Analysis on electric corrosion government of generator stator bar in the near Wake Island Hydropower Station

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Abstract. In view of generator stator bar corrosion problems in the near Wake Island Hydropower Station, performed causal analysis and technical innovation. The effect of cleaning and repairing measures were analyzed and verified. In view of the security hidden danger still exist after processing, put forward the stator bar transformation ideas and carried it on. The reconstruction effect was test verification as well. The results of the study can provide reference for power plant generator to handle similar stator bar corrosion problems.

1. Introduction

Electric corrosion is defined as the high-energy capacitive discharge caused by the loss of electric contact between generator slot, stator bar surface and slot wall, then resulting in thermal and mechanical effects on the stator bar surface [1-2]. Electric corrosion usually occurs between the insulation surface of generator stator bar slot and the slot wall, or between the corona proof coating and the main insulation [3]. It causes the burning and corrosion of corona proof coating on stator bar surface, main insulation, slot wedge and spacing strip. The consequences varies from change color to corona proof coating become crisp. Then the major insulation pitting appears, accompanies by the odor of ozone [4-6]. The electric corrosion of stator bar was found in the near Wake Island Hydropower Station during maintenance, then the cause analysis and repair treatment were carried out, and the modification technology of stator bar was put forward.

The near Wake Island Hydropower Station is located at near Wake Island Town, the junction of Hengnan, Changning and Qidong counties. It is a runoff power plant, the seventh level in Xiangjiang mainstream development plan. Three SV628/80-155 bulb tubular units were installed. They were discharged in 1996 and put into operation in 2000. By the end of 2014, the equivalent operating hours of Unit 1, 2 and 3 were 59529.7h, 58950.6h and 57603.9h respectively. Main parameters of units are shown in Table 1.

In the station, each unit has 480 slots of stator core and 960 stator bars. The original design used the filling method with N189 semiconducting silica gel. The interlayer strip was installed within the upper and lower stator bar. No other filler between stator bar and iron core except silicone rubber.
Table 1. Main parameters of generator set.

| Name                      | Parameter      | Name                        | Parameter     |
|---------------------------|----------------|-----------------------------|---------------|
| Power rating              | 21.06MW        | Stator slot number          | 480           |
| Rated voltage             | 10.5kV         | Stator coil temperature rise | Maximum 78K   |
| Rated speed               | 75rpm          | Air gap                     | 7.5mm         |
| Rotor pole-number         | 40 pair        | Stator copper loss          | 214kW         |
| Insulation grade(stator, rotor) | F              | and stray load loss         |               |
| Rated excitation voltage  | 228VDC         | Rotor copper loss           | 226kW         |
|                           |                | and Excitation current loss |               |
|                           |                | Total loss                  | 563kW         |

2. Cause analysis and repair treatment

2.1. Cause analysis of stator electric corrosion

In 2014, during the maintenance of the power plant, two slot wedges in the No. 48 slot of stator winding of Unit 1 (Figure 1) were found fallen off, and the main insulation of the upper stator bar was partly damaged (Figure 2 and Figure 3). 56 stator bar ends had different degrees of electric corrosion on the upper and lower layers. All the electric corrosion happened on the high potential position on the upstream side (Figure 4) [7]. When the wedge of No.48 slot was punched out, it was found that the semiconductor silica gel in the slot was uneven. The semiconductor layer in the slot of the upper stator bar was burned out in large area due to electric corrosion and the interlayer strip was damaged.

![Figure 1. Falling slot wedge.](image1)

![Figure 2. The position of the falling slot wedge.](image2)

![Figure 3. Upper stator bar after falling off.](image3)

![Figure 4. Stator bar end corroded by electricity.](image4)

