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Analysis of corrosion and scaling in high-voltage direct-current valve cooling water system

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Abstract. In this paper, the problems of corrosion and scaling in the converter valve tower cooling water system based on the ±500kV Baode HVDC transmission project with Siemens light-triggered thyristor HVDC transmission technology are analyzed in detail. The corrosion and scaling phenomenon can cause the closure or emergency shutdown of converter valves and bring potential dangers to the safe and stable operation of power grid. So far, there is no fundamental solution to this problem. Based on the investigation of scaling phenomenon of grading electrode and corrosion of thyristor aluminum alloy heat sinks, the scaling law of the grading electrode is proposed and the cause of scaling is put forward and analyzed. Some suggestions are given.

1. Introduction
Converter valve is the core equipment of a high-voltage, direct current (HVDC) electric power transmission system. Considering the valve loss, which inevitably exists, the heat generated by valve loss could largely harm the performance of converter valve. Thus, the internal water cooling system, which effectively helps dissipating the heat out of valve, is of great significance to ensure the normal operation of the converter valve [1]. Unfortunately, operating experiences show that the problem of corrosion and scaling is very common in inner cooling water system of converter valves [2-12]. Despite the use of mixed ion exchange resin for desalination and purification of the internal cooling water of the converter valve, corrosion and scaling still exist in the internal cooling water system of the converter valve, leading to an unsatisfied performance of the heat dissipation and insulation of the converter valve. Accordingly, the safe and stable operation of the thyristor, reactor, damper capacitor and water pipe of the converter valve could be negatively affected.

In this paper, the scaling problem of bipolar grading electrodes in the ±500kV Baode HVDC power transmission project is taken as the research object and the corrosion and scaling issues of the internal cooling water system of the converter valve are analyzed and the relevant recommendations and solutions are proposed.

2. Valve cooling water path and grading electrode

2.1. HVDC transmission system
The HVDC transmission technology is one of the most advanced and energy-saving power transmission and transformation technologies in the world, and it is also the key developing technology in Chinese technical equipment field. It has the advantages of asynchronous operation between two AC systems,
fast response, precise adjustment, convenient operation, stable voltage distribution along the line and low operation loss. Moreover, the investment and operation cost of HVDC transmission line are less than that of AC transmission system [13]. HVDC transmission system usually consists of rectifier station, inverter station and HVDC transmission line. Its wiring principle is shown in figure 1.

![Figure 1. HVDC transmission system](image)

2.2. Valve cooling water system
Converter valve is one of the most important equipment in HVDC transmission system. Under normal operation, the thyristor generates high heat with high current flowing, which causes the temperature of the thyristor to rise sharply. The thyristor must be cooled effectively, or it will be burnt out. The temperature of the thyristor of the converter valve is generally less than 90°C. The heat dissipation of thyristor is realized by the aluminum alloy heat sinks which is closely contacted with thyristor by internal cooling water cooling. The system flow chart is shown in figure 2.

![Figure 2. Air cooling water system](image)

2.3. Valve assembly waterway
The valve hall of the converter valve is divided into three phases, namely A, B and C. Each phase is subdivided into left (L) and right (R) sides, each side being split into six layers. Each valve assembly is composed of series thyristors. The thyristors are separated by aluminum alloy heat sinks. The heat sinks are connected by waterways, and the heat of the heat sinks is derived by cooling water.

The connection modes of cooling water pipeline of valve assembly could be segmented to series type, parallel type and series-parallel type. The series type of connection mode is mainly based on ABB technology route. The flow rate in series type is large, but the temperature difference between the head and the tail is huge too. The parallel type is mainly based on SIEMENS technology route. The series-parallel type, mainly based on Zhonglian Puri technology route, combines the advantages of ABB and SIEMENS given water route arrangement of flow and temperature.

SIEMENS technology route was adopted in ±500 kV converter station. Its valve assembly waterway was parallel, A is thyristor, B is heat sinks, C is connecting water pipe. The schematic diagram is shown in figure 3, and the valve assembly is shown in figure 4.

