The development of intelligent dehydrate device for oil immersed transformer insulation system

Ruiliang Zhang, Yong Sun, Gang Lv, Huadong Tang, Wei Wang, Zhixun Xie*
China Southern Power Grid Co., Ltd EHV Transmission Company Guiyang Bureau, Guiyang, China

*Corresponding author email: zhouzhengchao@ltdet.com

Abstract. The transformer is the core equipment in the substation. The lifecycle and health of transformer will directly affect the reliability of substation, but the lifecycle of transformer depends on the oil-paper insulation status. Water, oxygen and temperature are the three factors that affect the performance of oil-paper insulation. The most important factor is the water. This paper designed an intelligent and safe dehydrating device based on the molecular sieve adsorption principle which can realize the on-line drying of transformer.

Keywords: Transformer; Paper-Oil insulation; Aging of insulation; Adsorbent material; Filtration; Dehydrate; Smart drying device.

1. Introduction
The transformer is the core equipment in the substation. The lifecycle of transformer depends on the health of transformer insulation system. The insulation system consists of oil and insulation paper. The lifecycle of insulation system will be directly affected by insulation paper which is cellulosic. Water, oxygen and temperature are the three factors that affect the performance of insulation paper. And the most important factor is the water.

The aging process of insulating material begin from the moment leaves factory. The traditional transformer operation and maintenance theory is based on insulation resistance of transformer, absorption ratio, absorption ratio, dielectric loss, winding leakage current, Micro-water analysis in oil and so on. With the theory the health of insulation system and moisture damage of transformer can be estimated. The insulation system will be renovated and repaired by off-line renovate and on-line oil filter. The impurities, acid, gas and water can be excluded by Vacuum oil filter, Hot-oil circulation, Low frequency heating and Vapor phase drying. But the regular and passive maintenance mode is backward, because of the equipment condition overhaul and active maintenance idea which is advocated by International Council on Large Electric systems (CIGRE).

With the aim to optimize transformer maintenance and extend its service life, a on-line intelligent dehydrate device is designed which can avoid the defect in traditional device. Base on the adsorption ability of molecular sieve for the water, the on-line dehydrate device is the best and safest maintenance method.
2. The aging reason of transformer insulation system

2.1. The aging factor for the transformer insulation system

![Diagram of the aging model for the transformer insulation system]

The water, oxygen and oil which react with each other will produce acid and Particulate matters. The products will be spread in the insulation system. With the influence of heat, electricity and electromagnetic field, the life of transformer will be significantly shorten. It is the aging model for the transformer insulation system in the figure 1.

2.2. Water

There are three sources of water in the insulation system. First is the residual water come from the insulation process in factory. Second, water can come from the air during the transportation and installation. At last insulation paper and oil can broken down into water during the aging process.

Atmospheric moisture was a major source of water for insulation system. The osmosis of water may attribute wet air and dissociative water, which get into the transformer because of pressure and sealing failure. For example, when it rains and cools down, the pressure will have a rapid decline. Rain water may be absorbed by transformer within a few hours if sealing failure happen. In addition, it is also one important reason that insulating material may be affected with damp.

With the temperature of insulation material go up, the water come from aging process may destroy the insulating property. in most cases water will be created at winding hot spot. Water will dissolve in oil. With the polarity of oil aging, the oxidability of oil will be strong. And its water solubility will be improved.

2.3. Particulate matter

The particulate matter possibly comes from fibrous material, iron, aluminum, copper and particle produced during manufacturing operation.

When transformer work normal or overload, aging process produces sludge particulate. local overheating over 500°C may produce carbon granule. The metallic particulate appears when bearing of oil-submerged pump wears.
particulate pollution is the major factor for the reduction of transformer dielectric strength. The most dangerous particulate is electric one, which include metal, carbon and wet fibre. Many transformer fault can attribute to particulate pollution. The recognition and count of particulate is important accordance for condition monitoring and assessment of transformer. And removing the particulate is important target for Transformer oil treatment.

2.4. The process of insulation aging
Insulation aging is chemical phenomenon. Various mechanisms of degradation, hydrolysis, pyrolysis and oxidation act simultaneously. Figure 2 shows the process of insulation aging [1].