After discovering the problem of electric corrosion of generator stator bar, the hydropower station organized the manufacturer and relevant research institutions to conduct specialized analysis, and summarized the reasons:
The stator bar was fixed in the slot and corona proof by filling and injecting semiconductor silicone rubber [8]. Practice proved that it was difficult to fill the gap between the stator bar and the slot wall, to fill the gap between the stator bar, the partition and the slot wedge completely, even if the high-pressure pump was used to inject according to the manufacturer's process. Because the single-side gap in the slot was only 0.2 mm, and the viscosity of the silicone rubber is relatively high and the fluidity is poor, meanwhile the air in the slot was difficult to overflow during the injection process. Therefore, there must be a large number of gap between the surface of the stator bar, the slot wall, the partition and the slot wedge (this was fully verified in the process of transformation in the later stage). Due to the air gap and bubbles produced by the injection process defects, the potential gradient of the unit was not uniform in these parts during operation, and corona discharge was generated, gradually corroded the slot wedge and insulation layer. The slot wedge became smaller and deteriorated due to electric corrosion and eventually fell off. At the same time, the thickness of interlayer strip of this unit were up to 4mm (generally 2mm in China), which led to the increase of discharge gap and further aggravated the corona corrosion.

After reviewing the electromagnetic program of the original manufacturer, it was found that the thermal load, stator electric density, stator temperature rise, rotor temperature rise, air gap flux density and other parameters of the unit were all very high. The calculated value of stator temperature rise was about 73K, and the value of air gap flux density was close to 1T, which was beyond the allowable range of this model. At the same time, in order to reduce the magnetic flux density, the ventilation slot which is usually used in the iron core was cancelled. The current-carrying capacity per unit area and the magnetic flux density of the iron core were close to the allowable limit value, which led to the increase of temperature rise of the stator and rotor, and aggravates the electric corrosion of the stator bar insulation.

2.2. Repair treatment
In order to avoid long-term outage of generators and reduce the economic loss, temporary repairs were carried out for No. 1 generator according to the technical scheme provided by the original manufacturer:

1. Replace the No. 48 upper stator bar in the main insulation.
2. Repair other parts with electric corrosion:
   Clean the damaged point and contact point; repair the corona proof coating; repair the corona injury parts of stator core area; repair the stator bar end; repair the high and low stopband; brush the insulation paint in the whole repair area (Figure 5).

After the Unit 1 had been repaired, the same inspection was carried out on Unit 2 and Unit 3.
The end of No. 122 slot winding of Unit 2 was electro-corroded. No falling of slot wedge or arching was found. The end of No. 69 slot winding of Unit 3 was electro-corroded. No falling of slot wedge or arching was found.

The test data of the three units were analyzed, the result is as follows:

1. The voltage of PD test was set according to rated voltage. Partial discharge of Phase B of Unit 3, Phase B and Phase C of Unit 2 exceeded the standard. Phase A of three units was relatively good. The stator insulation and DC voltage withstand test were carried out for the three generating units respectively, and the AC voltage withstand of the Unit 1 were qualified. DC voltage withstand of Unit 1 and Unit 2 was 2.0 Un(nominal voltage) according to Maintenance Standard B, and Unit 3 was 1.5 Un according to Maintenance Standard C. The ozone concentration of Unit 1 was the highest, and there was ozone odor in operation; Unit 2 and 3 had lower ozone concentration, no obvious ozone odor in operation. This is consistent with the severity of electric corrosion.

2. Although the PD test data exceeded the standard, the insulation and DC leakage test and AC voltage withstand test of Unit 1 were all qualified because of the long failure reaction of the whole insulation system. Due to the design and manufacture, completely eliminate the air gap between the stator bar and the iron core by filling and injecting the semiconductor silicone rubber by the repairing technology was difficult. The unit could only operate for a short time after electric corrosion was
temporarily treated. The ozone release and the development of electric corrosion should be monitored to keep track of the real-time situations and prevent the stator bar from appearing short-circuit during operation. In order to keep track of the corrosion of generator stator winding and the temperature of stator bar, an on-line PD tester and an infrared temperature tester were installed on Unit 1.

