Research on differentiated quality control strategy of UHV converter transformer based on economic sensitivity analysis

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Abstract. ±800kV converter transformer is the most difficult and valuable equipment in UHVDC converter station. The total price of converter transformer in a single project is up to RMB 4.9 billion. The converter transformer connects the AC power grid and the converter valve hall, which is the hub of DC transmission. It realizes the electrical isolation, power exchange, voltage matching and on load regulation of AC / DC system through electromagnetic induction. The cost and quality performance of UHV converter transformer also determine the economy and reliability of power system operation. The purpose of this paper is to Taking 800 kV converter transformer as the research object, through a large number of investigation and field investigation, the establishment of the ± Procurement cost estimation model of 800 kV converter transformer. In this study, through exploring the cost characteristics and quality characteristics of the main materials and components of the transformer, the concepts of cost sensitivity and quality sensitivity are proposed, and the four quadrant matrix analysis method is used to analyse the cost and quality control of the transformer, and then the differentiated quality control strategy is formulated. It can guide the quality grading control of converter transformer in engineering, and realize the collaborative improvement of power equipment economy and reliability.

1. Introduction

UHV converter transformer is one of the most expensive equipment of DC transmission project. In the Xiangjiaba-Shanghai UHVDC project, converter transformer accounts for 40.7% of the total investment of converter station equipment. The cost of a single converter transformer reaches RMB 70-90 million. Its operating position connects AC power grid and converter valve hall, and undertakes AC electric field, AC / DC superimposed electric field, harmonic and other operating conditions. At the same time, the HVDC transmission project may suffer from special conditions such as impulse voltage in case of re fault. The HVDC transmission project will operate at full load for a long time, and the converter transformer will also operate at full load or short-term overload. The purchasing cost and quality performance of UHV converter transformer also determine the economy and reliability of power system operation. On the one hand, affected by the current bidding strategy, the bidding price of power grid enterprises in purchasing power transformers is determined by the quotation of several transformer manufacturers. The bull's-eye price is determined by the quotation of the manufacturers. The more the price is lower than the bull's-eye price, the greater the possibility of winning the bid. In order to win the bid, some manufacturers may lower the price and profit, which will increase the probability of converter transformer quality problems. On the other hand, with the increasing requirements of power grid enterprises on the operation reliability of UHV converter transformer,
converter transformer manufacturers carry out quality control by purchasing high-performance, high-quality raw materials, improving the quality of manufacturing process, improving the quality of operators, increasing the quality inspection process and other measures. The above measures can play a positive role in improving product quality, but the resulting increase in personnel, materials, manufacturing and other costs cannot be ignored, which will cause the increase in procurement costs of power grid enterprises. Therefore, the procurement cost and quality control of UHV converter transformer are a pair of interrelated and game. In this paper, through the analysis method of cost and quality control correlation analysis, the economic cost sensitivity analysis model of UHV converter transformer is built, and on this basis, the differentiated quality control strategy of main parts of transformer is proposed. The research results can guide the power grid enterprises to formulate reasonable procurement strategies, and guide the transformer manufacturing enterprises to save manufacturing costs and improve the quality at the same time. It lays a foundation for manufacturing enterprises to save energy and reduce consumption, and for power grid enterprises to improve operation reliability. Figure 1 shows the schematic diagram of UHV converter transformer [1]-[3].

2. Economic sensitivity analysis of UHV converter transformer

Based on the fuzzy logic analysis, this paper establishes the procurement cost model of UHV converter transformer, investigates the converter cost of UHV project in operation, and estimates the manufacturing cost of transformer quickly by combining the basic parameters and material unit price of transformer, so as to provide reference for power grid company to make target price for purchasing transformer and minimize the impact of manufacturer's quotation on target price.

![Figure 1. The main material and components of UHV converter transformer](image)

2.1. Composition of transformer manufacturing cost

The main material and components of UHV converter transformer are shown in Figure1. The cost of transformer is composed of direct cost and indirect cost. Therefore, the cost estimation model consists of two parts, one is the direct cost calculation, the other is the indirect cost calculation, and the sum of the two is the final cost of the transformer [4][5].

Transformer procurement cost = main material cost + group component cost + labor cost + manufacturing cost + period cost

Among them, the cost of main materials and components is called direct cost. Direct labor cost, manufacturing cost and period cost are collectively referred to as indirect costs. The specific components of each cost are described as follows by integrating the investigation results of transformer manufacturers:

- Cost of main materials: including the cost of five main materials, such as silicon steel sheet, copper wire, insulating oil, steel, insulating material, etc. required for transformer manufacturing.
Cost of components: This paper includes the components of the group which account for more quality problems when the transformer costs the same, such as the cost of tap changer, casing, transformer, valve and meter, oil storage tank, cooling system, relay, moisture absorber, etc.