Hydrolysis is the decomposition of compounds by reaction with water, Cellulose, the main component of insulation materials, is a large molecule connected by many glucose groups through 1-4 glycoside bonds. It is easily soluble under the action of acidic aqueous solution and high-temperature water to generate furan compounds and finally decompose into acidic substances, gases, and water.

Pyrolysis is the decomposition or transformation of compounds caused by heat, and the degradation of cellulose in transformer insulation materials at high temperatures causes that cellulose decomposes into water molecules, acidic substances and gases.

Oxidation is the combination of substances and oxygen. The oxidation of oil will produce acid, which will destroy the dielectric strength of the cellulose in the insulating paper and the insulating oil, and promote the hydrolysis of the cellulose.

![Fig. 2. Insulation aging process](image-url)

The most important of the above three reactions are the hydrolysis and pyrolysis processes. Since the pyrolysis activation energy is 1.4-2.0 times the hydrolysis activation energy, the hydrolysis process is the main factor affecting the insulation aging when the transformer temperature is within 120 degrees. The water is the most important factor in cellulose aging.
2.5. The ageing fault of transformer insulation system

The water, acidic substances and gases generated with the aging of the insulation materials will cause breakdown and partial discharge failures through the following processes to make the transformer insulation failure.

First of all, water will enhance the conductivity of insulation materials and reduce the electrical strength of insulation materials, leading to insulation breakdown or partial discharge.

Secondly, water is a strong polar liquid, so the free water in the insulation material will be attracted the high electric field strength, especially in the high electric field area, which tends to accumulate more water, and finally cause fault such as breakdown.

In addition, as the temperature rises during the operation of the transformer, the insulation material gradually produces gas. At the same time, the water vaporizes and form bubbles under the action of temperature. The bubbles first dissociate and discharge, and the free charged particles collide with oil molecules. The oil will decompose into gas. The gas volume expansion will develop the freeing, and ultimately reduce the breakdown voltage and partial discharge field strength of the oil, and cause insulation breakdown and partial discharge.

In summary, removing water, oxygen and oil aging products is the most effective way to repair transformer insulation system and extend transformer life.

3. The analysis of transformer water content

The distribution of water in the transformer is not uniform, most of the water exists in the insulation paper. In fact, 97%-99% of the water in a stable operating transformer exists in the insulation material, and the remaining water exists in the transformer oil by a dissolved state. The water content of the new transformer oil requires a water content of 10PPM, and the water content of the transformer insulation material is 0.2%-0.5%, so the water in the insulation material of the body is hundreds of times the water in the oil and maintains a stable Balance.

Studies have found that the distribution of micro-water in oil-paper insulation is closely related to temperature. Water in the oil and paper will reach equilibrium under permeation and migration. Finally, the partial pressure of water vapor in the insulation paper is equal to the partial pressure of water vapor in the oil. Based on the relative humidity equivalent theory and a large amount of relevant experimental data can get the steady-state distribution curve of oil-paper insulation at different temperatures [2], as shown in Figure 3:

![Fig. 3. Oil-paper insulation water content balance relationship curve](image)

The figure shows the saturation content of insulation paper water (Y axis) corresponding to the saturation content of water in the oil (X axis) at the main temperature points of the oil temperature
from 0°C to 100°C. According to the balance curve, if the transformer is running at a temperature of 40°C, the micro-water content of oil is 10PPM, the corresponding balanced micro-water content insulation material should be 2.5%, and the body water content after the body drying process is generally 0.2%-0.5%, far below the 2.5% of the balance curve. For a long period of time after being put into operation, for the oil-paper insulation system to reach a water balance, it must be the continuous transfer of water from the oil to the cellulose material. The new generated water by internal decomposition and external moisture in the transformer oil will enter the fiber material through the balance process, while the water content in the transformer oil remains at the original level without significant changes. For example, when the transformer operating temperature is 70°C, after several years of operation, the water content of the insulation material has increased from the initial 0.2%-0.5% to 1% through equilibrium. According to the equilibrium curve, the water in the oil will still not exceed 10PPM. The water in the fiber of the material is saturated. If the total amount of 220kV insulation material is 7000kg, its insulation material actually absorbs 56kg water. It can be seen that the micro-water is 10PPM. It is same with the initial state, and the dryness of the transformer insulation material has been completely different from the original [3] [4], and according to the test data, the water content in the insulation material is increased by 0.5%. The insulation aging speed will be twice the original level.

