Failure analysis of phase B pull rod of HGIS circuit breaker operating mechanism in 220 kV Substation

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Abstract. The B-phase pull rod of HGIS circuit breaker operating mechanism in a 220kV substation was broken at the root. The broken pull rod was analyzed by macro examination, metallographic examination, chemical composition analysis, fracture morphology analysis and impact test to find out the reason for the fracture. The results showed that: 1. Due to the improper heat treatment in the manufacturing process, the metallographic structure of B-phase pull rod appeared network ferrite and widmanstetten structure, which made the material brittle and impact toughness lower than the standard requirements; 2. The content of alloy elements Cr, Ni and Ni were significantly higher than the standard requirements, which reduced the plasticity and toughness of the material; 3. The low temperature of substation environment led to the decrease of material toughness and the viscosity of the lubricant decreased, causing the transmission parts to jam. The joint action of three factors led to cleavage fracture of B-phase pull rod in the stress concentration area.

1. Introduction
HGIS is the abbreviation of gas insulated composite electrical apparatus, which is composed of circuit breaker, disconnector, grounding switch, current transformer and other components, and is enclosed in a container filled with insulating gas. The structure of HGIS is the same as that of GIS, but the inside of its enclosed container does not include bus equipment, so it has the advantages of clear wiring, simple, compact, convenient installation and maintenance, low cost, and is widely used in high-voltage switchgear of 220kV and above substations. In the process of power transmission in a substation, the B-phase pull rod of HGIS circuit breaker operating mechanism fractured at the root. The specification of the B-phase pull rod of HGIS circuit breaker was Φ 33.5mm, and the material was 35 steel.

2. Test method
The macro morphology of the broken B-phase pull rod was observed to determine whether there were traces of original defects, wear and corrosion, and the fracture mode was determined. The full element chemical composition of the B-phase pull rod was analyzed by using SPECZROMAX desktop direct reading spectrometer to determine whether its chemical composition met the standard requirements of the design material. By using Axio Observer.Alm to determine the change of metallographic structure. ZBC-300B digital impact testing machine was used to carry out impact test on the sampling position.
of phase B pull rod to determine whether the impact toughness met the standard requirements. HITACHIS-3700N scanning electron microscope was used to analyze the fracture morphology of phase B pull rod.

3. Test results and discussion

3.1. Observation and analysis of macromorphology
The fracture surface was located at the bottom of the first thread of the finer part of the variable cross section of the B-phase pull rod, which was the stress concentration area of the pull rod. The fracture surface was flat without plastic deformation, and the cross section was rough with silver white metallic luster. Under strong light, there were many radial stripes and small facets on the fracture surface, without obvious mechanical damage and corrosion damage. The characteristics of typical cleavage faults was observed from the fracture section of pull rod, as shown in Figure 1.

3.2. Scanning electron microscopy.
Scanning electron microscope (SEM) was used to detect the fracture surface of phase B pull rod. The fracture surface morphology was shown in Figure 2[1-4]. From the electron microscope photos, the fracture morphology presented river pattern, the fracture direction was along the cleavage plane of different heights, and the cracks between the cleavage planes of different heights converge to form river pattern. At the same time, the cleavage cracks propagate along the interface between the twin crystal and the matrix and presented tongue pattern. Therefore, from the macro morphology and micro fracture characteristics of the fracture of the B-phase pull rod, the brittleness of B-phase rod was larger.

Figure 1. Macroscopic Fracture Morphology of Phase B Tension Rod

Figure 2. SEM morphology of tensile fracture.
3.3. Analysis for Chemical Composition
The chemical composition of B-phase pull rod was detected, and the detection data was shown in Table 1. The results showed that the contents of Cr and Ni in the alloy elements of B-phase pull rod were obviously higher than the chemical composition requirements in «GB / T 699-2015 Quality carbon structure steels». With the increase of alloying elements Cr and Ni, the hardness, tensile strength and yield strength of the steel increased, and the plasticity and toughness of the steel decreased. The cold brittle tendency of the steel increased, and the brittle transition temperature increased. The safety and reliability of the structural parts would reduced.

