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Defect Analysis and Process Improvement of Metal-Oxide Arrester

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Abstract—Metal-Oxide Arresters are important equipment to ensure the reliable operation of power systems. An experimental protocol for judging the nature of MOA defects accurately is introduced in this paper and applied to engineering practice. Through diagnostic tests and dismantling inspections, it is determined that a certain batch of 110kV line MOA has a familial defect of poor sealing. Then, the reasons for dampness are analyzed, and other defects except the dampness of the varistor are discovered. Besides, the improvement of manufacturing process is proposed from aspects of terminal structure and the coating material on the side of varistor;the actual data proves that adding fillers such as quartz sand or silica gel inside the MOA can reduce the failure rate effectively. This article provides a certain technical reference for the manufacture and defect disposal of MOAs.

1. Introduction

Metal-Oxide Arresters (MOA) can be treated as a complete insulator when subjected to low voltages. It will experience a momentary short circuit fault when subjected to breakdown voltage [1]. Therefore, MOA can protect substation equipment and line equipment from damage caused by operating overvoltage or lightning overvoltage, thus ensuring the reliable operation of the power system [2]. Polymeric housed MOA has the advantages of better anti-fouling, water repellent and anti-seismic. Thus, it has replaced the bulky porcelain sleeve arrester gradually and is widely used in power systems. However, to save production costs and speed up production, some of the MOA manufacturers cannot guarantee the manufacturing process of their products, and these products often have problems of poor sealing. This will accelerate the damping, partial discharge, heating, and aging of the varistor inside the MOA, which may threaten the safe operation of the power system seriously [3].

At present, the commonly used MOA detection methods include resistive current detection, infrared temperature measurement, and DC reference voltage test. With the development of information technology, online remote monitoring devices are widely applied in power system industry. An evaluation method based on leakage current waveforms was proposed in [4], which is used to diagnose the operation of arresters and is capable of detecting many types of arrester defects. In [5], an online monitoring system for arrester leakage current based on harmonic analysis method is proposed, which can predict possible defects and aging of the arrester effectively. However, due to the unavailability of reference voltages at the installation site of the line MOA, it is difficult to detect resistive current effectively. Literature [6] points out the distribution of hottest spots and infrared temperature measurement strategies for MOA at each voltage level through an experimental study of the thermal characteristics of MOAs. Unfortunately, the installation position of the line MOA is high and the infrared temperature measurement is not easy to detect the heating defects. Literature [7] uses statistical methods to obtain the distribution characteristics of MOA outage test data and summarizes the regular relationship between test data and operating life, temperature and humidity, which can make the judgements on the condition of MOA more accurately. However, due to the requirements of power supply reliability, power outage testing is also often not executed on a cycle basis. Consequently, the reliability of MOA cannot be ensured by means of testing alone. It is necessary to formulate a series of analysis and experimental protocol to investigate the causes of the MOA defects, and to propose targeted production technical specifications, thus ensuring the reliability of power system operation.

In this paper, an experimental protocol is proposed to judge the defect nature of the MOA. The protocol can also be used to check whether there are familial defects in the same batch of MOAs. The effectiveness of such protocol is verified through field application, where a family defect of poor sealing of a batch of MOAs is found. Furthermore, the improved methods of the manufacturing process are proposed from perspectives of MOA terminals, filling materials and varistor side coating, and the effectiveness of improvement methods that is demonstrated through application. This paper provides a technical reference for the manufacture of MOA and the disposal of defects, and is of great significance for improving the reliability of power supply.

The article is structured as per following.The defect situation of MOA is described in Section 2. The experimental protocol and procedure is presented in Section 3. Additionally,Section 4 analyses the causes of the defects. Continuing the process improvement approach and experimental verification are described in Section 5. The conclusions are drawn in Section 6.

2. Defective conditions of MOA

The defective MOA is a non-gap polymeric housed arrester, type YH10WZ-108/281, which was produced in Nov. 2019, and was installed on the 110kV cable terminal tower and put into operation on Dec. 24, 2019. The inside of the MOA is a cavity structure, and the outside of the epoxy resin insulating cylinder is a silicone rubber outer sheath formed by high temperature vulcanization. There are 31 varistor blocks and 6 aluminum conductive blocks in the core group. The bottom is fastened by a metal flange and the top is fitted with a metal flange and a wiring plate [8].

