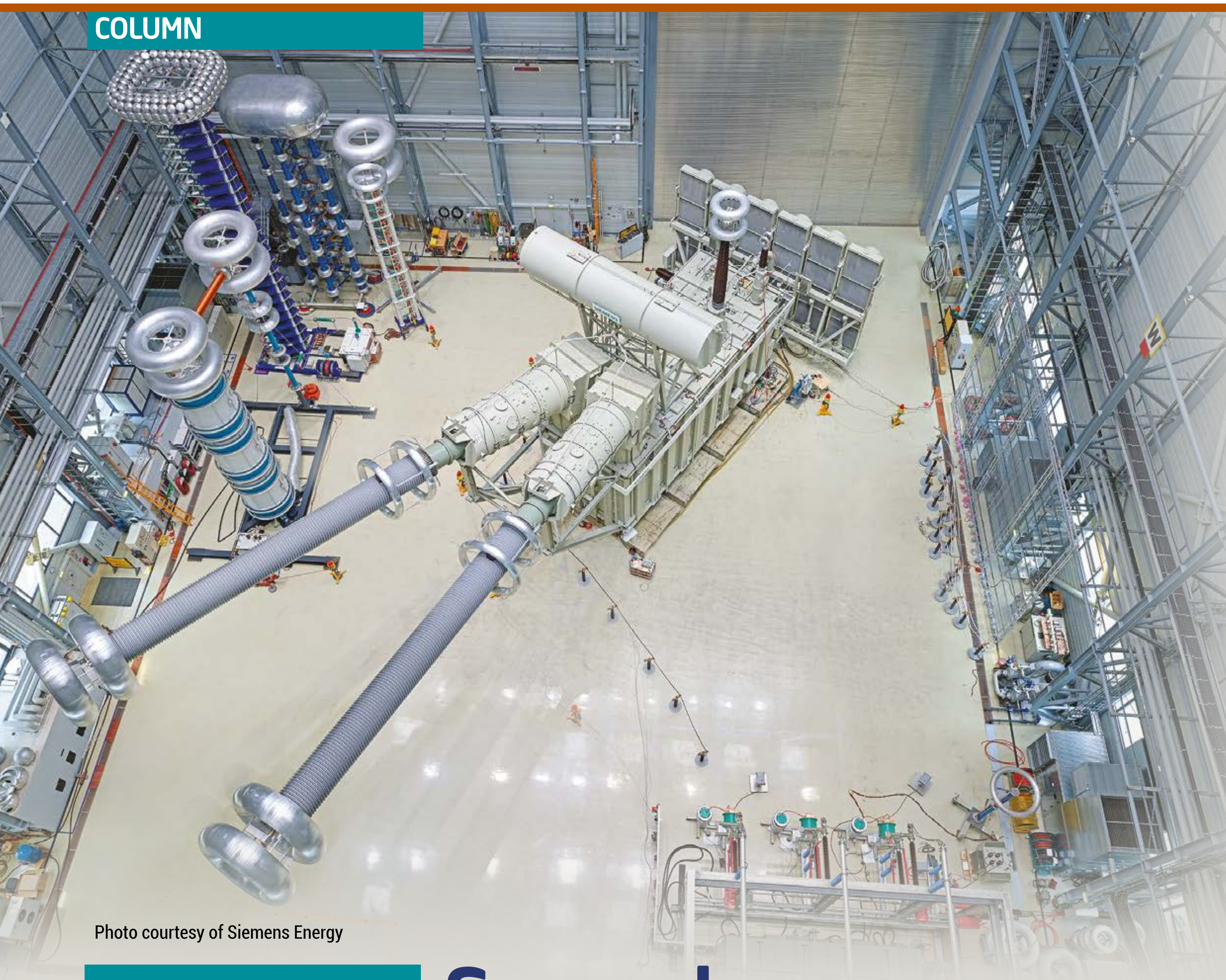

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ABSTRACT

Nowadays, the huge demand for long-distance UHVDC transportation prompts research on the super large capacity converter transformer. Especially in China, UHVDC projects are widely built and put into use. This article reviews the history of converter transformer research and introduces details in the design of the converter transformer. The recent advances in the fundamental study of converter transformers such as partial discharge, space charge, and material performance test are also introduced in the article. In the end, this article summarizes the application status of the converter transformer in China and looks forward to its future prospects.