Table 1. Results of chemical composition of tie rod unit:%

| Detection elements | Carbon (C) | Silicon (Si) | Manganese (Mn) | Phosphorus (P) | Sulfur (S) | Chromium (Cr) | Nickel (Ni) | Copper (Cu) |
|--------------------|------------|--------------|----------------|----------------|------------|---------------|-------------|-------------|
| Sample             | 0.35       | 0.21         | 0.50           | 0.007          | 0.007      | 1.70          | 1.47        | 0.009       |
| ~                  | 0.32       | 0.17         | 0.50           | ~              | ~          | ~             | ~           | ~           |
| Standard           | 0.39       | 0.37         | 0.80           | ≤0.035         | ≤0.035     | ≤0.25         | ≤0.30       | ≤0.25       |

3.4. Microstructural examination and analysis
Metallographic microscope was used to detect the microstructure of B-phase pull rod, and the sampling position was near the fracture of B-phase. The metallographic morphology was shown in Fig. 3. It was observed that the microstructure was pearlite + network ferrite + widmanstatten structure, and there was no obvious distortion. Widmanstatten structure was nearly parallel acicular ferrite growing from austenite grain boundary and pearlite existing in it. This kind of acicular ferrite could be directly precipitated from austenite, or first precipitated along austenite grain boundary, and then precipitated from network ferrite. The formation of Widmanstatten was related to the carbon content, austenite grain size and cooling rate. Only when the austenite grain was larger, the carbon content was 0.15% - 0.35%, and the cooling rate was faster, widmanstatten could be easily formed. The existence of network ferrite and widmanstatten structure seriously broke the connection between pearlite in the steel, which greatly reducing the strength and toughness of the steel and causing brittle fracture.

3.5. Analysis of mechanical properties
The impact test and analysis of the broken B-phase tension bar at room temperature were carried out. The test results were shown in Table 2. It could be seen from the test data that the impact property of phase B tie rod at room temperature was obviously lower than the requirements of «GB / T 699-2015 Quality carbon structure steels»
Table 2. Impact test results of phase B tie rod

| Detection elements | Sample number | Impact fracture energy $K_u$ /J |
|--------------------|---------------|-------------------------------|
|                    | 1             | 35                            |
|                    | 2             | 38                            |
|                    | 3             | 33                            |
| **Sample**         | **Average**   | **35**                        |
| **Standard**       |               | **≥ 55**                      |

4. Summary

Based on the analysis of the above test results, the fracture causes of phase B tie rod were as follows:

From the analysis of chemical composition, the contents of Cr and Ni were obviously higher than the standard requirements. An appropriate amount of alloying elements Cr and Ni could not only improve the mechanical properties of steel, but also improve the wear resistance, oxidation resistance and corrosion resistance of steel. However, if there were too many alloying elements Cr and Ni in steel, they would dissolve in ferrite and austenite to form solid solution or carbide in varying degrees. If the carbide particles were too large or unevenly distributed in the steel, it would cause the corrosion of steel with the increase of hardness, tensile strength and yield strength. However, the plasticity and toughness of the steel decreased, especially the cold brittle tendency of the steel increased, and the brittle transition temperature increased. The safety and reliability of the structural parts were reduced. The impact test at room temperature showed that the impact toughness of B-phase pull rod was lower than the standard requirements, which verified that the plasticity and toughness of the material were poor.

According to the macro morphology analysis, the fracture surface was located at the bottom of the first thread of the finer part of the variable cross section of the B-phase pull rod, which was the stress concentration area of the pull rod. The fracture surface was flat without plastic deformation, and the fracture surface was rough with silver white metallic luster. Under strong light irradiation, the radial stripes and small facets appeared on the fracture surface, without obvious mechanical damage and corrosion damage. The fracture direction was along the cleavage plane of different heights, and the cracks between the cleavage planes of different heights converged to form a river pattern. At the same time, the cleavage crack propagated along the interface between the twin crystal and the matrix, which presenting a tongue pattern. From the above characteristics, it could be seen that the B-phase pull rod fracture belonged to cleavage fracture, and the material was brittle.

The metallographic structure of B-phase pull rod was pearlite + network ferrite + widmanstatten structure. Widmanstatten structure was the overheated structure of steel, which could significantly reduce the mechanical properties, especially the impact toughness and plasticity of steel, it also could increase the brittle transition temperature of steel. The formation of widmanstatten structure often made the austenite grain coarser due to too long final forging temperature and heating time.

To sum up, the fracture of phase B pull rod of HGIS circuit breaker operating mechanism in substation was due to improper heat treatment process in the manufacturing process, network ferrite and widmanstatten structure distributed along grain boundary were formed in the structure, which increasing the brittleness of the material and making the impact toughness lower than the standard requirements. The contents of alloy elements Cr and Ni were obviously higher than the standard requirements, which reducing the shaping and toughness of the material. Due to the lower temperature in winter, the toughness of the material was further reduced [5-6]. The operating mechanism was easily jammed due to the decrease of lubricant viscosity and poor fit clearance in the process of rotation. Under the comprehensive influence of various factors, the cleavage fracture of the B-phase tension rod occurred in the stress concentration area.
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