Fracture Failure Analysis of the Connecting Bolt of Circuit Breaker in 500kV Converter Station

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Abstract. Through a macroscopic inspection, a stereomicroscopic inspection, a material analysis, a hardness inspection, a metallographic analysis, scanning electron microscope and energy spectrum analysis, the reasons for the breakage of the connecting bolts of the circuit breaker in a 500kV converter station are studied. The results show that the bolt fracture is caused by the combined effect of a hydrogen embrittlement and a high-stress low-cycle fatigue. The corresponding recommended measures are proposed to improve the reliability of the bolts and ensure the safe operation of the circuit breaker.

1.Introduction
Due to the advantages of simple structure, high reliability, and easy assembly, bolt connection is one of the most widely used connection methods in mechanical systems[1-3]. In practical applications, under the influence of factors such as vibration and impact, bolt fasteners often have failure problems mainly caused by loosening and fracture of bolt connections[4-5]. The vibration and shock caused by the opening and closing operations of high-voltage circuit breakers is the main cause of bolt fracture, and the fracture of bolt fasteners may cause abnormal operation of the circuit breaker, which may be dangerous for the safety of the power grid[6-10]. Therefore, the reliability of the bolt is very important for the stable operation of the circuit breaker.

In this paper, a failure of a connecting bolts of the circuit breaker in a 500kV converter station was studied. Through a macroscopic inspection, a stereomicroscopic inspection, a material analysis, a hardness inspection, a metallographic analysis, scanning electron microscope and energy spectrum analysis, the reason for the bolt fracture is analyzed, which provides a useful reference for the design and selection, manufacturing and processing of the connecting bolts of the circuit breaker.

2.Experimental analysis

2.1. Macro inspection
The bolt is broken at the tenth buckle from the bottom end of the thread, and there is no obvious plastic deformation mark, showing a macroscopic brittle fracture feature. In addition, it can be seen that the surface of the bolt has been blackened, as shown in Figure 1.
2.2. Stereoscopic examination

Perform stereo microscope inspection on broken bolts, as shown in Figure 2. It can be seen that the entire fracture is composed of three parts: the crack source area (close to the surface of the thread root, there are obvious traces of rust, which accounts for about 5% of the surface area of the entire fracture), crack propagation area (approximately 75% of the surface area of the entire fracture) and the final instantaneous area (approximately 20% of the surface area of the entire fracture). Combining the service characteristics of the circuit breaker with fewer opening and closing times and severe vibration during operation, it can be judged that the bolt is a high-stress low-cycle fatigue fracture.

2.3. Material analysis

The components of the broken bolts were tested, and the results are shown in Table 1. According to the test results, it can be inferred that the design material should be alloy structural steel. However, inquiring about the GB/T 3077 "Alloy Structural Steel" standard, no brand corresponding to the material of the fractured bolt was found.

| Element | C    | Si   | Mn   | S    | P    | Cr   | Mo   | Ni   | Fe   |
|---------|------|------|------|------|------|------|------|------|------|
| Sample  | 0.325| 0.136| 0.973| 0.0134| 0.0153| 1.18 | 0.0096| 0.289| balance |

Figure 1. Appearance of broken bolt

Figure 2. Stereo microscope fracture
2.4. Hardness testing
Take the axial mid-section of the broken bolt to be ground and polished. From the thread tip to the bolt core, 5 points (numbered 1 to 5 respectively) are selected for the Vickers hardness test, as shown in Figure 3. The test results are shown in Table 2. The hardness distribution of the entire section is relatively uniform, and it meets the requirements of GB/T 3098.1-2000 "Mechanical Properties of Fasteners Bolts, Screws and Studs" standard that the Vickers hardness of 12.9 bolts is not less than 385HV and not more than 435HV.

![Figure 3. Schematic diagram of Vickers hardness test](image)

| Hardness | 1# | 2# | 3# | 4# | 5# | Avg. |
|----------|----|----|----|----|----|------|
| HV       | 392| 395| 394| 402| 397| 396  |

2.5. Metallographic analysis
The microscopic morphology of the thread root is shown in Figure 4, and the metallographic structure of the bolt matrix is shown in Figure 5. It can be seen from Figure 4 that the transition of the thread root is relatively smooth, indicating that the thread processing process is a rolling process. In addition, there is no metal streamline at the root of the thread, indicating that the processing sequence is to process the thread first and then perform quenching and tempering treatment instead of first quenching and tempering and then processing the thread. Figure 5 shows that the metallographic structure of the bolt matrix is tempered sorbite.

![Figure 4. Micro morphology of thread root](image)

![Figure 5. Metallographic structure of bolt base](image)

2.6. Scanning electron microscope analysis (SEM) and energy spectrum analysis (EDX)
The morphology of the crack source area, the crack propagation area and the final transient area are shown in Figures 6, 7, and 8, respectively. Perform energy spectrum analysis on point A, and the results are shown in Table 3. It can be seen that the particulate matter at point A is FeS inclusions, which are located in the crack source area, so it is likely to be the crack source of bolt fracture. In addition, it can be seen that there are a large number of secondary cracks in the crack source area and the crack...
propagation area, and they extend along the grain boundary, which is consistent with the characteristics of hydrogen embrittlement fracture. There are a large number of small dimples in the final instantaneous fracture zone, which indicates that the plasticity of the bolt is low.

Figure 6. SEM morphology of crack source area

Figure 7. SEM morphology of crack propagation area

Figure 8. SEM morphology of the final transient region

Table 3. EDX test result at point A (at%)

| Element | Fe   | S    |
|---------|------|------|
| A       | 50.63| 49.37|

3. Cause analysis

The bolt design material is unknown. According to the aforementioned test results, it can be known that its composition does not meet the requirements of the GB/T 3077 "Alloy Structural Steel" standard. The metallography and hardness were tested, and they all met the requirements of relevant standards, indicating that the material was not too problematic. According to the results of fracture analysis, the cause of the fracture is probably caused by hydrogen embrittlement and fatigue. High-strength bolts have a certain delayed fracture tendency. The higher the strength level, the greater the delayed fracture tendency, because they are very sensitive to hydrogen embrittlement. The process of bolt manufacturing and surface blackening treatment will inevitably undergo a pickling process, and hydrogen atoms may be introduced. In addition, hydrogen atoms may also be introduced in the external environment. This is the essential reason for the delayed fracture tendency of high-strength bolts. At the same time, the circuit breaker has huge vibrations during the closing and opening operations, which will make the bolts bear a large impact load. The high-strength bolts are very sensitive to the gap. Once a crack is initiated, the crack will grow very rapidly under the impact of the impact load, until the remaining section can not withstand the impact load and break completely.
4. Conclusions and Suggestions

4.1. Conclusions
The bolt fracture is caused by the combined effect of a hydrogen embrittlement and a high-stress low-cycle fatigue.

4.2. Suggestions
(1) High-strength bolts should be used with caution, especially the higher the strength level, the more cautious it is.

(2) If high-strength bolts must be selected, it is required to undergo hydrogen removal treatment after the last pickling process in the manufacturing process to minimize the possibility of hydrogen embrittlement.

(3) It is recommended that the bolts adopt the rolling process of the thread after quenching and tempering treatment to improve their fatigue resistance and life.

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