KEYWORDS

bushing; converter transformer; partial discharge; space charge

Super large capacity converter transformer

1. Introduction

Driven by the growing prosperity of fast-growing developing economies, the demand for energy will continue to grow in the future. In order to cope with the challenge of climate change, clean energy is more preferred in the world. Therefore, with the continuous development of the social economy, the proportion of electric energy in terminal energy consumption and the demand for electric energy are increasing. According to the forecast of the International Energy Agency (IEA) [1], the share of electricity in terminal energy consumption may exceed that of oil by 2040, which is currently less than half of oil. Electricity demand will also increase by 70 %, with more than 50 % of the demand growth coming from China and India.

Column by the University Transformer Research Alliance (UTRA) www.university-transformer-research.com

How to transport clean energy such as wind, water, and other clean energy to the economic development with strong demand is the current research focus of the researchers. Especially in China, a country with a vast territory and unbalanced regional development, the energy transmission distance may exceed 1000 km, so the power transmission with large capacity and long-distance has become a necessary choice. However, the transmission capacity of the existing AC power grid is reaching its limit, and the loss of energy in ultra-long-distance AC system is also uneconomical. The huge demand for energy consumption and optimal allocation of resources promotes the rapid development of long-distance, low loss UHVDC (ultra-high voltage direct current) transmission technology. The UHV converter transformer connects the AC power grid and converter valve hall, which is an important component of UHV AC / DC conversion. Converter transformer accounts for 43 % of the total investment of the converter station, which is the highest technical level, highest value, and most core equipment in ± 800 kV DC transmission project.

For a very long power transmission, UHVDC technology has become beneficial compared to conventional AC power transmission systems in terms of stability and losses

2. The development history

In the 19th century's debate about AC and DC, the AC system won out. However, with the development of power electronics, HVDC transmission technology has become popular because of its high system stability and low line loss. In 1954, the world's first commercial HVDC transmission project undertaken by ABB was put into operation in Sweden. In the 1970s, Siemens began to develop a high voltage converter transformer. Since then, ABB and Siemens have been industry leaders in the design and construction of converter transformers. They provided converter transformers for the first two ± 800 kV UHVDC transmission projects in the world (Xiangjiaba-Shanghai project and Yunnan-Guangdong project) and made a breakthrough in the ± 1100 kV UHV converter transformer.

Beside ABB and Siemens, Chinese researchers have also made great progress in the converter transformer due to the rapid development in the UHVDC transmission project. In 1989, China imported foreign technologies and built the first HVDC transmission project, the Gezhouba-Shanghai project. With the Lingbao back-to-back project in 2005, China had fully mastered the ± 500 kV converter transformer design and manufacturing process. In 2010, by importing high technology converter transformers, China built the world's most advanced ± 800 kV DC transmission project, Yunnan-Guangdong project, and Xiangjiaba-Shanghai project. By 2013, China was able to design and manufacture ± 800 kV converter transformers independently, but still needed to make breakthroughs in some key component supporting technologies. In 2017, the Belo Monte project in Brazil undertaken by State Grid Corporation of China was put into operation, marking that China's UHV converter technology entered into the global market. In 2018, China produced the world's first 1100 kV converter transformer and applied it to the Fuchangji-Guquan UHVDC transmission project. Up to now, there have been 15 UHVDC transmission projects in operation in China, and more than 50 converter transformers in a single

Figure 1. Wind and solar power

> **UHV converter transformer is subject to complex stress, including long-term AC / DC superimposed electric field, high harmonic voltage, serious DC magnetic bias, lightning, and switching overvoltage**

project. China is the only country in the world releasing large-scale commercial application of UHV transmission technology and has ranked at the forefront of the world in the converter transformer design, manufacturing, operation, and maintenance technology.