In Sept. 2021, power workers found that the online operating monitor of the A-phase MOA on a 110kV cable termination tower showed a leakage current was about 2mA. Compared to last recorded data, an increase of 1.6mA was discovered. To assess the MOA operating conditions accurately, infrared temperature measurement of the MOA was carried out at night. The results show that the A-phase MOA has serious heating phenomenon, and the maximum temperature difference between phases is 4.9 ℃. Infrared temperature measurement was carried out on the MOA of the same manufacturer and the same batch, and it was found that most of the MOAs had different degrees of heating. 18 of the 42 MOAs had critical defects with a temperature difference of more than 1K.

3. Experimental Protocol and Process

3.1. Experimental protocol

Fig.1 presents the work flow of the defective nature of MOA experimental protocol.When discovering that the data of multiple MOAs in the same batch are abnormal through infrared temperature measurement and leakage current live detection, one MOA with abnormal data (referred to as MOA A) and another MOA with qualified data (referred to as MOA B) should be replaced by power outage. The full current, resistive current and infrared temperature measurement were tested by applying an industrial frequency voltage to both MOAs to verify the accuracy of the charged test results. Then, the MOA A is subjected to a DC 1mA reference voltage (U_{1mA}) test and a leakage current test at 0.75 times the DC 1mA reference voltage ($I_{0.75U1mA}$). If the data passes, the nature of the defect is moisture in the internal epoxy insulating cylinder. If the data fails, dismantle the MOA A for disintegration and investigation, and carry out U_{1mA} and $I_{0.75U1mA}$ tests before and after drying of the insulating cylinder containing the varistor core set. If the data is normal after drying, the nature of the defect in MOA A is moisture in the epoxy insulating cylinder. Instead, the MOA A should be disassembled and inspected for traces of moisture. Furthermore, U_{1mA} and $I_{0.75U1mA}$ were detected before and after drying on varistor. If the data after drying is acceptable, the nature of the defect is that the varistor is damped. On the contrary, the varistor is considered to have an abnormal side insulation coating. After removing the insulating coating from the side of varistor and testing again, if the data passes, the nature of the defect is damage to the side coating of the varistor, otherwise, the varistor itself is damaged. Finally, a high current impulse test is used to verify that the side or body of the varistor is indeed damaged. The seal test was carried out on MOA B and combined with the results of the electrical test and the test analysis of MOA A to determine whether the batch of MOA had a familial defect of poor sealing.