2.4. Grading electrode position
In order to avoid discharging unevenly on the inner and outer wall of cooling water pipeline in the converter valve due to uneven voltage distribution, and leakage current caused by the contact between metal equipment and water pipeline in the valve assembly, grading electrodes were installed on the main cooling water pipe of the valve tower and the water distribution and catchment pipes in the valve assembly. The appearance of the grading electrodes is shown in Figure 5. For the grading electrode, the effective part presented is platinum, of 23.8 mm in length and 2 mm in diameter; the remaining part is stainless steel. The installation of grading electrodes could help realizing even voltage distribution on the inner and outer wall of the main water cooling pipeline and help releasing leakage current, which now transfer from thyristor aluminum alloy heat sinks to inert platinum electrode. By doing this, the corrosion phenomenon of electrical equipment could be avoided [14].
There were 432 grading electrodes installed in the single pole of Baoji Converter Station, including 24 zero potential electrodes. The number of grading electrodes installed on the T-type connection part of valve assemblies and main water pipe was 144, the number of grading electrodes installed on the anode side of thyristor valve assemblies was 288 and the number of grading electrodes installed on the cathode side was 288. The rest were electrode valve tower interlayer electrodes. The installation positions of grading electrodes could be divided into the following categories, as shown in table 1, L: left side, R: right side, L1: on the left and level 1, R1: on the right and level 1, R2\L3\L4\R4\R5\L6 and so on.

| Valve tower electrode location          | Number of electrodes |
|-----------------------------------------|----------------------|
| Top part tube                           |                      |
| L sides                                 | 2                    |
| R sides                                 | 2                    |
| L1 and R1 upper part                    | 4                    |
| R2 upper part                           | 2                    |
| L3 upper part                           | 2                    |
| S-shape tube                            |                      |
| L4 and R4 upper part                    | 4                    |
| R5 upper part                           | 2                    |
| L6 upper part                           | 2                    |
| T-type tube                             |                      |
| L and R sides                           | 12                   |
| Cathode sides.                          |                      |
| Water distribution pipe and confluence pipe |            |
| Anode sides                             | 24                   |
| Bottom part tube                        |                      |
| L and R side                            | 2                    |

3. Scaling on Grading Electrodes
Based on the investigation of several HVDC transmission projects in China, it is found that the scaling phenomenon of grading electrodes exists in different degrees. Figure 6 (a) and (b) illustrate the difference in scaling for grading electrodes of ABB technical route and grading electrode of Siemens technical route, respectively. In addition, figure 6(c) shows a third type of grading electrode of Zhonglian Puri technical route with some scaling presented.
3.1. Scaling phenomenon in Inverter station

The scaling phenomena in Baoji Converter Station were as following: the scaling of the grading electrodes on the anode side of thyristor on the valve assembly was slight and loose; the scaling of the grading electrodes on the cathode side was serious and firm; the zero potential point of the main water pipe of the valve tower was not scaling. The scaling of the grading electrode at the T-type connection between the water distributing pipe of the valve assembly and the main water pipe was moderate, but scaling was very firm.

The scaling on the anode side was slight. The thickness of the scaling of electrode could be calculated as the following: the diameter of the electrode with scaling minus the diameter of the electrode without scaling, and then divide the result by 2. The average thickness of scaling was 0.1-0.2 mm. The scaling distributed evenly, the scaling was crisp and easy to fall off. The scaling on the upstream side was slightly thicker than that on the back side. Only the root part was not covered by scaling, as shown in figure 7.

The scaling of the grading electrodes on the cathode side is serious. Generally, the scaling thickness is 0.6-0.8 mm, the end is thick, the tail is thin, the scaling is firm, and it is not easy to fall off. There is no difference between the scaling on the front and back surfaces. Only the root is not covered by scaling, as illustrated in figure 8.
Figure 8. Deposition of grading electrodes at cathode side of valve assembly of Invert station

Observing the grading electrode at the T-type connection of valve assembly distributing pipeline and main water pipe, general scale thickness is 0.6-0.8 mm, scaling distributed evenly, scaling is very firm, firmly attached to the electrode surface. The scaling is no difference between water front side and back side. Only half of length of the platinum electrode part is covered by scaling, as seen in figure 9.