Labor cost: refers to the cost of technical personnel directly engaged in production and manufacturing, but does not include the labor cost of factory management personnel.

Manufacturing cost: refers to the indirect costs incurred by enterprises for the production of products and services. It includes the salary of production management personnel, social insurance expenses of production personnel and production management personnel, difference cost of production system personnel, overtime meal in workshop, depreciation cost of production equipment and production plant, water consumption, electricity, steam cost, labor insurance fee, inspection equipment inspection fee, equipment repair cost and outsourcing processing cost.

2.2. Manufacturing cost characteristics of UHV converter transformer
As mentioned above, the cost of UHV converter transformer is also composed of direct cost and indirect cost. Due to the huge volume of UHV converter transformer, the total weight of a single equipment is usually more than 500ton, which needs to consume a lot of raw materials in the manufacturing process. Compared with the conventional power transformer, the main material cost and component cost of UHV converter transformer account for a large proportion. This study is mainly based on a large number of market research, on the basis of not involving the trade secrets of manufacturing enterprises, using the cost ratio to replace the price. The average proportion of each part of the manufacturing cost of UHV converter transformer is shown in Table 1.

Table 1. Cost proportion of each part of ±800kV UHV converter transformer system

| Cost Type       | Cost Account | Ratio/% |
|-----------------|--------------|---------|
| Materials       | Silicon Steel| 12      |
|                 | Insulation Paper| 8      |
|                 | Oil          | 6       |
|                 | Copper Wire  | 6       |
|                 | Other Materials| 2      |
|                 | Bushing      | 42      |
| Components      | OLTC         | 5       |
|                 | Turret       | 2       |
|                 | Cooling      | 4       |
|                 | Other Components| 2    |
| Manufacture Cost|              | 7       |
| Labour Cost     |              | 4       |

2.3. Economic sensitivity analysis of UHV converter transformer
As mentioned above, the main materials and components of UHV converter transformer are cost sensitive, which are proposed on the premise of cost and quality control correlation analysis of transformer, and are parameters reflecting the cost characteristics of main parts of transformer. Because of the transformer itself and its quality attributes, indirect costs such as direct labour cost, manufacturing cost and period cost are not included in the analysis of cost sensitivity. The cost sensitivity of UHV converter transformer is determined by the following calculation method.

\[
d_i = \frac{r_i}{\sum_{i=1}^{m} r_i}
\]
Among which, $d_i$ is the cost sensitivity of the main materials or components of the transformer, $r_i$ is the cost price of the main materials or components of the transformer, and $\sum_{i=1}^{n} r_i$ is the direct cost of the transformer. For UHV converter transformer, the economic sensitivity of raw materials and components is shown in Table 2.

| Cost Type          | Economic Sensitivity |
|--------------------|----------------------|
| Silicon Steel      | 0.13                 |
| Insulation Paper   | 0.09                 |
| Oil                | 0.07                 |
| Copper Wire        | 0.07                 |
| Other Materials    | 0.02                 |
| Bushing            | 0.47                 |
| OLTC               | 0.06                 |
| Turret             | 0.02                 |
| Cooling            | 0.04                 |
| Other Components   | 0.02                 |

Among them, silicon steel sheet, insulating parts, insulating oil and copper wire are the four types of raw materials with the highest proportion. These four types of raw materials constitute the ‘skeleton’ and ‘blood’ of UHV converter transformer, and are the most used raw materials in the manufacturing process. The valve side bushing of converter transformer is about 14 meters long and crosses the transformer tank. Its main function is to isolate and support high voltage conductor to realize reliable crossing with the grounding body. It needs to bear electric, magnetic, thermal and mechanical stresses in a narrow space at the same time, so it is very difficult to design and manufacture. In the casting process of its core manufacturing, there is a certain scrap rate in the manufacturing process due to the combined effect of temperature, stress and vacuum. Therefore, it has the highest economic sensitivity and is significantly higher than other components and raw materials.

