Analysis and research on failure of B-phase lower bridge arm through wall casing in converter station

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Abstract. Based on the actual failure of the bushing, this paper conducts analysis and research. Firstly, it analyzes the protection action, on-site harmonic components, bushing structure and disassembly step by step. Then it conducts the research on the discharge and breakdown characteristics of epoxy insulation. Finally, we results show that there are bubbles or impurities in the outer capacitor layer of the capacitor core inside the casing, and the harmonic content is higher under the operating conditions of the converter station. Meanwhile, we gives some relevant suggestions for the through-wall bushing in the design and manufacturing stage to consider relevant harmonic factors are of certain significance to extend the life of the bushing.

1. Introduction
DC wall bushing is the key equipment of the UHV DC transmission project, and it is connected to the wall through the fixing plate on the wall barrel. The bolt connection method is adopted. The wall barrel is the main load-bearing component. It is welded with high-strength steel and filled with a certain pressure of SF₆ gas. Its operating environment is harsh, which is essential for the safe and reliable operation of the DC wall bushing [1].

2. Event overview and equipment information
Converter station caused zero-sequence voltage protection on the AC valve side and tripped due to the voltage breakdown of the B-phase lower bridge arm through the wall bushing during the charging stage. After charging to before trip, there are 20 sub-modules converter valve failed, including 7 phase B upper bridge arms and 13 phase B lower bridge arms.

Table 1. Information about faulty wall bushing equipment.

| Equipment name                           | Epoxy resin impregnated paper capacitive wall bushing |
|------------------------------------------|---------------------------------------------------------|
| Model                                    | EAA-252/1250-3                                         |
| Number                                   | 1400776                                                 |
| Maximum equipment Voltage                | 252kV                                                   |
| Rated current                            | 3150A                                                   |
| Capacity                                 | 723pF                                                   |
| Frequency                                | 50Hz                                                    |
After replacing the B-phase lower bridge arm through-wall casing, it was reactivated. And the converter valve was put into operation on December 20 without obvious abnormalities.

Faulty wall bushing is epoxy resin impregnated paper capacitive bushing produced by XX company. Production date is 2014. It related equipment technical parameters are shown in Table 1.

3. Analyze and research from different aspects

We analyze and research step by step from the test data over the years, the protection action situation, the on-site harmonic component, the casing structure and the disassembly of the return to the factory.

3.1. Test data over the years

Over the years, wall bushing (B-) has not been abnormal in the insulation resistance, dielectric loss, and capacitance tests, as shown in Table 2 and Table 3.

| Phase | Tgδ | Capacity | Insulation resistance(MΩ) |
|-------|-----|----------|---------------------------|
|       | %   | pF       | Main insulation | Last screen |
| A+    | 0.416 | 719.7   | 50000          | 2500        |
| A-    | 0.411 | 710.5   | 50000          | 5000        |
| B+    | 0.346 | 709.6   | 50000          | 5000        |
| B-    | 0.420 | 707.3   | 50000          | 5000        |
| C+    | 0.402 | 706.5   | 50000          | 5000        |
| C-    | 0.405 | 707.2   | 50000          | 5000        |

Table 3. Test data of wall bushing over the years.

| Phase            | Tgδ [2] | Capacity | Factory capacity |
|------------------|---------|----------|------------------|
|                  | %       | pF       | pF               | Insulation resistance(MΩ) |
|                  |         |          |                  | Main insulation | Last screen |
| Handover         | 0.502   | 705.8    | 723              | 50000          | 2500        |
| December 2015    | 0.444   | 713.1    |                  | 50000          | 5000        |
| Sep 2017         | 0.414   | 711.8    |                  | 50000          | 5000        |
| November 2018    | 0.432   | 706.5    |                  | 50000          | 5000        |
| November 2019    | 0.581   | 707.0    |                  | 50000          | 5000        |
| October 2020     | 0.420   | 707.3    |                  | 50000          | 5000        |

3.2. On-site harmonic content analysis

Figure 1 and Figure 2 respectively select the normal operation of the system on November 13 (the four modules in the fault are distributed with four bridge arms) bridge arm current harmonics (the breakdown bushing is located between the bridge arm reactance and the converter valve) and before 11.20 trip (at this time, the number of faulty modules is 13 at B down, 7 at B up, 3 at C up, 2 at A down, and 1 at C down). Comparing the current harmonics of the lower bridge arm under B before the system is in normal operation, the low-order harmonic distribution is basically the same, the harmonic content is slightly changed, and the high-frequency harmonic cannot be analyzed.