In order to systematic understand the operation of this type of unit in other hydropower stations in China, special investigations were carried out on Nanjindu hydropower station in Hunan Province and Wangfuzhou hydropower station in Hubei Province, where similar units were installed. The findings are as follows:

Nanjindu Hydropower Station and the near Wake Island Hydropower Station belong to a river basin. The capacity of the power station was basically close, and the equipment layout was basically the same. There had been many stator earth protection actions caused by electric corrosion. From external inspection, serious corona corrosion occurred in high potential area. At the later stage of the corrosion, the bulb heads of the three units all had strong ozone odor, and gas masks were needed when inspecting the equipment. Serious electric corrosion and frequent stator earth protection actions had brought serious hidden dangers, huge economic losses and high processing costs of imported equipment. Therefore, the three units had been reformed locally by replacing domestic stator bar. After the government, the actual output, operating temperature and vibration of the unit were excellent, and could run steadily at full load for a long time.

In Wangfuzhou hydropower station, there was an interphase short-circuit and earth protection action of stator bar slot opening in Unit 3. The treatment was carried out by hanging out stator, replacing part of stator bar and repairing electric corrosion of slot opening. The operation is normal at present, but ozone smell still exist.
Comparing the treatment methods between the two power plants, the new stator bar technology can completely eliminate the hidden danger of electric corrosion caused by the design and manufacture, and improve the safety and reliability of the unit equipment. But the cost is high, the construction period is long and the preparation work is numerous. The repair treatment cost is relatively small, the construction period is short, but stator bar electrical corrosion and hidden dangers cannot be completely eliminated.

In July 2015, Unit1 was installed on-line PD monitoring device. Monitoring data show that the trend of partial discharge data had been on the rise.

In 2016, the on-line PD data of Phase B and C of Unit 1 increased rapidly, and the maximum QM+ of Phase C in July was 500 mV (about 3 times that of one year ago), which was close to 95% of the empirical database provided by the manufacturer (525 mV), indicating that the development of electric corrosion of Unit 1 presented a rapid aggravation trend (Figure 6).

![Figure 6. On-line PD tendency chart of Phase A, B, C.](image)

In order to completely eliminate the hidden danger of stator electric corrosion and avoid more losses, it was advisable to reform the stator bars of the generator through comprehensive analysis.

3. Transformation and construction technology

3.1. Modification idea of stator bar

According to the analysis of stator bars with corona corrosion in near Wake Island Hydropower Station, the lowest voltage was about 1.5 kV, meanwhile the corona voltage was low. In order to increase the initial voltage of spark discharge between slots, the distance between the surface of corona proof coating and the contact point of slot wall of iron core should be shortened as far as possible.

The fundamental cause of the corona at the stator bar end was the concentration of electric field at the slot opening [9, 10]. Therefore, the electric field should be homogenized to effectively inhibit the occurrence of the end corona. The electric field at the stator bar end would be homogenized and the voltage drop near the slot opening would be decreased by reducing the surface resistivity. In addition, in order to improve the potential gradient of the whole corona proof system, semiconductor insulating
corona proof paint should be sprayed on the surface of the slot wall of the iron core. The resistivity of the semiconductor paint is equal to that of the semiconductor corona proof coating in the stator bar slot.

At present, the technology of laying two kinds of semiconductor layers with different resistance at the stator bar end are commonly used in stator bar manufacturing in China. The semiconductor layers with lower resistance values are used near the slot opening and the layers with higher resistance are used far away from the slot opening. Thus, the potential gradient distribution is changed and electric field concentration at the slot exit has been reduced. In addition, the problem of assembly gap in the height and width direction of the stator bar slot can be solved by the stator bar insertion technology of large domestic generator manufacturers.

3.2. Requirements for new stator bar transformation

The modification of stator bars in the near Wake Island Hydropower Station required that the stator core should not be changed and only the stator bars should be redesigned and produced. In order to eliminating the hidden danger of the unit completely, the transformation requirements are as follows:

1. Only the stator bars and insertion technology should be modified. The stator core and other key structure remain unchanged, and the generator capacity and performance parameters remain unchanged. The temperature rise of the generator bar should be reduced or unchanged.

