Early Faults and Characteristics of Large Capacity Non-salient Pole Synchronous Electric Machines

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Abstract. Large-capacity synchronous machines are prone to failure due to their complicated structure. The timely detection and processing in the early stage of the failure can avoid further expansion of the fault and avoid huge economic losses. By studying the structure of water-hydrogen-hydrogen turbine generators, this paper analyzes the types and characteristics of early faults of every component, and provides reference for the operation and state maintenance of synchronous machines.

1. Introduction

In recent years, the requirements for operational safety and reliability of the synchronous generators are increasing with the capacity. Synchronous generators faults are inevitable in the course of operation due to the large capacity and the complicated structure, which affect the safe operation of the unit and bring huge economic losses to the equipment manufacturing enterprises and users of synchronous machine, especially in the event of a serious accident.

At present, scholars have analyzed the causes and treatment of accidents of turbine generators and provide some typical failure cases which are repaired with the huge cost [1-17]. Therefore, it is very important to master the common faults and characteristics of the generators, which is helpful for detecting and treating them in the early stage of fault, and prevents the slight fault evolving to serious accident.

On the basis of consulting a large number of references related to generators fault cases, the early fault types, fault causes and fault characteristics of large non-salient pole synchronous machines are analyzed. The work can provide reference for the operation and condition maintenance of large capacity synchronous generators.

2. Structure of large capacity Non-salient synchronous electric Machines

The large non-salient pole synchronous machine is generally used as a turbo-generator. At present, the capacity of the turbo generator has reached 1000MW [1]. The increase in synchronous generators capacity is mainly determined by its cooling system. The common cooling methods for large-capacity synchronous generators are water-hydrogen-hydrogen and fully air-cooled. Since the cooling effect of water and hydrogen is better than that of air, the weight and volume of the water-hydrogen-hydrogen turbine generator are less than that of the fully air-cooled synchronous generator under the same capacity, while its operation and maintenance are more complicated than that of the fully air-cooled generator [2].

The major components of the synchronous electric machines, such as the stator, rotor, cooling system and bearing, are all composed of different parts. Water-hydrogen-hydrogen turbine generator is
a widely used type of unit, in which the stator windings are cooled by water flowing in hollow-strands and the stator cores and rotors are cooled by hydrogen. In this paper, the water-hydrogen-hydrogen non-salient pole synchronous generator is taken as an example to analyze its early fault types, causes and characteristics.

3. Fault and characteristic Analysis of synchronous generator

3.1. Stator section

The stator of the synchronous generator is mainly composed of stator core, stator winding, cooling water system, stator end, etc., and they are analyzed one by one in the following parts.

3.1.1. Stator core. Common faults in the stator core are interlamination short-circuit, partial blockage of the ventilating duct, loosening of the core, wear, cracks, and so on [3-5,11]. Manufacturing and assembly process reasons, which include uneven paint film of silicon steel sheet in the manufacturing process, the quality problem of the insulating paint, and the damage of the silicon steel sheet insulating paint when the core is stacked etc., may cause short circuit between the sheets, which may increase the eddy current loss in the core and cause local overheating under the action of alternating magnetic field. During the manufacturing process, the ventilating duct between the core segments flattened and the debris entering the ventilating duct can cause partial blockage of the ventilating duct. The consequence is that the cooling capacity of the gas is weakened, resulting in local overheating and temperature increasing of the core. Therefore, monitoring the core tooth temperature, yoke temperature, gas temperature of inlet and outlet of ventilating duct, and comparing the temperature difference between different monitoring points can help to determine the short circuit and poor ventilation faults online.

During the manufacturing process of the machine, the iron core is not tightly packed, and the metal foreign matter is mixed, which may cause the stator core to resonate under the action of alternating electromagnetic force during the operation of the machine, resulting in looseness, wear and crack of the stator core. The vibration caused by core loosening, wear and crack is double frequency one. When the excitation current is removed, the vibration disappears [6]. The fault types and characteristics of stator cores are shown in Table 1.

In off-line condition, the core failure can also be found by experiment of the loss or measuring the surface temperature of the inner core of the stator by using the infrared thermal imager.

| Component          | Fault type                  | Fault characteristics                                                                 |
|--------------------|-----------------------------|---------------------------------------------------------------------------------------|
| Stator core        | Interlamination short-circuit| The local temperature rises, and the temperature difference between different temperature points of the stator core increases |
|                    | Local blockage of ventilator duct | Local temperature rises, temperature difference between different gas outlets increases |
|                    | Loosening of the core, wear, cracks | Double frequency vibration occurs and is related to the excitation current. When there is no excitation, the amplitude is zero |

3.1.2. Stator windings. The early failure of the stator winding mainly includes insulation defects, wear and insulation performance degrading. Insulation faults in the stator windings occur mostly at the end-windings, such as the hand-making insulation worn at the hydroelectric connector due to vibration and the stator bar worn by poor fixing at the nasal tip. Vibration during operation and long-term erosion of oil and moisture can easily result in fatigue fracture and insulation damage of the connecting copper wire. More seriously, if the early insulation degradation can not be detected, it maybe develop to
insulation breakdown which will cause accidents such as inter-turn short circuit, grounding, and even phase-to-phase short circuit in the stator winding [3-5, 8-14].

