Failure analysis of stator lead line burning loss of 600MW Turbogenerator

Qingxu Yang¹, Yu Wan, Xianbiao Yang, Xubi Liu and Chao Yang
Jiangsu Frontier Electric Technology Co. LTD, 58th Su Yuan Avenue, Nanjing, China

¹ E-mail: whuyqx@126.com

Abstract. In view of the failure of the stator lead line in a power plant with a short period of time operation, combined with field survey, macroscopic examination, elemental analysis, metallographic analysis, electron microscope analysis and other methods to carry out failure analysis. It is considered that the excess of impurity composition and the presence of inclusions in the raw materials of stator lead line lead to the increase of local resistance of stator leads, which is the main reason for the failure of burn loss.

1. Overview
A 600 MW turbogenerator in a power plant shuts down after 168 hours of trial operation. It starts at 2:00 on the 14th of the same month after eliminating the deficiency. On the 15th, it stops at 16:06 due to the faults of C2 phase stator lead-out line. The start-up to shut-down time is 38 hours.

The stator lead-out wire is made of TU2 oxygen-free copper hollow conductor with an outer diameter of 45 mm and an inner diameter of 19 mm. Cooling water is flowed through the pipe during operation. The inlet temperature is 40-50 °C, the outlet temperature is less than 85 °C, the inlet pressure is 0.36 MPa, and the stator working current is 19245 A.

2. Test and analysis method
On the basis of investigation and analysis of the accident site, the burned C2 phase lead-out line and its parallel unburned C1 phase lead-out line are analyzed macroscopically, and the sample is dissected by wire cutting method. After further analysis of the internal and external macroscopical characteristics of the sample, the samples are sampled in several different situations, and the corresponding samples are analyzed macroscopically and the main chemical composition respectively. Separate analysis and optical metallographic analysis. The impurities found by metallographic analysis are analyzed by energy spectrum to determine their main components. Finally, the burning and fracture accidents of lead-out wires are analyzed comprehensively combined with macroscopic analysis, experimental analysis and operation conditions.

3. Test analysis results
3.1. Accident site survey
Open the upper end cover of the generator and find that the excitation End C2 Bridge line is burned by about 210 mm (Figure1), and there are some burning splashing residual copper on the parts near the C2 phase lead line. When the lead line and the insulation is removed, it is found that the outlet
side of the C2 phase fuse area is clogged, and the osmotic flaw detection shows that there are five cracks in the C2 phase extraction line. In addition to the burned fracture site (Figure 2). The lead line is broken in two by a small external force at the crack 3 in Figure 2.

3.2. Macro Inspection

The burned C2 phase lead-out line as Figure 1 and Figure 3, A is the inlet end, the B end is after the arc burning Place, the burning end is molten, the wall is thinner, near the B end there is a fuse area (Figure 3 arrows, that is, the crack in Figure 2), its fracture morphology as shown in Figure 4, the fracture is a typical red brick brittle fracture morphology, and some metals melt. In addition, the lateral and longitudinal distribution of the outer surface of the pipe wall in different parts of the inner part of the outlet has irregular cracks (cracks 1, 2 in Figure 2) and the seepage characteristics of the metal liquid (Figure 5), and some local outer surfaces also have irregular voids.

Try to pass the water at the inlet, the result cannot be through the water description tube has been blocked. In order to understand the blockage in the tube and the internal characteristics, the tube
segmented, the use of wire cutting from the diameter of the tube half cut, the results as shown in Figure 6, after the cut can be clearly seen in the arc burning B end of the surface is smoother, thin wall, the inner hole is the horn mouth. Not far from the B end there is a rugged scar-like metal melting feature, and a black oxide is attached to the dent. After stitching the copper pipe cut open, we can see the shape of the molten metal flowing from the burning B end to the end of the inlet, where some of the local melting is serious and lead to fracture (Figure 7), some of which form more holes (Figure 8) and black oxidizing slag clots when solidified after local melting. The whole inner hole melting situation is uneven, some areas are more serious, some areas are lighter, some of the inner wall is not melted but is blocked by molten copper liquid (Figure 9). Close to the inlet of the inner hole has been completely blocked (Figure 10), so that the wire cutting process cannot be carried out, after a manual sawing to see the inner hole in addition to copper liquid blockage, there are more black slag.

