Fault Investigation and Operation Strategy of Dry Type Air-core Reactor in Severe Cold Environment

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Abstract: The influence of extreme climate such as severe cold temperature on power transmission system can not be ignored, the low temperature could cause complicated mechanical and dielectric deterioration to electrical materials and devices. In China's recent operation experience of reactors, it is found the burning fault rate of dry type air-core reactors in cold northeast region was obviously higher than that of other regions, which had inflicted negative impact on substation equipment and personnel safety. To tackle with the problems and prevent potential faults, typical fault characteristics and mechanism at low temperature, the specific influence of low temperature on materials and reactor performance, as well as corresponding operation strategies would be studied and proposed in this paper.

1 Introduction

At extreme low temperature, transmission system faults may occur such as wire icing, metal fittings breaking, deformation and cracking of outer porcelain and synthetic insulation materials, and also circuit breaker locking caused by SF_6 pressure drop [1-4]. Since the extreme low temperature could cause complicated mechanical and dielectric deterioration to electrical materials and devices, the fault characteristics and operation strategy of electrical devices at low temperature have been paid more attention to enhance operation quality and safety.

In China, the northeast region is very cold in winter, the average temperature is about -20℃, some areas could even reach -40℃ [5], in such a harsh operating environment, power transmission system and related equipment are facing great challenges. In recent years, China's power transmission projects have been developed in a more compact trend, with less floor space for transmission lines and larger transmission capacity, thus leading to increasing demand for reactors for reactive power compensation and filtering functions [6]. However, in recent operation experience of new commissioned reactors, it is found that compared with other regions in China, the burning fault rate of dry type air-core reactors in cold northeast region was obviously higher, which has inflicted negative impact on substation equipment and personnel safety [7-10].

In order to improve reactor operation safety and quality, typical low temperature fault characteristics were summarized based on fault investigation, the fault mechanism and low temperature impact on equipment were analysed by simulation and material test, and strategies aimed at reactors operation at extreme cold temperature were proposed in this paper.

2 Fault investigation

2.1 Dry type air-core reactor structure

The main structure of the dry type air-core reactor is composed of several concentric cylindrical encapsulations, which are parallel connected. In each encapsulation, there are several shunted coils (commonly aluminium) with high dielectric strength of insulation coating, functioning as turn-to-turn insulation. The encapsulation of dry type air-core reactors is wrapped with glass fibre material impregnated with epoxy resin, and a glass wire drawing rod is used as strut between encapsulations to form a heat dissipation port, as shown in figure 1.

The coil ends on the top and bottom are welded on aluminium frames, which act as electrical connection also mechanical compression. The whole structure is heat curing sandblasting treated, and a layer of special organic silicon is coated to resist ultraviolet radiation.

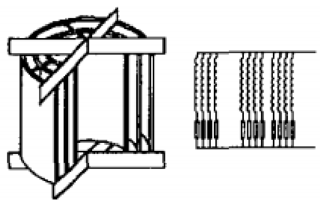

Fig. 1. Structure of dry type air-core reactor

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2.2 Fault investigation and analysis

12 recent typical burning failures of 66 kV dry type air-core shunt reactor in a northeast province of China were investigated and analysed, findings as below:

- 10 of 12 faults occurred in winter, accounting for 83% of the total.
- Except for 1 fault that caused by bad contact of turning-regulating ring, the other faults were all caused by inter-turn short circuit.
- Most of the discharge traces appear in the outer encapsulation layers.
- Surface cracks were found on most fault reactors, while impurities such as water stains and bird droppings were found.
- After some fault reactors were disintegrated back in the factory, it was found that manufacture defect like burrs, bubbles and uneven distribution of insulation materials appeared in inter-turn insulation of the reactors.

Since cracks and impurities were found in most of the fault reactors, the specific fault morphology in the case of cracks and bird droppings was described as follows:

After disassembly of some fault reactors, many small creepages were found on the surface of reactors, most of which occurred in the transverse cracks near the strut and lead exit. The initial creepages developed horizontally, and the more serious creepages began to develop longitudinally along the strut. Meanwhile, bird droppings were usually found near the discharge marks, the traces of discharge were illustrated as figure 2:

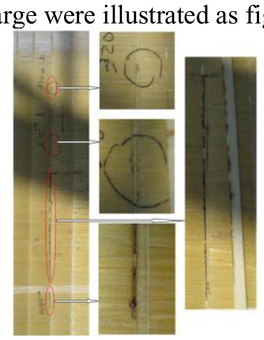

Fig. 2. Reactor discharge with cracks and bird droppings

From the discharge picture, it could be found that discharge developed along bird droppings, and mostly located near the lead exit and strut, and most of the starting points of discharge were accompanied by obvious cracks. For those cracks located far from electric field concentration area, no obvious discharge marks were found.