3. The design of the UHVDC converter transformer

As one of the core components of the UHVDC transmission project, the UHV converter transformer has played an unreplaceable role in the system. For example, it can realize voltage conversion and AC / DC electrical isolation, restrain DC fault current, weaken overvoltage of AC system invading DC system, and reduce harmonics injected into the AC system by the converter. Therefore, the UHV converter transformer is subject to complex stress, including a long-term AC / DC superimposed electric field, high harmonic voltage, serious DC magnetic bias, lightning, and switching overvoltage. The electric, magnetic, and thermal environments inside the transformer are harsh, and the design requirements are high.

3.1 Insulation design

As the electrical isolation between the AC system and converter, all energy will flow between the AC system and the DC system through the converter transformer. Moreover, its ultra-high voltage level requires the converter transformer to have a higher insulation level, which means that the converter transformer has a larger physical volume. However, due to the transportation limits, the size is limited for the converter transformer, which often needs to be transported as a whole unit. Moreover, the size of the converter transformer is not linear with its insulation level. Too much insulation margin will lead to a rapid increase in the cost, which is uneconomical. Therefore, insulation design is an important issue in the UHV converter transformer.

The converter transformer must bear both AC voltage and DC voltage under normal working conditions. When the power flow reverses, the DC voltage it bears will also reverse in polarity [2]. It has been proved that the most complex and difficult challenges in the insulation design of converter transformer are how to design the converter transformer insulation to withstand the action of AC / DC composed electric field for a long time, and the DC step voltage such as polarity reversal.

Under AC voltage, the electric field distribution in the insulation structure of the converter transformer is determined by the dielectric constant. Due to a small difference in dielectric constant between insulating oil and paperboard, the electric field distribution is relatively uniform. The resistivity of paperboard is much higher than that of insulating oil, so the electric field is mainly distributed in paperboard under DC voltage. Therefore, compared with the power transformer, the main insulation of the converter transformer uses more paperboard to form a "thin insulating board – narrow oil gap" insulation structure.

However, it should be noted that the resistivity of insulating materials varies over a wide range affected by temperature, humidity, and electric field strength. At the same time, it is difficult to process the large-size insulation paperboard and insulation molding used in the UHV converter transformer, and the finished products are dispersive. In order to solve these problems, changes in dielectric parameters of different types of insulating parts from different sources and with different specifications under different conditions are measured. The measurement is used to realize the accurate calculation of insulation margin under the special working condition of ± 800 kV converter transformer. Furthermore, by optimizing the oil gap at the end, the insulation distance can be reduced. In this way, the compact design of the main insulation structure of ± 800 kV converter transformer is realized.

3.2 Electric field control of outlet device

The converter transformer's valve side outlet device is the key insulation structure connecting the valve-side winding lead of the converter transformer and DC high voltage bushing. At present, there are mainly two types of valve-side outlet devices in the market. One is an open structure designed by ABB, which adopts a simple multi-layer straight paperboard cylinder, uncovered electrode, and insulation shield against axial flashover. This structure is used together with an oil-paper bushing without a porcelain sleeve, and the structure of the field is relatively simple. The other is a closed structure designed by Siemens, which uses a multi-layer special-shaped paper cylinder and an insulated covered electrode, which is used together with a resin-impregnated paper bushing.

The valve-side outlet device works under harsh working conditions of high AC/DC composite voltage, large current, and long-term vibration. The space is limited, and the electric field is especially concentrated. It is difficult to control the field strength. Therefore, the number, shape, and position of insulated paper cylinders need to be carefully designed according to the calculation results of the electric field distribution.

In addition, the valve-side outlet device can be independently placed outside and inside the tank. When the valve-side outlet device is placed independently outside the tank, it can reduce the transportation size of the converter transformer. However, due to its large weight, large volume, and complex interfaces, the assembly is very difficult. Therefore, it is easy to cause damage to the devices during the test and assembly process. When the valve-side outlet device is placed inside the tank, the field installation can be simplified, and the risk is reduced. But it is difficult to arrange the valve-side lead in the tank with a very limited space, which requires a lot of calculation, analysis, and optimization of the design.