In summary, the aging state of transformer insulation cannot be judged solely from the traditional way to measure micro-water content of transformer oil. Even in a well-functioning transformer, the water produced by the aging of the transformer insulation may cause transformer internal insulation accidents. On the contrary, even if there is insulation aging, transformer oil may also be qualified, and its breakdown voltage can also meet the specified requirements or even higher. However, this situation cannot be discovered only by monitoring the water in the transformer oil. It is necessary to further measure the insulation resistance, absorption ratio, polarization index, dielectric loss, winding leakage current, etc. to determine whether the transformer needs to be dried.

4. The analysis on the effect of traditional insulation dehydrated technique

The water in the transformer insulation system will gradually increase due to long-term operation, which will cause the insulation performance to decrease. When the insulation performance drops to an unsafe value, in order to ensure the safe and reliable operation of the power grid, the transformer must exit from the system and dried.

The basic principle of traditional transformer insulation on-site drying treatment is to transfer the water from the insulation material to the surrounding medium, and discharge the water in the surrounding medium from the tank by appropriate method.

There are two dynamic balance processes and parameters between the moisture in the insulation material of the transformer body and the water in surrounding medium [5].

When the medium surrounding the insulation material of the transformer body is liquid-phase insulating oil, there is always a dynamic balance process between the water of the insulation material and the water of the oil in the oil-paper insulation structure. When the contact temperature of the oil-paper increases, the water will migrate to the oil. When the oil-paper contact temperature decreases, the water in the oil will migrate to the insulation material. The balance process is affected by the flow of transformer oil. The balance speed of the oil in the dynamic state is faster than that in the static state, and the flow of the oil will accelerate the balance of water between them.

When the medium surrounding the insulation material of the transformer body is vapor-phase water vapor, there is a balance between the water in the insulation material of the transformer body and the water vapor in the surrounding space. When the water vapor pressure decreases, the water transfers from the inner layer of the insulation material to The surface then diffuses into the surrounding medium, and water transfer to where the lower water vapor pressure is.
Common on-site drying treatment methods for transformer insulation include hot oil circulation drying method, hot oil spray drying method and vapor phase vacuum drying method in Figure 4. The selection of drying process parameters should not only facilitate the removal of moisture in the insulation material, but also pay attention to avoiding its negative impact on the body insulation. The principle of temperature selection is: not only does not damage the insulation, but also gets a higher drying effect. When dry without oil, the temperature of the body should not be higher than 95℃, and the oil and paper will not be damaged by heat at this temperature. To avoid oil aging when drying with oil, the oil temperature should not be higher than 80℃. Another important factor affecting the drying process is the partial pressure of water vapor. During the drying process, the water in the insulation material fibers can only diffuse outward through the fiber capillary of the insulation material in the form of vapor. In order to overcome the flow resistance in the process of vapor diffusion through the fiber capillary, a pressure difference must be formed between the vaporized part and the surface of the insulation material. The greater the pressure difference of this vapor, the faster the water will be discharged from the surface of the material. Obviously, the easiest way to obtain the vapor pressure difference is to make vacuum intermittently during the drying process to discharge water from the insulation material out of the box. When the transformer to be processed can withstand high vacuum, a higher vacuum degree should be used, otherwise a lower vacuum degree should be used. The vaporization temperature of water can also be reduced by increasing the vacuum degree in the transformer box, which can reduce the heating temperature of the transformer body, slow down the aging of transformer insulation materials and insulating oil at high temperatures, and can also make the water in the transformer insulation materials vaporizes at a lower temperature. Since the oil flow can accelerate the balance, in order to promote the oil flow inside the tank, the oil flow inlet and outlet should be opposite angles arranged, and the forced circulation cooling transformer should regularly start the submersible pump during the hot oil circulation drying process.