According to the fault investigation result above, it can be inferred that the typical process of dry-type air-core reactor burning failure at extreme low temperature is that: unbalanced stress release of reactor materials caused the form of transverse cracks on the insulation surface, and cracks near the electric field concentration area such as lead exit strut might lead to more serious electric field distortion. Besides, impurities such as water and bird droppings could enter into inner structure of reactor through the cracking parts, resulting in the insulation deterioration. The insulation weakness and distorted electric field both contributed to discharge and inter-turn short circuit, when inter-turn short circuit happened, loss of reactor could increase sharply, then followed rapid burning. In addition, if the reactor itself had material or manufacturing defects, such as burrs and bubbles in inter-turn insulation or wires that lack of tensile strength, the possibility of insulation deterioration and inter-turn short circuit fault would further increase.

3 Fault mechanism analysis

In the above chapter, the process and possible influencing factors of typical reactor burning faults at extreme low temperature were analysed based on fault investigation. Further analysis of the fault mechanism, and the specific influence of low temperature on reactor property were discussed in the following:

3.1 Cracking mechanism of encapsulation

The main wire material of dry type air-core reactor is aluminium, coated with polyester film, and the insulation between strands is also polyester film. In order to ensure insulation and isolation from the external environment, each encapsulation is composed of multiple layers of shunted wire, coated with fiberglass and epoxy composite. Due to the difference in thermal expansion coefficient between the wires and encapsulation insulation material (aluminium 2.3×10^{-5}/K, epoxy/fiberglass composite 2.7×10^{-6}/K), thus when the temperature changes, the original solidly combined structure of wire and insulation will shrink in different amplitude, then inflict stress on the joint part of two materials. If the tensile/compressive strength of epoxy glass and wire could not withstand the stress produced by unbalanced shrinkage and electric stress produced by short circuit current during operation, the material and reactor structure deformation happens, and further develop into surface cracking.

Therefore, the deformation and cracks of reactor is determined by not only the actual stress produced by shrinkage and short circuit current, but also the mechanical tensile, compressive, bending strength of the materials.

3.2 Material mechanical strength analysis

In order to study the mechanical strength of reactor windings and insulation material, the epoxy resin and aluminium materials were bonded together by adhesive and then divided into small pieces to simulate wire with insulation coating. Then tensile tests for those aluminium/ epoxy resin pieces were carried out under different temperatures. The test pieces were stretched with gradually increased mechanical load, until the aluminium and epoxy resin were completely detached from each other. The tests were conducted at room temperature 27 ℃, -25 ℃ and -40 ℃, respectively, and repeated several times at each temperature. The withstand load for the samples were shown in table 1:

Table 1. Tensile test result of epoxy wire bonding

Sample number	27 ℃ (kPa)	-25 ℃(kPa)	-40 ℃(kPa)
1	340.3	322.8	311.8
2	349.5	259.4	413.9
3	339.4	255.7	264.0
4	392.7	372.5	329.3
5	341.2	417.5	248.3
6	342.1	428.6	249.2
7	456.2	262.1	240

It could be seen that the low temperature environment had a great influence on the maximum withstand load of the samples, the tensile strength decreased obviously with the decrease of temperature. The average maximum withstand load is 365.9 kPa at room temperature of 27 ℃, 331.2 kPa at -25 ℃, which is 10% lower than at room temperature, the withstand load fell to only 293.8 kPa at -40 ℃, which is 20% lower than at room temperature.

This test result may be caused by the different degree of shrinkage of winding wires and epoxy resins at low temperature, and may also be related to property changes of adhesives. The decrease of the maximum withstand load indicated that the bonding performance between two materials were weakened compared with that at normal temperature, which makes the joint surface more fragile. When the reactor materials undertook transient electric force or unbalanced stress, the cracks between insulations and windings were more easily to form due to the declined mechanical strength at low temperature.