In addition to adopting the insulation barrier with an equipotential profile to reduce the field strength along the surface, Chinese manufacturers have also adopted a split type for the insulation structure outside the barrier, and the insulation of each split is overlapped by steps from inside to outside. Moreover, they conducted the insulation margin test of the 1:1 valve-side outlet device. Based on the test results, they proposed a design of "pin-free" in the high field strength areas and developed a built-in valve-side outlet device.

Compared with the power transformer, the main insulation of the converter transformer uses more paperboard to form a "thin insulating board – narrow oil gap" insulation structure

3.3 Temperature rise control and loss

The ageing of insulation material is closely related to temperature, so the thermal design of the converter transformer is very important for its life. Compared with a power transformer, the converter transformer bears a lot of harmonic power and serious DC magnetic biasing, which leads to a serious magnetic leakage and increased loss. However, the converter transformer has a compact structure and complex oil circuit. So, when the oil resistance of the cooling channel is increased, the temperature rise control is very difficult.

Therefore, the converter transformer's key point of temperature rise control is to accurately control the heating caused by the leakage flux of structural parts, winding ends, and magnetic shunt. A lobe-type magnetic shield could be adopted to control the whole flux leakage of a large capacity converter transformer. And the copper plate is set on the inner wall of the tank to reduce the leakage flux into the tank. In addition, the tap lead of the voltage regulating winding of the large capacity converter transformer will produce a strong magnetic leakage field. The diamagnetism of the copper compensation ring on the core surface can greatly reduce the eddy current loss on the core structure. In addition, using the structure of a reverse spiral double-layer voltage regulating coil, the magnetic leakage flux can be counteracted in the reverse direction in order to weaken the heating of structural parts and reduce the temperature rise.

In terms of heat dissipation, the ODAF cooling mode is often used in large capacity converter transformers. This cooling method has a high oil flow rate and good cooling capability, but the welding slag and other metal particles produced by the metal oil guide box may easily enter the device body through the oil path, causing potential safety hazards. At the same time, the oil flow guiding structure must be reasonably designed to avoid serious oil flow electrification and local oil flow dead

Figure 2. Core and coils of oil impregnated transformer

The converter transformer's valve side outlet is the key insulation structure connecting the valve side winding lead of the converter transformer and DC high voltage bushing

angle leading to temperature rising out of control. Chinese manufacturers have designed a horseshoe-shaped oil guide device to improve heat dissipation capacity.

But even with various measures, precise control of the transformer temperature rise is still a difficult problem. This is because the temperature of the hottest part of the hottest coil affects the thermal life of the transformer. Unfortunately, the hot spot temperature cannot be directly measured. Moreover, the oil flow control inside the transformer is not simple. The existing calculation software is actually based on a simplified and idealized model, which has a large uncertainty. Reliability of the calculation results can only be verified with a test. Therefore, it is of great significance for the converter transformer design to accurately calculate the loss of the converter transformer and conduct a reasonable temperature rise test.

3.4 Manufacturing process

A UHV converter transformer is not only the heart of a complex system but also a huge and complex system itself. The ± 800 kV converter transformer contains more than 30000 parts and components with a weight of more than 500 tons. The assembly and manufacturing process involves more than 100000 operations. Most of these operations need to be done manually by experienced technicians.

Because the converter transformer plays a key role, it requires high reliability. The manufacture, installation, and debugging of the converter transformer are the key to avoid any fault. Therefore, requirements of the manufacturing environment and processing quality of the converter transformer are very strict.

For example, installation of the bushing is a major difficulty in the assembly process of the converter transformer. Due to the transportation problem, the high-voltage bushing of the UHV converter is transported separately from the converter body. Therefore, the bushing will undergo several assembly and disassembly processes from the moment of being manufactured in the converter plant until put into service. Once the insulating paper of the outlet device is knocked, it is easy to cause damage to the outlet device. Even if the outlet device is not damaged, the damage to the insulation paper is also a safety risk to reliable operation of the converter transformer in the following period. Therefore, it is necessary to precisely guide and control the bushing, which weighs several tons and needs to smoothly

Figure 3. Manufacture of transformers – winding copper wire

enter more than 10 meters into the outlet device.