Figure 9. Deposition of grading electrodes at T-junction of the valve assembly and the main water pipe of Invert station

3.2. Scaling phenomenon in Rectifier station

Deyang converter station basically operates as a rectifier, and the scaling of anode side grading electrodes on valve assembly was serious, as shown in Figure 10, which was basically consistent with the scaling of cathode side of valve assembly in rectifier station. The scaling of grading electrodes on cathode side was slight, as shown in figure 11, which was basically consistent with the scaling of anode side of valve assembly in rectifier station; the zero potential point of main water pipe in valve tower was not scaling. The scaling degree of grading electrodes installed on T-type connection of water distributing pipe and main water pipe was at intermediate level, as seen in figure 12.

Figure 10. Deposit on grading electrodes at anode side of valve assembly of rectifier station

Figure 11. Deposit on grading electrodes at cathode side of valve assembly of rectifier station
Scaling

0.6~0.8 mm

Figure 12. Deposit on grading electrodes at T-junction of the valve assembly and the main water pipe of rectifier station

4. Scale distribution principle

4.1. Distribution characteristics of scaling

According to the electrode scaling thickness, that is, the diameter of the electrode after scaling minus the diameter of the electrode without scaling, and then divided by 2, and position of grading electrodes scaling, the 864 branch electrodes of bipolar at the BAOJI converter station were all sampled for detection. The electrodes scaling were divided into 6 classes: valve assembly cathode side with serious scaling; anode side with slight scaling; valve assembly T-type tube electrodes with scaling in the middle; S-shape tube electrodes, top part electrodes, pole II bottom screen electrodes with scaling situation in agreement with those at anode side; and pole I bottom screen electrode with scaling situation in agreement with those at cathode side, as seen in tables 2 and 3, the diameter of the electrode after scaling is listed. note: The pole I converter valve has been operating for 44 months, the bottom voltage of the valve tower is -500 kV, the pole II has been operating for 39 months, and the bottom voltage of the valve tower is +500 kV. CL:CL represents the left side of the valve tower of the C phase converter valve, CR/BL/BR/AL/AR and so on.

Table 2. Pole I grading electrode with deposits’ data analysis (unit: mm)

| Average value         | CL     | CR     | BL     | BR     | AL     | AR     |
|-----------------------|--------|--------|--------|--------|--------|--------|
| Top part              | 2.04   | 2.04   | 2.02   | 2.02   | 2.03   | 2.05   |
| Mid-upper part        | 2.11   | 2.02   | 2.00   | 2.01   | 2.01   | 2.02   |
| S-type tube           | 2.05   | 2.04   | 2.07   | 2.05   | 2.03   | 2.03   |
| Cathode side          | 2.63   | 2.94   | 2.96   | 2.95   | 2.94   | 2.94   |
| Anode side            | 2.13   | 2.23   | 2.23   | 2.23   | 2.23   | 2.23   |
| T-shape tube          | 2.04   | 2.16   | 2.13   | 2.08   | 2.12   | 2.09   |
| Bottom part           | 2.88   | 2.72   | 2.73   | 2.65   | 2.68   | 2.83   |

Table 3. Pole II grading electrode with deposits’ data analysis (unit: mm)

| Average value         | CL     | CR     | BL     | BR     | AL     | AR     |
|-----------------------|--------|--------|--------|--------|--------|--------|
| Top part              | 2.04   | 2.05   | 2.04   | 2.04   | 2.04   | 2.04   |
| Mid-upper part        | 2.45   | 2.52   | 2.49   | 2.72   | 2.62   | 2.02   |
| S-shape tube          | 2.06   | 2.04   | 2.06   | 2.06   | 2.05   | 2.08   |
| Cathode side          | 2.34   | 2.28   | 2.30   | 2.28   | 2.31   | 2.29   |
| Anode side            | 2.99   | 2.93   | 3.09   | 2.89   | 2.95   | 3.05   |
| T-type tube           | 2.24   | 2.10   | 2.23   | 2.14   | 2.19   | 2.07   |
| Bottom part           | 2.01   | 2.01   | 2.02   | 2.01   | 2.02   | 2.03   |

4.2. Distribution and treatment of scaling

Baoji converter station functions as an inverter station, therefore, the scale distribution of 432 grading
electrodes of pole I and pole II were basically identical. Thus, the scaling regularity of grading electrodes of Inverter station could be obtained: scaling on the cathode side of thyristor is serious and sturdy, the scaling on the anode side is slight and loose, while scaling degree at the T-type connection is moderate and very firmly attached.