Therefore, during the operation of the electric machines, it is very important to strengthen the insulation monitoring of the stator windings, and to detect the deterioration of the stator winding insulation by partial discharge analysis and insulation overheat monitoring. For the older units without partial discharge and insulation over-temperature on-line monitoring equipment, the insulation performance of the windings should be evaluated by testing the insulation resistance, AC leakage current, dielectric loss, maximum partial discharge, etc. [7]. The stator winding fault and its characteristics are shown in Table 2.

Table 2. Stator winding faults and their characteristics

| Component          | Fault type         | Fault characteristics           |
|--------------------|--------------------|---------------------------------|
| Stator winding     | Insulation deterioration | Insulation resistance drop |
|                    |                    | Increase in dielectric loss     |
|                    |                    | Leakage current increase       |
|                    |                    | Partial discharge increase     |

3.1.3. Stator internal cooling water system. Early failures in the stator cooling water system are leaking and clogging. The leakage of internal cold water is usually caused by material defects, substandard internal cooling water leading to corrosion and cracks of hollow copper wire, abnormal vibration of unit, etc. The blockage of waterway is usually caused by the corrosion and scaling of hollow copper wire which is produced by the entry of sundries into the internal cooling water system or the low PH value of the inner cooling water [8].

When the stator water system leaks, the flow rate of internal cooling water increases, and hydrogen with the higher pressure seeps into the water and accumulates at the top of the stator inner chiller. When the stator waterway is blocked, the inlet pressure increases and the temperature rise. The temperature varies according to the location of the blockage. The temperature rise of the stator windings and the water outlets generally increases when the blockage is in the busbar [9]. When the blockage occurs inside the hollow conductor, the temperature of the outlet of the bar and temperature of the layers’ insulation of that slots rise, which causes the temperature difference between slots and the temperature difference between the outlet of the bars to increase [10]. The faults and their characteristics of the stator inner cooling water system are shown in Table 3.

3.2. Rotor section
The rotor of the synchronous generator is mainly composed of rotor winding, rotor shaft, collector ring and brush, rotor retaining ring, bearing etc. [11]. The rotor rotates at the power frequency. When a vibration abnormality occurs, the variation amplitude is positively correlated with the rotor speed.

3.2.1. Rotor winding. Early failures of the rotor winding mainly include insulation degradation of the rotor winding, thermal deformation, and slight inter-turn short circuit [12]. The characteristics of the rotor winding insulation degradation are the same as those of the stator winding. The thermal deformation of the rotor winding is usually caused by local overheating of the rotor winding due to the inter-turn short circuit or the clogging of the ventilating duct. The thermal deformation of the rotor winding causes the rotor power frequency vibration to increase. The turn-to-turn short circuit of the rotor windings causes the excitation current to increase, the output reactive power to drop, the shaft voltage to rise, and the power frequency vibration to increase [13-14].

The thermal deformation of the rotor winding causes the thermal stress distribution on the rotor to be uneven, and the degree of deformation is related to the magnitude of the excitation current.
Therefore, the magnitude of the power frequency vibration caused by the thermal deformation of the rotor is related to the rotor speed and the magnitude of the excitation current.

**Table 3.** The faults and their characteristics of stator inner cooling water system

| Component       | Fault type | Fault characteristics                                      |
|-----------------|------------|-----------------------------------------------------------|
| Stator winding  | Leak water | Internal cooling water flow increased                     |
|                 |            | Hydrogen at the top of the cooling water tank in the stator increase |
|                 |            | Leakage parameter changes                                 |
| Blockage        |            | Increased Inlet pressure                                  |
|                 |            | Increased temperature difference between the total inlet and outlet pipes of the stator |
|                 |            | Increased interlayer temperature difference between upper and lower layer bars in different slots |
|                 |            | Increased interlayer temperature of the plugged bar       |
|                 |            | The water quality of the cooling water in the stator deteriorates (conductivity, oxygen content, pH value and copper ion content are out of range) |

The turn-to-turn short circuit of the rotor winding reduces the effective ampere-turn of the rotor. When the excitation voltage is constant, the excitation current increases and the reactive power output decreases. In addition, the short circuit between turns can cause the rotor to be heated unevenly and the thermal stress distribution changes, resulting in vibration to increase, and the vibration amplitude increases with the increase of the excitation current.

