparison method, AC impedance method, etc., can be used as auxiliary methods for fault diagnosis.

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