3. Quality sensitivity analysis of UHV converter transformer

3.1. Supervision and operation analysis of UHV converter transformer

The quality of UHV converter transformer is very important. In the manufacturing process, the power company will organize personnel to supervise the whole process of the product, and investigate the material quality problems found in the supervision process of UHV converter transformer from 2017 to 2019. A total of 51 problems of raw materials and components were found, including insulation materials, copper wires, silicon steel sheets, core structures, bushing, the OLTC, cooling system, etc. There are many problems with insulating materials and electromagnetic wires, accounting for 76.4%, as shown in Figure 2. In addition, the power company makes statistics or reports on the operation of power transformers year by year, and investigates the operation of UHV converter transformers from 2017 to 2019. There are 23 kinds of defects and faults, including bushing, tap changer, lead wire, insulation, iron core and other defects, among which bushing and tap changer have the most defects and faults.
3.2. Quality sensitivity of UHV converter transformer
Normalize the above fault and defect data and calculate the quality sensitivity of UHV converter transformer, as shown in Table 3.

Table 3. Quality sensitivity of UHV converter transformer

| Cost Type   | Economic Sensitivity |
|-------------|----------------------|
| Silicon Steel | 0.13                 |
| Insulation Paper | 0.09               |
| Oil          | 0.07                 |
| Copper Wire  | 0.07                 |
| Other Materials | 0.02               |
| Bushing      | 0.47                 |
| OLTC         | 0.06                 |
| Turret       | 0.02                 |
| Cooling      | 0.04                 |
| Other Components | 0.02         |

4. Quality control strategy of UHV converter transformer based on joint analysis of economy and quality sensitivity

4.1. Joint economic quality sensitivity analysis of UHV converter transformer
In order to better analyze the cost sensitivity and quality sensitivity reflecting the cost characteristics and quality characteristics of the main materials and components of UHV converter transformer, this chapter uses the four quadrant analysis method as the analysis tool to divide the parts into different regions, which is the basis of formulating the differential control strategy. Four quadrant analysis method, also known as matrix analysis method, is to use two reference indicators to cut the data into four small pieces, so as to cut the disordered data into four parts, and then carry out targeted analysis for each small piece of data. Taking abscissa as economic sensitivity and ordinate as quality sensitivity, the associated indications of UHV converter transformer are divided into four categories, as shown in Figure 3.
Figure 3. Joint analysis on economy quality sensitivity of raw materials and components of UHV converter transformer

- Key control areas: areas with high economic sensitivity and quality sensitivity. For the parts in this area, it is necessary to focus on management and control, formulate targeted supervision quality control plan, and apply extended supervision, sampling inspection and other means when necessary.
- Quality oriented areas: areas with high quality sensitivity and low economic sensitivity. For the parts in this area, the purchasing cost can be appropriately increased to reduce the quality sensitivity. In the incoming inspection, manufacturing and factory test to improve the management and control, has met the quality requirements.
- Strategy optimization area: low quality sensitivity and high economic sensitivity. Since there are few quality problems in this area, the cost can be further reduced on the basis of maintaining low quality problems.
- Strategy keeping area: quality sensitivity and economic sensitivity are low. On the basis of maintaining the original quality control strategy, we can appropriately increase the cost of components, such as purchasing components with higher quality and reliability.

4.2. Quality control strategy of UHV converter transformer

Based on the above analysis of raw materials and economic quality sensitivity of components of UHV converter transformer, combined with the role of each component, the quality control strategy of UHV converter transformer is as follows:

4.2.1. Bushings

Bushings are located in key control area. The cost of bushing is the highest in converter transformer, which is mainly due to the difficulty of manufacturing high voltage bushing and low yield. The bushing leads the internal winding lead out to the outlet device outside the oil tank, which not only serves as the ground insulation of the lead, but also bears the role of fixing the lead. The bushing shall have the electrical strength corresponding to the voltage level of the converter transformer and the mechanical strength sufficient to resist the short-circuit electrodynamic force and the impact force of natural disasters. The bushing is also one of the important current carrying components. It can pass the load current for a long time in operation, and at the same time, it should be able to withstand the instantaneous overheating during short circuit, so it must have good thermal stability. When the casing is exposed to the atmosphere for a long time, it should be able to withstand the influence of high temperature, severe cold, windy sand, rain and snow, damp heat, large temperature difference, strong ultraviolet and acid-base and other harmful gases. At the same time, the bushing is an important
component installed on the converter transformer, which directly affects the overall dimension and operation performance of the converter transformer. It is required to be small in shape, light in weight, good in sealing performance, strong in versatility and easy for operation and maintenance. The quality control of casing mainly includes two aspects: first, in the purchasing and manufacturing stage, the key quality inspection should be carried out for the design and material selection of casing, the confinement force of key connection parts, and the grounding of casing end shield. In addition, with the development of manufacturing industry and materials, the casing manufacturing quality is improved and the manufacturing cost is reduced by increasing the yield and reducing the process difficulty.