Another example is the winding process of a coil. In the converter operation process, the coil is affected by the electric force. Especially in the case of a short circuit, the current passing through the coil is far beyond the rated current. The axial force and radial force on the coil will greatly increase, even deforming the winding. Therefore, the radial direction of the coil should be tightly wound. The axial height and radial dimension of the coil not only affect the coil assembly and its body but also affect the impedance value of the whole converter. After the coil is wound, it is necessary to dry it and impregnate with oil. This requires a correct process and reasonable pressure control to minimize axial and radial deformation.

In fact, for the huge and complex equipment such as a UHV converter transformer, it is necessary to have a complete set of production process and quality control methods in the whole process of converter transformer manufacturing, such as coil winding, core stacking, tank welding, and body assembly, so as to form high-end power equipment manufacturing capacity.

3.5 Bushings

The bushing of the converter transformer is a device that leads the internal winding out of the tank. The converter transformer connects AC and DC power systems, and the insulation bushing is also divided into grid-side bushing and valve-side bushing. The valve-side bushing of the converter transformer is an important piece of equipment to realize the electrical connection between the UHV converter transformer and valve tower. It is the core component that causes most of the manufacturing difficulties in the UHV converter transformers.

According to the insulation structure, the valve-side bushing can be divided into oil-impregnated paper gas-filled bushing, resin-impregnated paper gas-filled bushing, resin-impregnated paper foam-filled bushing, and dry-type resin-impregnated paper bushing. The head end of the bushing is provided with a grading ring, which is connected to the DC system terminal. The end of the bushing goes deep into the outlet device, which is connected with the winding lead. The capacitor core inside the bushing body is composed of an electrode plate and insulating dielectric, which is the place where the electric field is concentrated, especially the edge area of the electrode plate in the core.

A ± 800 kV converter transformer is a very complex system that contains more than 30000 parts and components with a weight of more than 500 tons

Compared with AC bushing, the influence of temperature should be especially considered in the valve-side bushing design. This is because the valve-side bushing needs to withstand AC / DC composite voltage. The DC voltage component mainly distributes according to the resistivity. However, the resistivity value is greatly affected by temperature, which is different from the dielectric constant. This leads to a fact that the electric field distribution of a bushing is different from that of isothermal state in the traditional design due to the radial temperature gradient distribution of the bushing. In addition to considering the influence of temperature distribution on the electric field, temperature distribution, especially hot spot temperature, is very important for the bushing's safe operation. Especially for the resin-impregnated paper bushing, an overheat trace near the plug-in structure is usually the starting point of an internal failure of the bushing from the analysis results of the failed bushing disassembly.

In terms of the current market share, the oil-impregnated paper gas-filled bushing is widely used and has good operation stability. However, the oil-contained valve-side bushing and ascending flange pass through a fireproof wall of the valve hall and directly connect with the valve tower. In case of a fire, the fire can easily develop in the valve hall through the casing, which will cause the equipment in the valve hall to catch fire. To reduce the fire risk, researchers have been paying more and more attention to the resin-impregnated paper bushing in the recent years.

4. Fundamental research

As a large-scale precision instrument of the UHV transmission line, it is necessary to have a clearer understanding of the fault mechanism of the converter transformer before the equipment is put into operation. Therefore, many scholars have carried out a lot of fundamental research on the insulation coordination, electric field calculation, and insulation breakdown of the converter transformer.

Liu Zehong and others of State Grid Corporation of China have studied ± 800 kV UHVDC transmission in China and pointed out that UHVDC transmission project must be designed according to higher reliability requirements in the main wiring, equipment parameter selection, overload capacity, filter design, arrester setting, and external insulation design. Wang Jian and others of TBEA Shenyang Transformer Co., Ltd. Have put forward improvement methods for DC magnetic bias in the converter transformer, which has effectively reduced the harm of DC magnetic bias current to the transformer. Mi Chuanlong and others of China West Electric Co., Ltd. Have put forward a harmonic equivalent circuit of the converter transformer with additional resistance, so as to better simulate the influence of harmonic frequency and harmonic voltage distortion rate on the no-load loss of the converter transformer, in order to guide the loss measurement of the converter transformer field test.