Figure 1 shows the current harmonics of the bridge arm during normal operation of the system, and the harmonic content is as follows: Phase B double-frequency harmonic content of the lower bridge arm is 14%, the fourth harmonic is 9%, and the fifth harmonic is about 6.5%. Due to the CT sampling accuracy, filtering processing of the bridge arm current and the recording sampling frequency, high-frequency harmonics cannot be analyzed [3, 4].
3.3. Introduction to fault casing structure

Fault casing bushing is an epoxy resin impregnated paper capacitive wall bushing produced by XX Company, which is mainly composed of conductive rods, capacitor cores, porcelain sleeves, flanges, etc., and insulating fillers are filled between core and porcelain jacket. Inside of the casing is not open to atmosphere at all. As shown in Figure 3.

Capacitor core is wound by insulating paper and aluminum foil and impregnated with epoxy resin after vacuum and drying to form an epoxy resin-impregnated paper capacitive insulator. Bushing capacitive core has 21 layers of capacitive screens, and capacitive screens mainly play the role of voltage equalization and insulation.
3.4. Disintegration of return to factory

Before disassembly, no abnormality was found in the appearance inspection of the casing. Terminal screen tap wiring was intact, and there was no trace of discharge. At the same time, an insulation test of the final screen to ground was carried out. Test voltage was 2kV, the dielectric loss of final screen was 0.868%, and capacitance was 691pF. Under 10kV, main dielectric loss and capacitance of the casing cannot be measured.

![Figure 4. Ablation position on capacitor core.](image1)

![Figure 5. Enlarged ablation position.](image2)

During disassembly of the casing, after removing porcelain sleeve, it was found that there was an ablation cavity inside the capacitor core on the side of the valve hall of the casing (Figure 4, Figure 5). The radial (thickness direction) of the capacitive screen was ablated by about 80% (Figure 6), and a penetrating breakdown discharge occurred (Figure 7). The center of ablation chamber is about 930mm from end screen tap toward valve hall, and there are obvious discharge ablation marks on the inner wall of the corresponding porcelain sleeve (Figure 8). This position is located at the edge of the outermost capacitive screen of capacitor core, in the high field strength region of the casing.

![Figure 6. Section of ablation position.](image3)

![Figure 7. Conductive rod ablation.](image4)
Figure 8. Discharge position on the inner wall of the porcelain sleeve.

4. Preliminary analysis conclusions and suggestions

4.1. Failure cause analysis

According to the phenomenon of the ablation hole morphology inside the capacitor core of the disassembled through-wall bushing, and the discharge ablation traces on the inner wall of the porcelain sleeve. We believe that the nature of the bushing fault is voltage breakdown, and there are obvious discharge channels during the fault process. There is an obvious breakdown point on the outer surface of the bushing capacitor core, breakdown point penetrates end screen to conductive rod, and the corresponding conductive rod position has a slight discharge trace.

The overall development of the fault can be divided into two stages:

One is the slow burning discharge process. Combining the characteristics of the ablation part of capacitor core (the ablation cavity gradually increases from the inside to the outside in the radial direction) and the disintegration of conductive rod where the ablation marks are not obvious, it can be preliminarily judged that the ablation development direction is from the outside to the inside. That is, the discharge of outer capacitive screen inward. At the same time, because the edge of capacitive screen outside the capacitor core is a high field strength area, and the project was designed for production earlier, the impact of operating harmonic content on the casing was not considered. Wall-through casing was designed and manufactured according to the power frequency operation. Harmonic loss will aggravate the electric field distortion at the edge of the capacitive screen, accelerate the aging of the insulation, and affect the safe and stable operation of the equipment. If there are tiny bubbles or impurities caused by the processing technology, the defect will stimulate partial discharge after long-term operation under the working condition with high harmonic content, and develop into a slow burning discharge. Which will cause the capacitive screen in this part to strike, and the number of capacitive screens to decrease, field strength between the remaining screens increases, the electric field distribution is abnormal, and the discharge is accelerated [5]. As shown in Figure 9.

Figure 9. Breakdown discharge path.
The second is the rapid breakdown discharge process. This process is due to the continuous ablation of internal insulating core, resulting in insufficient final insulation strength, final core insulation cannot withstand the operating voltage, and the capacitor core undergoes radial breakdown [6].

1. Through the failure analysis and disassembly process, it is found that the cause of the failure of the B-phase lower bridge arm through the wall bushing may be the presence of bubbles or impurities in the outer capacitor layer of the capacitor core inside the bushing. Long-term high field strength will cause partial discharge, continue to develop and then break down [7].

2. Through the harmonic analysis under operating conditions, it is proved that the harmonic content in converter station is relatively high, wall bushing has not considered relevant harmonic factors in design and manufacturing stage, and the ability to withstand harmonics is poor. A large number of harmonics loss causes the internal insulation of bushing to heat up, which can cause internal insulation damage in severe cases and severely reduce the service life [8, 9].

3. Carry out research on the discharge and breakdown characteristics of epoxy insulation to determine the process of failure development.

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