4.2.2. OLTC
OLTC is located in quality oriented area. The tap changer of transformer changes the transformer ratio step by step by changing the number of turns of winding, so as to achieve the purpose of regulating the output voltage of transformer. When the on load tap changer is switched, it is necessary to adjust the gear without cutting off the load current. Its electrical, mechanical and switching performance requirements are high. The on load tap changer of UHV converter transformer is installed inside the transformer body. Once the fault occurs, the whole converter transformer will not operate normally, and the fault consequence is serious. For the quality control of OLTC, it is necessary to focus on the inspection of arrival and installation in the process of supervision, and closely monitor after switching and tapping in the process of operation.

4.2.3. Insulation board
Insulation board is located in the quality oriented area. Solid insulating materials such as insulating paperboard play the role of insulation, support and partition of oil gap in converter transformer. During the operation of converter transformer, AC and DC electric fields work together. The DC electric field is mainly borne by the insulating paperboard, while the AC electric field is mainly borne by the insulating oil. The insulating paperboard plays a role in dividing the oil gap. In order to ensure that UHV converter transformer does not have partial discharge in the test, the performance and quality requirements of insulating paperboard are more stringent. When carrying out quality control of solid insulating materials such as insulating paperboard, cushion block and brace, we usually focus on the insulation characteristics of insulating paperboard, including conductivity, withstand voltage, partial discharge and other characteristic parameters. For the insulation board of UHV converter transformer, the appearance inspection and X-ray inspection can be strengthened to ensure the process quality of raw materials. The quality stability of electrical properties of solid insulation materials was verified by batch sampling.

4.2.4. Copper wire
Copper wire (electromagnetic wire) is located in the quality oriented area. The electromagnetic wires are connected in parallel to form a number of wire turns, and the winding is a component composed of a group of wire turns in series. Winding is one of the main components of transformer. According to the law of electromagnetic induction, magnetic field and electric field are connected together. In the structure, through the iron core (magnetic circuit) and winding (circuit), realize the power transfer and conversion. In order to ensure the reliability of material quality, the key performance indexes, such as material yield strength, have been added to the electromagnetic wires of UHV converter transformer.

4.2.5. Silicon steel sheet
Silicon steel sheet is located in strategy optimization area. Silicon steel sheets are bound by laminations to form the core of the converter transformer. The magnet of the core converts the electric energy of the primary system into magnetic energy and the magnetic energy into the electric energy of the secondary system, which is the main carrier of energy conversion. As the framework, its structure should have enough mechanical strength and stability to facilitate the installation and fixation of
internal leads, tap changer, outlet device and other insulating parts of converter transformer, and at the same time, it should be able to withstand various forces that converter transformer may be subjected to in manufacturing, transportation and operation. According to the quality control strategy of silicon steel sheet, on the basis of maintaining the existing appearance, burr and other production process detection, the economy can be improved by optimizing the management process.

4.2.6. Turret
Turret is located in the strategy holding area. The connection winding and bushing of outgoing line device should be controlled in quality control. Because it is located in the key area of connection, although its economic sensitivity is low, if this part fails, it will cause great threat to the operation of UHV converter transformer and bring huge economic losses. For the turrets, we should pay attention to its appearance without abnormality, internal without debris, and discharge during the test.

4.2.7. Coolers and other components
Coolers and other components, such as valves and meters, transformers, moisture absorbers, oil conservators, etc., are characterized by low quality sensitivity and low cost sensitivity. For this kind of components, the quality inspection and acceptance of arrival should be done well, and the conventional quality monitoring means should be adopted.

5. Conclusion and Prospect
For UHV converter transformer, the economic sensitivity index of UHV converter transformer is calculated by investigating the manufacturing cost of converter transformer. Through the operation of converter transformer in recent three years, the quality sensitivity characteristics of UHV converter transformer are calculated. Four quadrant analysis method is used to analyze the economic and quality sensitivity, and four sensitivity levels are divided. According to the operation of UHV converter transformer and the economic sensitivity of raw material components, the quality control and improvement measures suitable for UHV project are proposed.

This research mainly focuses on the operation of UHV converter transformer in recent three years. With the large number of UHV DC transmission projects put into operation, more and more operation data can be applied to this model for research and analysis. The analysis of economic and quality sensitivity will also be more accurate.

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