Fracture Failure Analysis of the Energy Storage Spring of the Circuit Breaker in the 110kV Substation

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Abstract. Through a macro inspection, chemical composition analysis, hardness inspection, graphite carbon inspection and energy spectrum analysis, the reason for the break of the energy storage spring of the circuit breaker in a 110kV substation are analyzed. The results show that poor manufacturing technology and anti-corrosion technology of the spring are the main reason for its fracture. Corresponding control measures are put forward to avoid similar failures from happening again.

1. Introduction

The high-voltage circuit breaker is one of the important components in the power system, and it plays an important role in the operation adjustment and fault isolation of the power system[1-7]. Reliable energy storage is the high-voltage circuit breaker to correctly cut off the fault current premise[8-9]. According to the statistics of the international survey report on the reliability of high-voltage equipment, the failure of high-voltage circuit breakers to open or close accounts for 45% of the total number of accidents[10]. If there is a problem with the energy storage spring, the high-voltage circuit breaker may fail to operate, threatening the safety of the power grid. Therefore, the high reliability of the energy storage spring is required.

In this paper, a failure of a energy storage spring of the circuit breaker in a 110kV substation was studied. Through a macro inspection, chemical composition analysis, hardness inspection, graphite carbon inspection and energy spectrum analysis, the causes of spring fracture were analyzed to provide a reference for design and manufacturing, inspection and testing, and operation and maintenance.

2. Experimental Section

A FOUNDRY-MASTER PRO Oxford full-spectrum direct-reading spectrometer was used to analyze the chemical composition of the fracture spring. The hardness test is carried out on the HRS-150M touch screen digital display Rockwell hardness tester. The graphite carbon of the fracture spring were observed under the Zeiss Axio Observer A1m metallographic microscope. Energy spectrum analysis is carried out on SEM3000S scanning electron microscope.
3. Results and Discussion

3.1 Macro inspection
The energy storage spring of the circuit breaker is a cylindrical spiral tension spring with a diameter of more than 8mm. It can be speculated that the manufacturing process is hot coil processing. The fracture location is located in the middle of the spring, as shown in Figure 1. There are obvious rust areas in the fracture, and there is no trace of plastic deformation, showing the characteristics of brittle fracture, as shown in Figure 2. It shows that the crack originated in the rusted area and experienced fatigue growth in this area, which is a typical fatigue fracture. The inner side of the spring is severely corroded, indicating that the anti-corrosion process of the spring is poor when it leaves the factory.

3.2. Chemical composition testing
The chemical composition of energy storage spring were illustrated in Table 1. It can be seen that the average chemical composition of the energy storage spring basically meets the requirements of 55SiCr steel in the GB/T 1222-2016 "Spring Steel" standard, so it can be inferred that its design material is 55SiCr. Si-Cr series alloy spring steel is the most widely used spring steel in my country, and 55SiCr is the most typical grade of this series. The hardenability of 55SiCr is much higher than that of carbon spring steel. It is not easy to produce cracks during quenching, has good tempering stability, and is not easy to produce temper brittleness. After quenching and tempering, it has better comprehensive mechanical properties and process performance. It is mainly used for Manufacture of coil springs of medium cross-section.

| Element | Test point 1 | Test point 2 | Test point 3 | average value | standard for 55SiCr |
|---------|-------------|-------------|-------------|---------------|------------------|
| C       | 0.587       | 0.591       | 0.574       | 0.584         | 0.51~0.59        |
| Si      | 1.563       | 1.594       | 1.613       | 1.590         | 1.20~1.60        |
| Mn      | 0.601       | 0.598       | 0.610       | 0.603         | 0.50~0.80        |
| Cr      | 0.559       | 0.575       | 0.554       | 0.563         | 0.50~0.80        |
| Ni      | 0.0320      | 0.0267      | 0.0414      | 0.0334        | ≤0.35            |
| Cu      | 0.112       | 0.121       | 0.118       | 0.117         | ≤0.25            |
| P       | 0.0056      | 0.0062      | 0.0056      | 0.0058        | ≤0.025           |
| S       | 0.0083      | 0.0079      | 0.0081      | 0.0081        | ≤0.020           |

3.3. Hardness measurement
Since the broken spring failed to be sampled for mechanical performance testing, samples can only be taken from the broken energy storage spring for Rockwell hardness testing. The results are shown in Table 2. According to the standard GB/T 23934-2015 "Hot Wound Cylindrical Spiral Compression
Spring Technical Conditions" in Appendix B, Table B.1, the hardness value of 55SiCr spring steel after heat treatment should be in the range of 45.8~51.5HRC. It can be seen that the hardness of the energy storage spring is higher than the upper limit required by the standard, indicating that the tempering temperature during the heat treatment process is low, resulting in poor plastic toughness.