3.3 Winding force analysis

During operation, the dry type air-core reactors could suffer mechanical stress such as tensile, vibration and extension force under alternating magnetic field, with the accumulation of these stresses, deformation or cracks of the reactor structure might happen. The stress of the reactor windings and influence of low temperature on the stress were analysed by simulation as follows:

The reactor model composed of three layers of windings was established, and epoxy strut between layers was set. The winding force was simulated with current RMS of 300A, at temperature of 27 ℃, -25 ℃ and -40 ℃. In order to fully consider the current distribution in the winding, field-circuit coupled method was used, the current source with amplitude of 424.26 A, frequency of 50 Hz was the input.

The magnetic field force density vector diagram of the reactor winding was shown in figure 3. It could be seen that the overall force on each winding was outward expanded under the interaction of current and magnetic field.

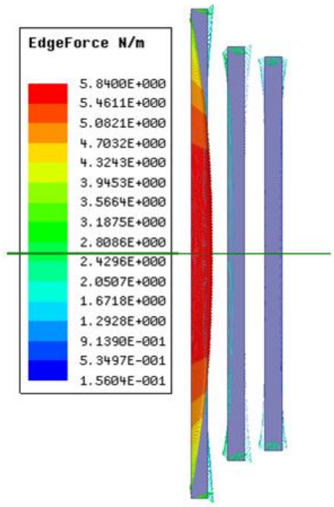

Fig. 3. Force density of reactor winding

Besides, a 3D model of reactor structure was established to study the stress and strain of the reactor windings under the action of the electromagnetic force. The windings, encapsulation and strut structures were all fully considered in the model. The axial view and top view of the model were shown in figure 4.

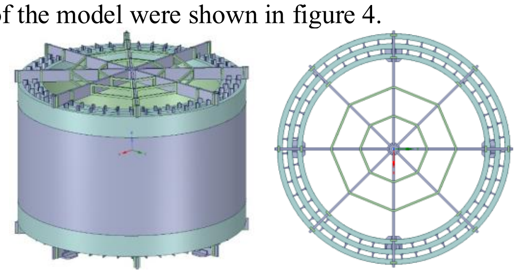

Fig. 4. 3D model of reactor structure

After subdivision of the model and establishment of a structure and electromagnetic coupled simulation environment, the electromagnetic force results were mapped to the structure model to simulate material strains. Figure 5 showed the electromagnetic density vector and deformation diagram. Due to the overall outward expansion, the lifting boom was concaved to the inside, and the deformation of each winding layer of the reactor showed a trend of large deformation in the middle and small deformation at both ends.

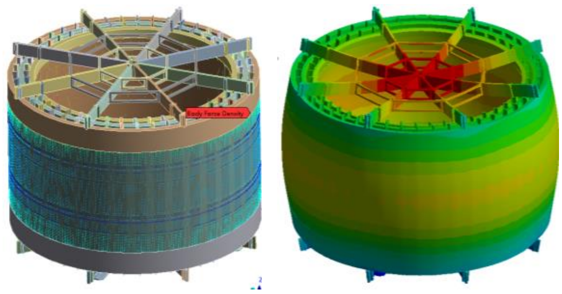

Fig. 5. 3D Electromagnetic model and deformation

In order to study the influence of extreme low temperature on the stress of the reactor, the stress of the reactor windings at temperature of -40℃, -25℃ and 27℃ were simulated and analysed. The stress diagram at three temperatures were shown as figure 6 to 8:

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Fig. 6. Reactor winding stress at -40℃

Fig. 7. Reactor winding stress at -25℃

Fig. 8. Reactor winding stress at 27℃

According to simulation result above, the magnetic field intensity in the centre of the reactor was the largest while the outer magnetic field was relatively small. It is also found that when temperature decreases, the overall stress of the winding tends to increase. When the temperature drops to -40℃, the stress of the reactor increases by about 2% compared with the normal temperature. Though the stress difference was slight, it might impact more with the accumulation effect.

3.4 Fault mechanism at low temperature

Based on the study of material mechanical strength and reactor winding force, it can be concluded that at low temperature, the stress suffered by reactor slightly increased, while the mechanical strength of main reactor materials decreased. Thus, compared with moderate temperature, extreme low temperature could be more likely to facilitate insulation deformation and cracking.

Besides, according to fault investigation and disassembly evidence, the material and manufacturing defects would also be a main cause of the reactor fault. Therefore, the manufacturing defects and extreme cold environment were considered to be the two main reasons for the failure of dry air core reactor in winter. Detailed analysis of the two factors were discussed as follows.