Insulation drying is an important process in the manufacturing and operation of oil-immersed transformers, which has a direct impact on the total quality of the transformer. If the drying treatment is not enough, it is likely to cause residual water in the insulation material, which will affect the performance of the insulation material. At the same time, excessive drying will cause the bound water in the insulation material to be discharged, thereby reducing the mechanical strength of the insulation material, which will lead to the aging and performance degradation of the insulation material [7]. The problems and shortcomings of the traditional dewatering and drying technology are:

The traditional drying process using heating and vacuum treatment may be over-dried if the control is not good. High temperature and pressure will affect the mechanical strength of the insulation material and may accelerate the aging of the oil-paper insulation;

The traditional water removal methods require transformer power outages and monitor the process, and the time is long, which affects power production and has high costs;

The traditional water removal method will affect the gas content in the oil, leading to misjudgment of the transformer health;
The traditional water removal method requires vacuum equipment, which may damage other components and is not safe enough; Therefore, it is necessary to design a safer, controllable and intelligent transformer oil-paper insulation drying and water removal system, online monitoring of insulation drying related parameters and adjusting the water content index to ensure the safety and health of the transformer.

5. The safe intelligent dehydrate device
Transec in the United Kingdom and Drykeep in the United States are the earliest transformer on-line drying devices based on molecular water removal technology [6] [8]. They have been applied and promoted in Europe, America and India. In recent years, Siemens and MR have also launched their own product according to users’ requires for online dehydrate device. And combined with its own transformer operation and maintenance experience, and made some improvements in structure, materials and algorithms. At present, a small amount of scientific research applications have been made in China, but they have not been promoted, and no domestically produced products have been launched. Molecular sieve [9] is a material containing precise and single micro holes, which can be used to adsorb gas or liquid. Usually molecular sieve is composed of aluminosilicate. The crystal has a honeycomb structure, the cavities and pores in the crystal communicate with each other, and the pore size is uniform and fixed, which is equivalent to the size of ordinary molecules. Only those molecules with a small diameter can be adsorbed by the molecular sieve through the pores, while molecules with a large configuration cannot enter the pores and will not be adsorbed by the molecular sieve. as shown in Figure 5:

![Fig. 5. structure of Molecular sieve](image)

A specific molecular sieve has a strong adsorption capacity for water. Even at a very low partial pressure or temperature, it still has a relatively high adsorption capacity. A molecular sieve can absorb up to 22% of its own weight. Compared with traditional silica gel materials, molecular sieves have the characteristics of large adsorption area, high adsorption capacity, fast adsorption speed, good thermal stability, stable operation cycle, and no breakage in contact with liquids.

The molecular sieve absorbs molecules that are smaller than its pore size. By choosing the appropriate molecular sieve size, all fluid components but water will not be adsorbed. Since there is no such co-adsorption effect, the water absorption performance is further improved. At the same time, because molecular sieves have excellent regeneration characteristics, the hydrated molecular sieves are rapidly dehydrated under specific conditions, and the activated crystals can reversibly absorb water and be recycled.

This paper has a design about the on-line intelligent dehydrate device of transformer, which improves the similar products and materials:

Select synthetic crystalline silicate to make molecular sieve. Its porous structure can successfully filter water molecules, but does not filter the main gas components and oil molecules of the transformer, and does not require heating and vacuuming. The operation does not produce disturbance and influence for the safety of the transformer.

The oil-paper insulation on-line dehydrate device of the converter transformer adopts an integrated design, including an external circulation system, an internal circulation system, and an automatic control system. It supports on-site installation, which can facilitate the input and withdrawal of the operating transformer [6], fully consider the oil inlet and exhaust methods when the device is started,
and facilitate the replacement of the water removal tank without secondary pollution to the transformer insulating oil and affect the normal operation of the transformer.

The device supports online monitoring of transformer oil temperature and micro-water content, and performs closed-loop control according to the water content balance curve of oil-paper insulation. It also supports users to independently set control strategies based on the measured values of dielectric spectra. Through the circulating filtration of insulating oil, it can effectively remove the trace water in the oil when the transformer is running, so that the water balance in the oil paper is at the optimal value, effectively improving the safety and reliability of the oil paper insulation, and extending the service life of the converter transformer.