The valve-side bushing (DC-side bushing) is the core component causing most of the manufacturing difficulties in the UHV converter transformer

Figure 4. Power transformer bushing

4.1 Partial discharge

According to the data on converter transformer fault released by the CIGRE working group, the fault rate of the converter transformer is about twice that of an ordinary power transformer, and the insulation accident of a converter transformer accounts for about 50 %. A partial discharge is one of the main reasons for insulation failure, and it is also an important indicator to reflect the degree of electrical ageing of the insulation.

In order to avoid discharge caused by a concentration of the local field strength, the electric field is barely uniform in transformers. However, in the actual operation process, a partial discharge is caused by the concentration of partial electric field due to mechanical deformation and insulation ageing of oil-paper insulation. When a partial discharge occurs at the junction of the metal oil paperboard, or when the discharge occurs near the paperboard and damages the paperboard, the partial discharge will develop along the paperboard and become the surface partial discharge [3].

Although partial discharge generally does not cause penetrating breakdown of the insulation, it can cause partial damage to dielectric (especially organic dielectric). If partial discharge exists for a long time, it will lead to insulation deterioration or even breakdown under certain conditions, and serious accidents may occur. Therefore, through a partial discharge test of the transformer, it is possible to monitor the insulation condition of the equipment and promptly detect problems related to manufacturing and installation time.

Chinese scholars have done a lot of research on partial discharge characteristics of the converter transformer. Lu Licheng and others of State Grid Corporation of China have discovered that the starting voltage of partial discharge is related to different voltage components in different models. In the plate-plate electrode model, only when the DC component increases to a certain extent can a partial discharge in the oil be directly caused. Li Chengrong et al. of North China Electric Power University have adopted different methods to diagnose and analyze the relevant data in the process of partial discharge. And the discharge process is divided into the initial stage, development stage, and near breakdown stage.

4.2 Space Charge

When the converter transformer is in operation, the DC electric field component will make the oil-paper insulation accumulate space charge when its valve-side winding bears AC and DC superimposed electric field. Space charge accumulates in the insulation medium, strengthening the local electric field, which may cause early insulation damage, and accelerate the ageing of the insulation medium [4].

It is generally believed that the space charge in the polymer is mainly composed of two parts. Some of them are the carriers injected into the electrode and transportable carriers. The other is due to the ionization and migration of inorganic or organic impurities in the medium under the influence of voltage, which is the main factor when the electric field is low. Simultaneously, as the charge injects, charge trapping is de-trapping, which causes a recombination. The energy transfer and release are accompanied by charge trapping and de-trapping, which will destroy the microstructure of the oil-paper insulation. At the same time, the complex electric field, high temperature, and mechanical stress can also aggravate the charge accumulation effect in the oil-paper insulation and cause irreversible damage.

Space charge accumulates in the insulation medium, strengthening the local electric field, which may cause early insulation damage, and accelerate the ageing of the insulation medium

The interface between the multi-layer oil-paper insulation structure accumulates the interface charge more easily than the dielectric itself [5]. The charge density at the interface is much greater than that in the dielectric. Under special working conditions such as polarity reversion, the speed of charge dissipation at the interface is slower than that of an applied electric field. An electric field generated by the interface charge and polarity inversion is overlapped with the applied electric field, which results in a distortion of the electric field in the oil-paper insulation. It can cause partial discharge, even flashover, and insulation breakdown along the surface.

Through a large amount of experimental data, the researchers have gained a certain understanding of space charge's characteristics and mechanisms. We have found that the space charge accumulation rate and dissipation rate of double-layer media are lower than that of single-layer media. The effect of DC pre-voltage on the local discharge of the oil-paper insulation is also studied. It has been found that the starting and extinguishing voltage of oil-paper insulation decreases gradually with the increase of DC pre-voltage amplitude.

4.3 Material performance test

The insulation materials of the converter transformer are composite insulation materials composed of insulating oil and insulating paper. Transformer oil is a kind of insulation material that plays the role of insulation, cooling, and arc extinguishing in the converter transformer. At the same time, it needs to be combined with insulating paper to form a better insulating oil-paper insulation media.