3.4.1 Material and manufacture defect

According to the fault investigation, manufacturing defect were found in considerable faults cases. If material or manufacturing defect existed in reactor, For example, burr, bubble and uneven distribution of insulating materials in turn to existed in inter-turn insulation, it would lead to poor heat and stress resistance performance of the reactor, with high possibility of insulation breakdown. For example, there are burr, bubble and uneven distribution of insulating materials in turn to turn insulation, which are more likely to cause insulation damage and failure under stress. Besides, manufacturing defects such as coil solidification problems will accelerate the formation air gap and uneven material distribution.

External environment such as extreme cold could aggravate those material and manufacturing defects and develop into more serious faults. The shrinkage mismatch of different materials caused by low temperature could also aggravate the air gap and other defects. Small defects may develop into larger ones, which will lead to the declination of both mechanical and insulation properties of the whole structure.

3.4.2 External environment

Since the dry type air-core reactors are often operated outdoors, it could be affected by external environment to a great extent. At low temperature, the bonding performance and tensile strength of the windings were significantly lower than that of the normal temperature, making the windings more vulnerable. For the same force stress suffered, the reactor windings were more likely to deformed and brought about insulation damage at lower temperature.

In addition, in low temperature environment, the temperature gradient of the reactor is large, leading to different shrinkage of encapsulation insulation and wires materials. The expansion strain of the winding caused shear force on the encapsulation, leading to insulation damage and cracking. When the cracks formed, impurities such as humidity, bird droppings, dust would enter to further deteriorate the insulation and more prone to develop into severe fault.

4 Operation and maintenance strategy

According to the fault investigation and mechanism analysis, some corresponding operation and maintenance strategies were proposed to avoid typical fault.

4.1 Reactor inspection and cleaning

Routine inspection and cleaning of the upper end surface and air duct should be carried out. The internal air duct of the reactor could be selectively checked with an endoscope to observe whether there are foreign matters, dirt, or discharge traces. For the impurities such as dust in the air duct, it should be considered to use high-pressure wind for purging. For bird droppings and other traces in the air duct, it is recommended to use pure cotton cloth stained with alcohol to wipe them off.

4.2 Measures against bird droppings

Since the bird droppings will accelerate the electric field distortion and development of partial discharge, the access to the reactor needs to be protected. It is suggested to add bird proof device on the inner diameter of lower and upper part of the reactor to prevent birds from entering the reactor, also to cut off access of bird droppings and other impurities into the reactor.

4.3 Air duct protection measures

Some of the early reactor air ducts were not coated with anti-pollution flashover coating due to technical reasons. It is recommended to spray coatings on the inner air duct surface to block the way of discharge caused by moisture or contamination.

4.4 Annual inspection regulation

It is suggested that an annual test inspection regulation be set for all outdoor operated reactors. The test items including DC resistance, grounding and radial insulation performance test, on-site power frequency loss test, on-site turn to turn overvoltage test, and also arc extinguishing performance and service life of the switch should be checked. Besides, if conditions permit, on-line monitoring for reactors could be set to track the operation parameter.

5 Conclusion

• Based on operation fault investigation and analysis, the fault rate of dry type air-core reactors was higher at extreme low temperature, in which most reactor faults at low temperature were caused by inter-turn short circuit, usually with cracking and impurities found on the reactor surface;
• According to material test and reactor electromagnetic simulation, it was found that the stress reactor suffered slightly increased at low temperature, while the mechanical strength of main materials of reactors decreased. Thus, cold environment was considered to have contribution in promoting deformation and cracks forming;
• The promoted surface cracks forming and decreased mechanical strength would lead to electric field distortion, reactor structure deformation and even serious discharge accidents. Therefore, the dry-type air core reactor operated in the extremely cold environment should have higher electrical and mechanical strength.
• Since the thermal expansion coefficient of reactor winding is different from that of encapsulation, theoretically there would be considerable thermal stress inside the reactor structure at extreme low temperature. In addition, after the reactor is energized, the encapsulation would also be impacted by electric force of the winding, thus the stress distribution of internal reactor is very complex. For further study, the more accurate simulation and test analysis of internal stress of reactor, the comprehensive materials characteristics at low temperature should be continuously investigated, so as to guide reactor selection rule and operation method in extremely cold environment.

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