The device supports abnormal protection functions, including pipeline leakage protection, equipment temperature control and protection, control device self-checking and circuit protection. When the oil temperature rises abnormally, the dewatering device automatically stops working, so as to protect the molecular sieve material from damage of high temperature. At the same time, it has the function of filtering particles, which realizes the simultaneous removal of water and particles, and ensures the safety of the oil circuit and the insulation system.

The online intelligent dehydrate device includes the following main components: oil inlet valve, oil return valve, throttle valve, filter tank, oil filter, exhaust tank, micro water sensor, oil flow indicator, oil pump, controller. The specific structure is shown in Figure 6:

![Fig. 6. Structure of intelligent dehydrate device](image)

The operation step of the intelligent dehydrate device of transformer is as follows:

- Open the vent of the exhaust tank;
- Keep the oil return valve closed, slightly open the oil inlet valve, and gradually exhaust to ensure that all the gas in the device pipeline is discharged;
- Close the vent of the exhaust tank;
- Open the oil return valve, and then fully open the oil inlet valve;
Start the oil pump and confirm that the oil flow indicator shows normal;
Monitor the normal operation of the dehydrate device for 20 minutes to ensure that there is no oil leakage or other abnormal phenomena;
Put into automatic control;
In addition, when the dehydrate tank and the oil filter need replaced, you need to stop the oil pump, close the oil inlet valve, close the oil return valve, and then close the pipe holes at both ends of the water removal tank and the oil filter for replacement. After the replacement is completed, follow the operation step again.
During automatic operation, the main control unit of the dehydrate device will collect the water content, temperature, pressure and other state parameters of the system through sensors, and automatically decides to start or stop the water removal and oil filtration process according to the set control strategy. The specific operation interface is shown in Figure 7:

Fig. 7. Operation interface of intelligent dehydrate device

6. Conclusion
Based on the research of the distribution and hazards of water in the transformer insulation system, the intelligent transformer on-line dehydrate device based on the molecular sieve adsorption principle designed in this paper can collect the transformer oil temperature and water content in real time and adjust the speed of filter according to the transformer oil-paper water content balance curve, so as to maintain the dry level of transformer insulation materials, to provide users with a safe and reliable online drying and dewatering method. The prototype of the device has been tested on the test platform and been running stably. Considering that the large transformers in the industry that have been in operation for more than 20 years will gradually have the need for safe dehydrate device, the device can be promoted and applied on-site in the future and continuously improved.

References
[1] Life Management Techniques for Power Transformers, CIGRE A2.18, 20 January 2003
[2] LIU Yuxian, Moisture Content Analysis of Oil-Paper Insulation in Transformer and Its Influence on Operation Safety, Transformer, 2002, Vol.39, No.5
[3] WANG Wei, MA Zhiqing, LI Chengrong, WANG Xin, Impact of Cellulose Aging on Moisture Equilibrium of Oil-pressboard Insulation, Proceedings of the CSEE, 2012, Vol.32, No.31
[4] LIU Min, Effect of Different Moisture Content on Oil Paper Insulation Aging Rate, Insulating Materials, 2008, Vol.41, No.3
[5] LIU Rui, LI Jinzhong, ZHANG Shuqi, TANG Hao, Study on the On-site Heating Method for Large-scale Power Transformers, Proceedings of the CSEE, 2012, Vol.32, No.1
[6] ZHANG Shuzhen, LI Dong, FU Xinian, A Kind of Online Dry System for Transformer, Electrical Equipment, 2004, Vol.5, No.4
[7] DENG Congyue, The analysis of the voltage transformation vacuum drying equipment for the oil immersed transformer, China Plant Engineering, 2018, No.21
[8] YAO Guang, LI Lihong, ZENG Minggui, XIONG Pan, WANG Yong, Research on the micro water online monitoring and life extension technology of transformer, Sichuan Electric Power Technology, 2014, Vol.37, No.2

[9] SITRAM-DRY-Portfolio_en, May 2014