**Figure 6.** Full picture of the failed parts after they are cut open.

**Figure 7.** Local inner wall melting fracture.

**Figure 8.** Local inner wall melts to form holes.

**Figure 9.** Melting metal and slag buildup and clogging of inner holes.

**Figure 10.** Melting metal and slag after anatomy at the inlet.

3.3. **Metallographic examination**

Metallographic detection was carried out from the vicinity of C2 phase inlet and from various parts of different melting degree. The inclusions were observed after grinding and polishing the samples. After
Further erosion, the grain size and the characteristics of tissue change after heating were checked. The same examination was carried out by the C1 phase anatomical sampling of the stator lead line used in parallel. The test results of the two phases are compared and analyzed. The C1 phase lead-out wire is not damaged and the whole inner wall is not melted after half-cutting.

The test results of inclusions in different parts are shown in Figure 11, there are very few inclusions such as copper oxide in the pipe wall without melting (Figure 11a), and there are relatively many inclusions such as copper oxide in the pipe wall with lighter local melting degree (Figure 11b), while copper oxide (Figure 11c), etc., is more dense and larger than the particles in the fracture where the melting is more serious (Figure 7). After enlargement, black rings can be seen at the edge of the particles (Figure 11d).

![Figure 11. Comparison of inclusions in different parts.](image)

After immersion, the grain at the inlet of the C1 phase stator lead line and the burned C2 phase stator lead line is finer, the grain can reach 0.030~0.035 mm (Figure 12a, Figure 12b), and the C1 phase stator lead line is close to the inlet due to the temperature of the molten metal liquid, The grain has a director of about 0.050~0.055 mm (Figure 12c), while the pipe wall metal in the melting zone...
and near the melting zone is greatly affected by high temperatures, resulting in a sharp growth of the grain to more than 0.180 mm (Figure 12d). When the molten metal flows within the pipe wall, it melts the inner pipe wall and fuses locally with the flowing metal liquid. Although the cold speed is not fast during the condensation process, the crystalline crystals of the liquid can still be seen perpendicular to the wall of the tube, slightly columnar crystals characteristics (Figure 12e). At the same time, the C1 phase was dissected by wire cutting method, the inner surface of C1 was intact, no abnormalities were found, and metallographic analysis was carried out at similar parts of the C2 phase fuse, and its microstructure was slightly larger than that shown in Figure 12f, compared with the grain at the inlet of C1 phase (Figure 12a).

3.4. Electron microscope Analysis
The inclusions of the C2 phase failure components were analyzed by scanning electron microscopy and energy spectrum components, and the granular inclusions were mainly copper oxide (Figure 13a, Figure 13b), while some copper oxide surfaces and edges also had copper sulfide inclusions (Figure 13c, Figure 13d), while the undamaged C1 phase lead samples were rarely mixed.

![Image](image1.png)

**Figure 13.** Analysis of energy spectrum components of inclusions.

3.5. Chemical Composition Analysis
From the used well C1 phase inlet, the damaged C2 phase does not melt the part, and the melting serious fracture site each take a piece, at the same time the C2 phase inlet at the blockage of the black
slag together for the composition analysis, the results, as shown in Table 1, can be seen in the melting fracture site sulfur content is high. Because the black residue cannot be quantitatively analyzed, so only for qualitative analysis, the results in addition to copper, iron, aluminum, silicon, calcium, boron, molybdenum, chromium, tin, lead, titanium, sodium, magnesium and other elements exist, analysis that may be related to the inner wall of black copper oxide and pull copper pipe attached to the surface of the lubricant and other factors, Causes the surface oxide to fall off, while the metal liquid is pushed into the inlet and so on to assemble into black slag.