The early failure of the rotor winding and its characteristics are shown in Table 4.

**Table 4.** Faults and characteristics of rotor windings

| Component       | Fault type            | Fault characteristics                                                                 |
|-----------------|-----------------------|---------------------------------------------------------------------------------------|
| Rotor winding   | Thermal deformation   | The power frequency vibration increases                                              |
|                 |                       | The vibration amplitude changes with the rotation speed and the excitation current    |
|                 |                       | The vibration has a gradual change feature                                            |
|                 | Inter-turn short circuit | Excitation current increases                                                           |
|                 |                       | Output reactive power drop                                                             |
|                 |                       | Axis voltage rise                                                                     |
|                 |                       | The power frequency vibration increases                                              |
|                 |                       | The vibration amplitude changes significantly with the change of the rotational speed and the excitation current |
|                 |                       | The vibration has a fast change feature                                               |
3.2.2. **Large shaft of the rotor.** The rotor shaft of the turbo generator is forged from integral steel, and its early failures include mass imbalance caused by manufacturing process, thermal imbalance caused by inter-turn short circuit or partial blockage of ventilating duct [15]. The amplitude of the power frequency vibration caused by the imbalance of the rotor mass is only related to the magnitude of the speed. When the speed is constant, the vibration amplitude remains unchanged. Partial blockage of the rotor ventilating duct causes local overheating of the rotor, resulting in thermal imbalance of the rotor shaft. The degree of imbalance is related to the degree of clogging and cooling parameters, and also to the magnitude of the excitation current. The large rotor shaft failure and its characteristics are shown in Table 5.

| Component               | Fault type                                      | Fault characteristics                                                                 |
|-------------------------|-------------------------------------------------|---------------------------------------------------------------------------------------|
| Large rotor shaft        | The local blockage of rotor ventilating duct     | The power frequency vibration increases,                                             |
|                         |                                                 | The vibration amplitude changes with the change of the rotation speed, the excitation   |
|                         |                                                 | current, and the cooling medium;                                                      |
|                         |                                                 | The vibration has a gradual change feature                                            |
| Rotor mass imbalance     | The power frequency vibration increases,         | The vibration amplitude changes significantly with the rotation speed                 |
|                         |                                                 | The vibration has stability                                                           |

3.2.3. **Collector-ring and brush.** The reliable contact between the collector ring and the brush is the key to ensure the normal operation of the synchronous electric machine [16]. The surface of the collector ring and the brush is rough and dirty, carbon powder is accumulated, the ventilation is poor, the gap between the brush holder and the collector ring or the brush holder and the brush is too large, and the brush is stuck, etc., all of which may cause poor contact between the collector ring and the brush.

The bad contact between the collector ring and the brush can produce spark. In severe cases, the ring fire is formed, resulting in accidents such as destroying the collector ring, the brush holder and the brush carrier [11-14].

The operation and maintenance of the collector ring and the brush are generally carried out by regular inspections, and the problematical one are promptly cleaned and replaced with new carbon brushes. The collector ring and brush faults and their characteristics are shown in Table 6.

| Component              | Fault type          | Fault characteristics                        |
|------------------------|---------------------|---------------------------------------------|
| Collector-ring and brush| Poor contact        | rough surface                               |
|                         |                     | The gap between the brush holder and the collector ring or the brush is too large |
|                         | Wear                | Toner accumulation                          |
|                         | Poor ventilation    | Increase in temperature                     |
3.2.4. Rotor retaining ring. The retaining ring failure mainly manifests as stress corrosion, crack and deformation. The larger humidity of the hydrogen in the generator is very likely to cause its stress corrosion and cracking. In addition, faults such as the inter-turn short circuit of the rotor winding are also likely to cause damage to the retaining ring [14-16]. The rotor retaining ring is mainly used to protect the rotor end coil, so the failure of the retaining ring may cause damage to the rotor winding and thermal imbalance of the rotor, causing power frequency vibration.

The rotor retaining ring fault can be detected by ultrasonic inspection and lamination metallographic examination during regular inspection.

The rotor retaining ring failure and its characteristics are shown in Table 7.

### Table 7. Faults and characteristics of rotor retaining ring

| Component               | Fault type                          | Fault characteristics                                      |
|-------------------------|-------------------------------------|-----------------------------------------------------------|
| Rotor retaining ring    | Stress corrosion, cracks and deformation | The power frequency vibration increases                  |
|                         |                                     | The vibration amplitude changes with the change of the rotational speed and the excitation current |
|                         |                                     | The vibration has a gradual change feature                |

3.2.5. Bearing. The problem of the bearing is mainly caused by the lubricating oil and the misalignment of the bearing. The pressure of the top shaft oil film drops, the oil quality of the lubricating oil is substandard, the oil film whirls, the oil film oscillates, etc., which may cause the bearing oil temperature to rise, the bearing bush to wear, and the vibration to increase. The vibration amplitude varies with the speed and bearing oil temperature and is abrupt [6]. The misalignment of the bearing causes the double frequency vibration, and the amplitude changes significantly with the rotation speed, which varies with the change of the bearing oil temperature too. Bearing failure and its characteristics are shown in Table 8.