2. The transformed generator should meet the requirements of GB/T7894-2001 "Fundamental Technical Specifications for Hydro Generators". Mainly including: a single stator bar should not be coronated at the 1.5 times of rated voltage. When the whole machine is under voltage, at the 1.0 times of rated voltage, there is no obvious golden bright spot and continuous corona at the end. The leakage current of stator winding at 3 times rated DC voltage should not increase with time, the difference of leakage current in each phase should not exceed 50% of the minimum value, and the time of DC withstand voltage can last for 1 minute. The whole machine can last for 1 minute at 2 times rated voltage + 3000V AC voltage according to the standard of factory test, without insulation breakdown.

3. The electrical performance of a single stator bar should meet the requirements of DS/ZJ011-2002 "Product Quality Grading of Large Hydro Generators", and a single stator bar should be tested for partial discharge.

4. The slot potential of stator bar should meet the requirements of GB/T8564-2003 "Specification Installation of Hydraulic Turbine Generator Units": After insertion, the slot potential or slot resistance should be measured at rated phase voltage. The slot potential is generally less than 10V, or the slot resistance meets the manufacturer's requirements (<5000Ω).

5. The fixing of the coil end should ensure that the coil would not sink in various operation conditions after long-term operation, and can prevent the vibration and deformation of the generator in the most serious short-circuit situation. The whole end support system should have sufficient strength, stiffness and good ventilation, and can be easy to check the end winding of the stator and measure vibration. The off-line PD measurement should be carried out after the stator bar is inserted, to retain the data and facilitate the subsequent unit status evaluation.

3.3. Design and manufacture of stator bar transformation

The gap between the bar and slot is 0.4 mm (total on both sides). In order to make it easy to insert, the new bar interlayer strip was designed to be thinned properly. The thickness of a single electromagnetic wire was increased; the width of a single electromagnetic wire was reduced; the cross section of the original electromagnetic wire was kept unchanged, and the thickness of the main insulation was adjusted properly. It was designed that in the same area the thickness of single strands increased by 0.02mm and the width decreased by 0.05 mm. The width of double strands could be reduced by 0.1 mm, and the gap between bar and slot wall could be increased from 0.4 mm to 0.5 mm when the total insulation thickness remains 2.4 mm, to meet the requirements of insertion. Good heat conductivity between the bar and core had been met similarly.

The new stator bar adopts the insulation structure of internal shield + major insulation + low resistance corona proof coating; the material is made of single-sided reinforced mica tape. The
breakdown field strength of the stator bar is guaranteed to be above 40kV/mm by VPR technology. Compared with the actual field strength of 32.7kV/mm, the new stator bar has more than 20% margin to ensure the breakdown voltage.

Analytical calculation of the temperature field showed that the temperature rise of the new stator bar decreased by 3-5K compared with the original one, and the temperature of the new stator bar did not exceed the temperature before.

After the trial production of the stator bar, the corona initiation, voltage resistance and dielectric loss tests were carried out. In view of the problems existing in the original unit's partial discharge, the PD test was added to the new test, and the test results met the design requirements. After the new stator bar had been developed, the batch production was started and the test was carried out one by one. Two stator bars were selected from the qualified products and sent to STIEE for thermal dielectric loss test and the results met the design requirements. The stator bar were sampled at 5% and 3% sampling rates after arrival to do the insulation, corona initiation, normal dielectric loss and withstand voltage test and the result were all qualified.

3.4. Insertion technology of new stator bar

The new stator bar adopts silica gel spiral insertion technology, as follows:

1. Mix and stir the special silica gel evenly
2. Coat the special glue evenly on the lining of the semiconductor slot with the special tool (the thickness of the glue is adjusted according to the actual section size of the stator bar).
3. Wrap the slot liner coated with silica gel around the core of the stator bar spirally.
4. Insert the stator bars wrapped by the slot liner into the slots and use the pressing tool to fix the bar temporarily.
5. After 24 hours of insertion, silica gel is solidified and then inserting the upper bar.
6. Insert the semiconductor strip between the upper stator bar and the slot wedge, and tighten the slot wedge.
7. Attention should be paid for the transformation:
   Before inserting, check the iron core of the unit. First, no overheating or rust in the iron core, if there is, wipe it with toluene. Second, if there is wear on partial silicon steel sheet, it should be grinded flat. Finally, check the tightness of the iron core with a tightening knife, if the insertion depth of the tightening knife is more than 3 mm, the iron core should be tightened. Iron loss test should be carried out after completion of inspection.
   The insertion of stator bar should be carried out according to the process requirements; insulation test should be carried out strictly in accordance with GB/T8564-2003 "Specification Installation of Hydraulic Turbine Generator Units "; the process should be strictly checked and the test data should be recorded in time.