Table 2. Rockwell hardness test results

| Hardness | 1#  | 2#  | 3#  | 4#  | 5#  | average value | standard for 55SiCr |
|----------|-----|-----|-----|-----|-----|---------------|-------------------|
| HRC      | 52.3| 53.2| 51.7| 52.4| 53.0| 52.5          | 45.8~51.5         |

3.4. Graphite carbon inspection

According to the standard GB/T 13302-1991 "Method for Microscopic Evaluation of Graphite Carbon in Steel", the entire cross-section of the broken spring is cut, grounded, flattened, polished, and then observed under a microscope with a magnification of 100 times and 200 times, as shown in figure 3. It can be seen that there are obvious fine clusters of flocculent graphitic carbon in the fractured spring, and its graphitic carbon grade is rated as 1.5 by comparing with the standard rating chart. The standard GB/T 1222-2016 "Spring Steel" stipulates that the silico-manganese spring steel after heat treatment should not have visible graphite carbon on the fracture. Silicon chromium spring steel can refer to this requirement, so the graphite carbon inspection of the broken spring is unqualified.

3.5. Energy spectrum analysis

The graphitic carbon test sample is placed under a scanning electron microscope for observation, and its graphitic carbon features are more prominent. The morphology after 1000 times magnification is shown in Figure 4. The morphology of the selected area in Figure 4 after being enlarged 2000 times is
shown in Figure 5. It can be seen that the precipitated graphitic carbon presents the characteristics of aggregation distribution, and the amount of precipitation is relatively large. The area shown in Figure 5 is scanned, and the EDS layered image is shown in Figure 6. It can be seen that the C element is significantly enriched in the area of the precipitated particulate matter, which further confirms that the precipitate is graphitic carbon.

![Figure 5. Graphite carbon morphology 2000×](image1)

![Figure 5. Graphite carbon morphology 2000×](image2)

![Figure 5. Graphite carbon morphology 2000×](image3)

3.6. Cause analysis

(1) Bad spring manufacturing process

As the aforementioned analysis shows, the design material of the spring is a 55SiCr alloy spring steel. Since silicon is an element that strongly promotes graphitization, this type of steel is prone to graphitization during annealing. The precipitation of graphitic carbon is equivalent to reducing the carbon content of spring steel, causing its Ar3 point to rise. The actual quenching heating temperature is low, so the degree of alloying of austenite is very low. After quenching, ferrite remains on the martensite matrix, and these structures still exist after tempering. This quenched underheated structure will severely reduce the various mechanical properties of steel and greatly reduce its service life. On the other hand, the hardness of the spring is high, indicating that the temperature of its tempering treatment is low, resulting in insufficient toughness. Due to the poor manufacturing process of the spring, the performance of the spring itself is poor.

(2) Poor spring anti-corrosion process

The circuit breaker has only been put into operation for 12 years, and its energy storage spring has been severely corroded, especially the inner coating of the spring has basically fallen off, and the surface has been severely rusted to form pits, indicating that the spring itself has poor anti-corrosion technology.

(3) Comprehensive analysis

The adhesion of the anti-corrosion coating of the spring is insufficient. Due to the maximum stress on the inner side of the spring, the coating on the inner side gradually falls off after long-term service,
causing serious corrosion on the inner surface and forming pits, which are prone to stress concentration and become fatigue source. Due to the poor manufacturing process of the spring, its mechanical properties are poor. During the operation of the circuit breaker, the spring with poor performance cannot withstand the stress of too fast loading speed, which leads to faster crack propagation. As time goes by, the cracks continue to expand, eventually leading to rupture.

4. Conclusions and Suggestions

4.1. Conclusions
Poor spring manufacturing technology and anti-corrosion technology have caused serious deterioration of spring performance and greatly reduced its expected service life. During the operation of the circuit breaker, the crack propagates rapidly under the impact load, and fatigue fracture occurs eventually.

4.2. Suggestions
(1) Check the spring of the manufacturer of the circuit breaker operating mechanism, and replace the energy storage spring in conjunction with power outage maintenance.
   (2) Strengthen the quality inspection of new replacement springs to ensure that its performance and anti-corrosion quality are excellent.

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