As a rectifier station, the scale distribution of 432 grading electrodes of pole I and pole II in Deyang converter station were the same, but it was different from that in Baoji converter station. Therefore, the scaling regularity of grading electrodes could be concluded that: scaling on the anode side of thyristor is serious, scaling on the cathode side is slight and scaling on the T-type connection is moderate.

Therefore, according to the scaling distribution law of grading electrodes, scaling removal could be carried out purposefully. Inverter station could aim at removing scaling on the cathode side of thyristor of valve assembly, while rectifier station could only focus on scaling on the anode side of thyristor of valve assembly [15].

5. Related detection analysis and treatment recommendations

5.1. Scale analysis
The scales of all grading electrodes were broken and dissolved in hot dilute sulfuric acid with 35% mass concentration. By doing this, the content of metal elements was detected by ICP emission spectrometer. Aluminum elements accounted for 90-96%, iron elements 5-8%, calcium elements 0.1-0.5%, magnesium elements 0.1-0.5%, sodium elements 0.05-0.1%. Detecting the resistance values of the extreme and tail parts of the grading electrode after scaling, the resistance values were found to be 280-350 kΩ. This indicates that the main harm of the scaling of the electrode lies in the gradual loss of the original function of grading voltage and transferring leakage current.

5.2. Water quality inspection
The main metal element found in scaling was aluminum. Analyzing the mass concentration of metal elements in inner cooling water and makeup water of pole I and pole II, see in Table 4. It was found that the mass concentration of aluminum was very low, only 1.1-1.3 ug/L. This indicates that the medium aluminum in scaling of grading electrode may come from the makeup water of valve tower. Therefore, the concentration of Mg$^{2+}$ and Ca$^{2+}$ and the mass concentration of aluminum in the makeup water should be reduced.

| Sample name         | Na$^+$   | NH$_4^+$ | K$^+$  | Mg$^{2+}$ | Ca$^{2+}$ | Al  |
|---------------------|----------|----------|--------|-----------|-----------|-----|
| Pole I de-gas jar   | 2.6      | 0.2      | 1.5    | 0.3       | 5.9       | 1.3 |
| Pole II de-gas jar  | 1.1      | 0.2      | 0.8    | 0.2       | 3.6       | 1.1 |
| makeup water        | 1105.8   | 0.2      | 389.5  | 10.3      | 75.8      | 1.5 |

5.3. Structure of aluminum alloy heat sinks
The aluminum alloy material directly contacting the internal cooling water system is only the aluminum alloy heat sinks of the thyristor. Unfolding a piece of aluminum alloy heat sinks running for 3 years, it could be found that there were many black corrosion points in the water inlet and outlet. As shown in figure 13, the water inlet channel (the so-called “double mosquito perfume water path” section) was bright and clean, while the outlet channel had black corrosion spots, as shown in figure 14. The results show that the corrosion products of aluminum alloy may come from the scaling of the grading electrodes, and the corrosion effect exerts no obvious harm to the aluminum alloy heat sinks.
5.4. Waterway voltage analysis
Since grading electrodes connect with heat sink, grading electrodes potentiality varies with the heat sink potentiality, the voltage difference among the grading electrodes is the sum of several heat sink voltage difference, the results listed in table 5.