4. Analysis and discussion

The stator lead line is a juxtaposition of two copper tubes composed of the same switch to control the inlet cooling, in the course of operation of the C1 phase stator lead line is good, while the C2 phase stator lead line has a melting fracture, the failure of the C2 phase close to the inlet of a section of a detailed inspection.

| Parts or standards       | Fe     | Ni    | Pb    | S     | P     | Zn    | Sn  |
|--------------------------|--------|-------|-------|-------|-------|-------|-----|
| C1 Phase                 | 0.035  | 0.021 | 0.032 | 0.04  | 0.013 | 0.035 | 0.012 |
| The C2 phase no melts    | 0.036  | 0.030 | 0.030 | 0.04  | 0.010 | 0.029 | 0.013 |
| The C2 phase melts and breaks | 0.041  | 0.028 | 0.034 | 0.07  | 0.010 | 0.030 | 0.010 |
| GB/T5231-2001 TU2        | ≤0.04  | ≤0.02 | ≤0.04 | ≤0.04 | ≤0.02 | ≤0.03 | ≤0.02 |

A section of the molten end pipe wall near the inlet is thinner, and the characteristics of the molten metal flowing to the inlet end with the inner wall of the tube can be seen after anatomy, and because of the higher temperature of the molten metal liquid, the inner wall of the tube will be melted to varying degrees. Usually from the melting end to the inlet end, the temperature should be gradually reduced from high temperature to low temperature, can be from the outer surface of the tube metal liquid seepage and the appearance of voids (Figure 5~8), as well as after the anatomy of the tube wall of the melting area is not uniform, some areas melting is more serious to disconnect, some areas are not melting Even some areas do not see the melting phenomenon at all, and the whole copper tube wall melts to form an irregular interval distribution.

The results of metallographic tissue examination in different areas were compared with the smaller grain size at the inlet (Figure 12), and the crystallization granularity of other parts increased gradually with the distance from the inlet, and then the coarse grains were maintained more evenly. These indicate that only the inlet of the stator lead line is affected by the cooling effect of the water to maintain the grain state of the raw materials, other parts due to the high temperature of the pipe wall, cooling water simply does not play the role of cooling, so the grain is very thick.

There are many mixed and large particles of copper oxide and copper sulfide in and around the melting fracture (Figure 11), which are magnified to see melting characteristics at the edge of the particles (Figure 11d), while less oxygen and sulfur compounds in the lighter melting area (Figure 11b). There are very few such inclusions in the non-melting region (Figure 11a), which show that the severity of melting has a significant correspondence with the presence of copper oxide and copper sulfide. According to the relevant data [1, 2], when the impurity content is low, the iron element has a great influence on the resistivity of oxygen-free copper, and the presence of impurity atoms in anaerobic copper increases the density of lattice defects [3, 4], especially dislocation, and then increases the resistivity of oxygen-free copper. The existence of Cu$_2$O and solute atoms in the lattice has little effect on the strength, but the influence on resistivity and thermal conductivity is very obvious. Therefore, "oxygen-free copper due to the removal of Cu$_2$O and improve the conductivity", so many data are mentioned that "oxygen and phosphorus and other impurities can reduce the
electrical conductivity of pure copper." As shown in Table 1, the content of iron and sulfur elements is close to or above the standard upper limit, and the presence of other impurity elements is also present, together with the accumulation of some oxides and sulphides, which eventually leads to an increase in local resistance and heat failure.

According to the above analysis, in order to avoid similar accidents, it is necessary to ensure the quality of oxygen-free copper rod. According to the literature [5, 6], the original smelting process and casting process in the production process of oxygen-free copper rod are the key to control oxides and sulphides. At the same time, the influence of technological factors on the abnormal aggregation of sulfide and oxides in the production process of stator lead line cannot be ruled out.

5. Conclusions
There are more inclusions in the matrix near the fuse site, and the main components of the energy spectrum analysis are copper oxide and copper sulfide. The aggregation of inclusions increases the local resistance of the stator lead out, and eventually leads to the failure of the local heat burnout. In order to control the occurrence of such accidents, the abnormal aggregation of oxides and sulphides in oxygen-free copper rods should be strictly controlled. Specifically, it is very good to control the original smelting process and casting process of oxygen-free copper rod, as well as the influence factors affecting the abnormal aggregation of oxides and sulphides in the production process of stator lead line.

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