Under a long exposure to high temperature and electromagnetic field, the oil in the converter transformer is easy to undergo a metathetical reaction, which generates a new chemical composition the oil ageing. Experiments show that oxidized oil absorbs moisture more easily and deteriorates more quickly after moisture exposure.

Figure 5. Dissolved Gas Analysis Test (DGA) for transformer oil

At present, 15 UHVDC transmission projects have been built in China, among which the Changji-Guquan ± 1100 kV project is the UHV project with the highest voltage level

Insulating paper is another key insulation material in the oil-paper insulation. The affinity between paper and water is better than that of oil and water, so paper generally absorbs water from oil. The presence of water can severely reduce the electrical and mechanical strength of the insulation and accelerate the ageing and failure of the insulation.

The ageing of oil-paper insulation of the transformer is an irreversible chemical reaction process. The research on the chemical diagnosis of the ageing condition of oil-paper insulation is relatively mature[6], which mainly includes micro-water analysis, dissolved gas analysis in oil, insulating paper polymerization degree test, and analysis of furfural content in oil.

Qi Bo et al. of North China Electric Power University have observed the electric field of the overlapping structure of oil-paper insulation by the Kerr effect. Li Peng et al. of the China Academy of Electrical Sciences have studied the electric field characteristics in different sizes of oil-paper insulation in the case of polarity inversion. Liu Dongsheng et al. of Baoding Tianwei Electric Power Company detected latent faults in transformers through a dissolved gas analysis in oil and gave a corresponding treatment suggestion.

5. The application and future development prospects in China

China is a vast country, but the energy center is located in the western inland area, far away from the economic center of the eastern coastal area. The demand for super large capacity energy transportation has led to a rapid development of UHVDC transmission technology in China. At present, 15 UHVDC transmission projects have been built in China, among which the Changji-Guquan ± 1100 kV project is the UHV project with the highest voltage level, the longest transmission line, the most advanced technology, and the largest transmission capacity in the world. Chinese enterprises have accumulated sufficient experience in the construction, operation, and maintenance of UHVDC projects. At the same time, the ± 800 kV converter transformer production process system with independent intellectual property rights has been established, and the manufacturing capacity of high-end power equipment has been formed.

In the future, with the continuous development of clean energy, the scale of offshore wind power will be expanded. However, the equipment is easy to corrode and rust in the humid and high salinity environment at sea, affecting the quality and stability of the wind power equipment. In addition, the offshore transformer is bulky and inconvenient to replace and maintain. Moreover, once it is corroded and damaged, the internal transformer oil will leak, easily causing environmental pollution. How to improve the reliability of the transformer and find more economical and environment-friendly insulation materials still needs further development. Finally, how to further optimize the insulation structure of the converter transformer, improve its reliability, and reduce the occurrence of faults is also an important topic.

Bibliography

[1] *Global electricity demand by region in the Stated Policies Scenario, 2000-2040*, the International Energy Agency (IEA), https://www.iea.org/data-and-statistics/charts/global-electricity-demand-by-region-in-the-stated-policies-scenario-2000-2040

[2] Y. Shuai et al., *Major Insulation Design Consideration of Converter Transformer,* 2016 International Conference on Condition Monitoring and Diagnosis, 2016

[3] Y. Zhou et al., *Space charge characteristics in two-layer oil-paper insulation*, Journal of Electrostatics, Vol. 71, No. 3, 2013

[4] T. Judendorfer, et al., *Assessment of space charge behavior of oil-cellulose insulation systems by means of the PEA method*, Proceedings of IEEE International Conference on Solid Dielectrics (ICSD), 2013

[5] J. Yan et al., *Product analysis of partial discharge damage to oil-impregnated insulation paper*. Applied Surface Science. Vol 257, No. 13, 2011

[6] R. Liao et al., *A comparative study of thermal aging of transformer insulation paper impregnated in natural ester and in mineral oil*, European Transactions on Electrical Power, Vol. 20, No. 4, 2010

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