### Table 8. Faults and their characteristics of bearing

| Component             | Fault type              | Fault characteristics                                                  |
|-----------------------|-------------------------|-----------------------------------------------------------------------|
| Bearing               | Oil film whirl          | Vibration with (0.40-0.48) times the power frequency occurs            |
|                       |                         | The vibration amplitude changes obviously with the rotation speed, and the bearing oil temperature |
|                       |                         | Vibration has sudden change feature                                    |
|                       | Oil film oscillation    | The vibration of the first critical speed of the rotor increases       |
|                       |                         | The vibration amplitude changes obviously with the rotation speed, and the bearing oil temperature |
|                       |                         | Vibration has sudden change feature                                    |
|                       | Bear misalignment       | Double frequency vibration occurs                                     |
|                       |                         | The vibration amplitude changes obviously with the rotation speed, and the bearing oil temperature |
It can be seen from the above analysis that the early failures and their characteristics of large synchronous electric machines show diversity and crossover, as shown in Table 9. Therefore, comprehensive analysis using multi-information fusion method for fault diagnosis can improve the accuracy of fault diagnosis.

Table 9. Early failures and its characteristics of water-hydrogen-hydrogen Non-salient Pole Synchronous Machines

| Unit                                      | Main section | Component                        | Fault type     | Fault characteristics                                                                                                                                 |
|-------------------------------------------|--------------|----------------------------------|----------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| Water-hydrogen-hydrogen non-salient pole synchronous electric machines | Stator       | Stator internal cooling water system | Leak water     | Internal cold water flow Increased Hydrogen at the top of the cold water tank in the stator Leakage parameter changes                                |
|                                           |              |                                  | Blockage        | The water quality of the cold water in the stator deteriorates (conductivity, oxygen content, pH value and copper ion content are out of range) |
|                                           |              |                                  |                 | Insulation resistance drop Increase in dielectric loss Leakage current increase Partial discharge increase                                             |
|                                           | Stator       | Stator winding                   | Insulation      | The local temperature rises, and the temperature difference between different temperature points of the stator core increases.                        |
|                                           |              |                                  | deterioration   | Local temperature rises, Temperature difference between different gas outlets increases.                                                              |
|                                           |              |                                  |                 | Double frequency vibration occurs and is related to the excitation current. When there is no excitation, the amplitude is zero.                         |
|                                           | Stator       | Stator core                      | Interlaminatio n short-circuit | Excitation current increases Output reactive power drop Axis voltage rise | The power frequency vibration increases, and the amplitude changes significantly with the change of the rotational speed and the excitation current; the vibration has a fast degeneration. |
|                                           |              |                                  |                 | Thermal deformation | The power frequency vibration increases, and the amplitude changes with the rotation speed and the excitation current; the vibration has a gradual change. |
|                                           | Rotator      | Rotor ventilation duct blockage  |                 | Rotor mass imbalance | The power frequency vibration increases, the vibration amplitude changes                                |
| Component | Condition | Description |
|-----------|-----------|-------------|
| Rotor retaining ring | Stress corrosion, cracks and deformation | The power frequency vibration increases, and the amplitude changes with the change of the rotational speed and the excitation current; the vibration has a gradual change. |
| Bearing | Oil film whirl | (0.40–0.48) times the power frequency vibration occurs; the amplitude changes obviously with the rotation speed, and changes with the change of the bearing oil temperature and is sudden |
| | Oil film oscillation | The vibration of the first critical speed of the rotor increases; the amplitude changes significantly with the rotational speed, and changes with the change of the bearing oil temperature and is sudden |
| | Bearing misalignment | Double frequency vibration, the amplitude changes obviously with the rotation speed, and changes with the change of bearing oil temperature |
| Collector-ring and brush | Poor contact | Rough surface |
| | Wear | The gap between the brush holder and the collector ring or the brush is too large |
| | Poor ventilation | Increase in temperature |

4. Conclusion
Due to the complicated structure and large coupling of electric, magnetic, thermal, fluid and stress during operation, the large capacity non-salient pole synchronous electric machines has many kinds of faults, and the causes of faults are complicated. There is a many-to-many relationship between fault types and fault characteristics. Especially for early faults, the fault characteristics are not obvious, and it needs to be diagnosed from multiple aspects. Therefore, mastering the mapping relationship between the fault type and the fault feature can be detected and dealt with them in the early stage of the fault in time, so as to prevent the fault from further expanding and serious accidents and huge losses.

5. References
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