| Title                        | Voltage at two ends(V) | Valve condition | Current direction     |
|------------------------------|------------------------|-----------------|-----------------------|
| Two electrodes               | 26                     | turn-on         | Anode to Cathode      |
| Neighboring heat sinks       | 2                      | turn-on         | Anode to Cathode      |
| Head-tail heat sinks         | 26                     | turn-on         | Anode to Cathode      |
| Two electrodes               | 41665                  | turn-off        | Cathode to Anode      |
| Neighboring heat sinks       | 3205                   | turn-off        | Cathode to Anode      |
| Head-tail heat sinks         | 41665                  | turn-off        | Cathode to Anode      |

5.5. Electrolytic corrosion and scaling analysis
Based on the aluminum-hydroelectric potential-pH chart [16], the following patterns are possible. If the potential exceeds 1.35V above zone with oxygen reaction, the electrolytic water product is oxygen, see Eq.(1). If the potential is below 0.12V zone with the hydrogen reaction, see Equation (2). If the potential
is between 0.12-1.35V, the absorption oxygen corrosion will take place, see Equation (3). If the potential is over -1.676V, aluminum loses electrons and is electrolyzed, see Equation (4).

\[
\begin{align*}
4\text{OH}^- - 4e^- & \rightarrow 2\text{H}_2\text{O} + \text{O}_2 \uparrow \quad (1) \\
2\text{H}^+ + 2e^- & \rightarrow \text{H}_2 \quad (2) \\
\text{O}_2 + 2\text{H}_2\text{O} + 4e^- & \rightarrow 4\text{OH}^- \\
\text{Al} & \rightarrow \text{Al}^{3+} + 3e^- \\
\end{align*}
\]

Through the calculation of \(\text{Al(OH)}_3\), \(\text{pks}=32.89\) and \(\text{H}_3\text{AlO}_3\), \(\text{pK}_1=11.2\), at 18~25℃, the pH value is 5.6~5.8, the oxide film of alumina has the minimum solubility, that is, the aluminum alloy protective film is the best. When the pH value is less than 4.6 or more than 8.3, the protective film begins to dissolve, see Equations (5) and (6):

\[
\begin{align*}
\text{Al(OH)}_3 & \leftrightarrow \text{Al(OH)}^{2+} + 2\text{OH}^- \quad (5) \\
\text{Al(OH)}_4^- & \leftrightarrow \text{H}_3\text{AlO}_3 \leftrightarrow \text{H}_2\text{AlO}_4^- + \text{H}^+ \quad (6)
\end{align*}
\]

Therefore, the aluminum alloy heat sink is subject to electrolytic corrosion. The production of hydrogen or oxygen will generate \(\text{Al(OH)}_4^-\). So, in the cooling water system, when the valve is turned on, the aluminum hydroxide is absorbed by the electrode surface of valve anode side. When the valve is turned off, the aluminum hydroxide is absorbed by the electrode surface of valve cathode side. In addition, the electrode at the positive potential can produce oxygen, with its volume being about 50% of that at the negative potential, and the electrolysis gas can remove the scaling. Therefore, both rectifier and invert stations have more severe scaling in the electrode at the positive potential than at the negative one.

6. Conclusions

Corrosion in HVDC valves cooling water system was analyzed. The chemical composition of the scaling on the electrodes revealed a large amount of aluminum. Further investigation showed that the aluminum detected was a corrosion product coming from the makeup water of internal cooling water and aluminum alloy heat sinks. It could be found that the surface conductive resistance of the grading electrode increased significantly and the function of grading voltage and transferring leakage current were lost after scaling. Observing the internal of the heat sinks of aluminum alloy, corrosion spots were found. But they are not enough to harm its safe operation. The experiments illustrated that the scaling at the positive potential was higher than that at the negative potential. The scaling principle was different in the rectifier and inverter stations. In the rectifier station, the scaling of grading electrodes at the anode side of valve is serious, while the scaling of grading electrodes at the cathode side is more severe in the inverter station. Based on these regularities of the distribution of the scaling on grading electrodes, targeted scale removal measurements could be carried out. On account of the corrosion of aluminum alloy heat sinks caused by leakage current electrolysis, the conductivity of the internal cooling water system should be lowered as far as possible, and the pH value should be adjusted to a reasonable range.

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