4. Results and discussion

The iron core was cleaned and rusted before the insertion, and the iron loss test was carried out after brushing the insulating penetrating paint. The results are as follows:

1. Core loss test: the maximum loss: $B = 1.04 \times 10^{-4} T$, $P_0 = 1.09W/kg$; the maximum temperature rise: $\Delta t_1 = 7^\circ C$; the maximum temperature difference: $\Delta t_2 = 4^\circ C$. All the results were qualified.
2. Stator bar test: insulation was tested one by one before the stator bar insertion, and subsection withstand voltage test was carried out during the installation of the bar. Test qualified.
3. Voltage withstand and slot potential test: after insertion, the insulation, leakage, voltage withstand and corona test were carried out, withstand 2 Un+3kV voltage in one minute was qualified; under 1.05Un voltage, no obvious golden bright spot and continuous corona found at the end of the stator bar and the slot potential < 10V. Test qualified.
4. Off-line PD test: the maximum PD was 1200pc at rated phase voltage, meets the requirements.
5. Monitoring of on-line PD of unit 1:
   (1) On-line PD data before transformation:
The Qm+ of Phase A fluctuated from 30mV to 140mV, and the Qm- fluctuated from 50mV to 265mV. The PD data showed an upward trend over time.

The Qm+ of Phase B fluctuated from 100mV to 500mV, and the Qm- fluctuated from 90mV to 500mV. The PD data increased rapidly over time.

The Qm+ of Phase C fluctuated from 100mV to 600mV, and the Qm- fluctuated from 80mV to 250mV. The PD data increased rapidly over time.

(2) On-line PD data one month after transformation:

The Qm+ of Phase A fluctuated from 10mV to 20mV, and the Qm- fluctuated from 10mV to 20mV. No upward trend in PD data.

The Qm+ of Phase B fluctuated from 10mV to 20mV, and the Qm- fluctuated from 10mV to 20mV. No upward trend in PD data.

The Qm+ of Phase C fluctuated from 10mV to 30mV, and the Qm- fluctuated from 10mV to 30mV. No upward trend in PD data.

6. Changes in operating temperature:

The stable operation time of unit was more than 10 hours, the load of generator was the same (20.3 MW), and the cooling water temperature of generator was the same (16.2 ℃). The comparison data are as follows:

Before transformation: average temperature of 1 # generator core, Phase U winding, Phase V winding, three phase winding average temperature and temperature difference between three phase winding was 52.97 ℃, 77.33 ℃, 80.6 ℃, 77.13 ℃, 78.35 ℃ and 25.38 ℃ respectively.

After transformation: average temperature of 1 # generator core, Phase U winding, Phase V winding, three phase winding average temperature and temperature difference between three phase winding was 56 ℃, 76.73 ℃, 74.1 ℃, 77.03 ℃, 75.95 ℃ and 19.95 ℃ respectively.

Under the same operation condition and environment, the average temperature of core rose by 3.03 ℃, the average temperature of three-phase winding dropped by 2.4 ℃, and the average temperature difference between the three-phase winding and the core decreased by 5.43 ℃. The result showed that the air gap between the original stator bar and the iron core was basically eliminated, the contact between the stator bar and the iron core was better, the cooling condition was improved, and the condition of electric corrosion was further eliminated.

5. Results and discussion

Regarding the problem attempted in the present case. The new stator bar adopts VPR technology, the thickness of main insulation is only 2.2 mm. After the replacement of the stator bar was completed, the electrical indexes and performance specifications of the stator were tested. With the new insertion technology, the temperature rise and cooling condition of the bar and iron core had been improved since the Unit 1 was connected to the grid. The on-line PD data were stable and the expected purpose had been achieved. But the overall transformation effect still needs to be verified after long running.

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