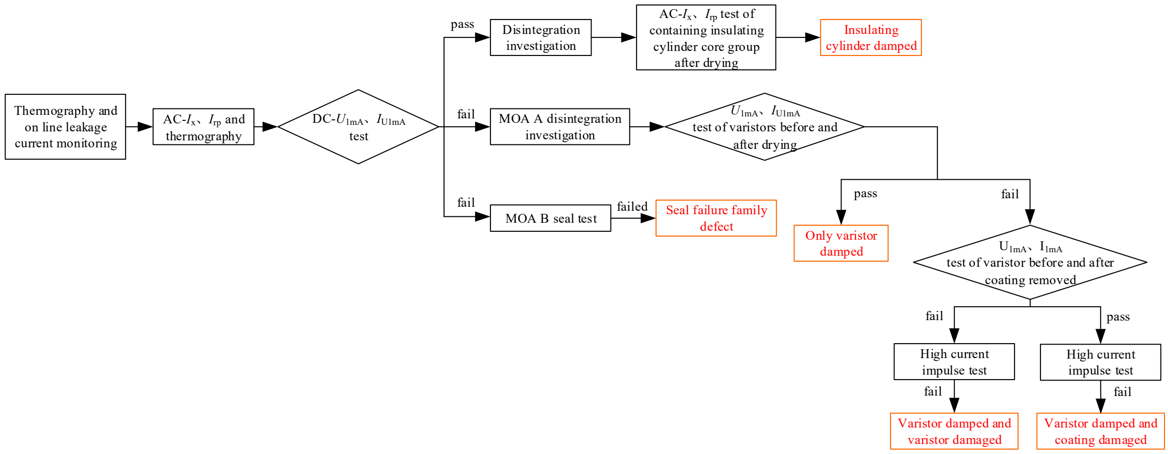


Fig.1 Flowchart of the defective nature of MOAs experimental protocol

3.2. *Experimental process*

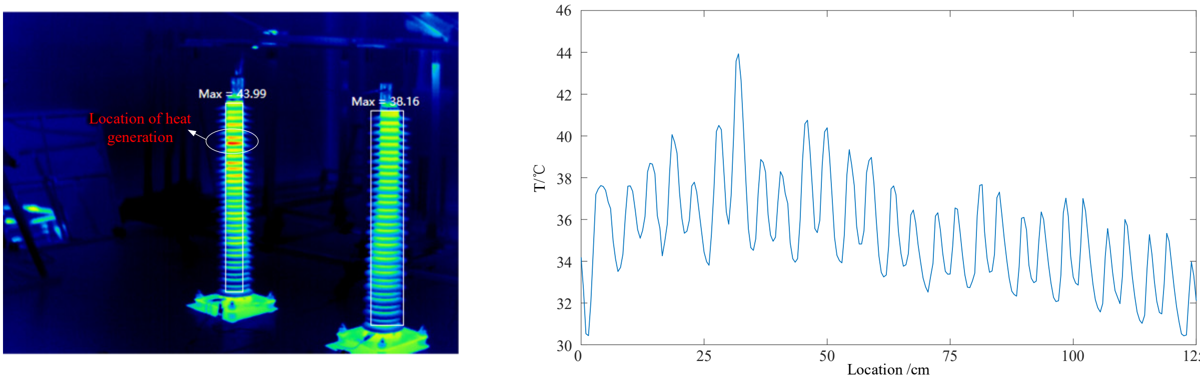
In accordance with the experimental protocol proposed in section 3.1, the MOA A is subjected to full current at operating frequency voltage,undergoes resistive current, infrared thermographic detection, U_{1mA} and $I_{0.75U1mA}$ test, disassembly inspection, U_{1mA} and $I_{0.75U1mA}$ test before and after drying of the varistors, U_{1mA} and $I_{0.75U1mA}$ test after removal of the side insulation coating of the varistor, high current impulse test.MOA B undergoes seal test.

3.2.1. *The industrial frequency voltage testing*

AC voltage is applied to MOA A and MOA B respectively, and leakage current and infrared thermographic tests are carried out. The resistive current (I_{rp}) and full current (I_x) detections are performed on both MOAs during the voltage application. The experimental results are shown in Table 1. As can be seen, the full current of MOA A is higher than MOA B, and the resistive current of MOA A is large, accounting for 40.1% of the full current, more than 20% of the reference value. The resistive current changes significantly, and it is judged that there is moisture or the deterioration of the varistor inside the MOA. Fluke TIX640 infrared thermal imaging, as shown in Fig.2 After 10 minutes of voltage application, the temperature of MOA A was 5.8°C, higher than MOA B. Using the software of Fluke Connect and Smart View to analyse the temperature distribution curve of MOA A, it was shown that the highest temperature was located in the upper middle area.

Table 1. The data of sustained leakage current

MOA	I_{rp} (mA)	I_X (mA)	Proportion
A	0.375	0.935	40.1%
B	0.072	0.405	17.8%



(a) The infrared thermography (b) The temperature at different locations of MOA A

Fig.2 The infrared thermography infographic

3.2.2. DC reference voltage test of the MOAs

The two MOAs were tested separately for U_{1mA} and $I_{0.75U1mA}$. The test results are shown in Table 2. The reference voltage U_{1mA} of the MOA A is 131.1kV, which is far lower than the handover test of 163.9kV, and also lower than the standard of 157kV specified on the manufacturer's nameplate. The $I_{0.75U1mA}$ is 59.4μA, which exceeds the standard of 50μA. The test data of MOA B is normal.

Table 2. The test data of MOA body

MOA	U_{1mA}/kV			$I_{0.75U1mA}$/μA
	Test data	Pre-operation data	Deviation rate	
A	131.1	163.9	17.6%	59.4
B	163.7	164.5	0.5%	18.3

3.2.3. MOA disassembly and inspection

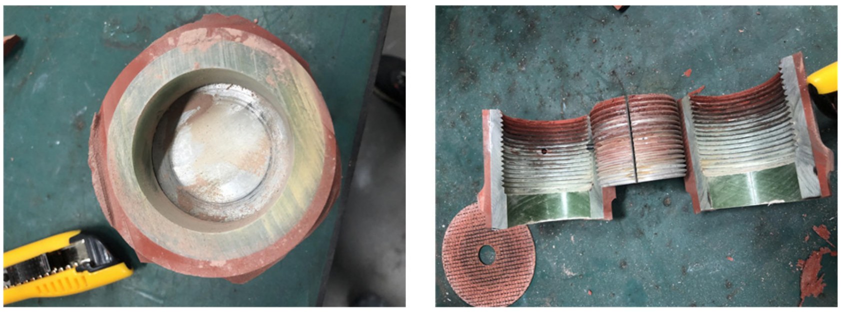


Fig.3 Anatomical view of the MOA body

After dismantling MOA A, as shown in Fig.3, there were water marks inside the epoxy resin insulating cylinder. The silicone rubber jacket was cut and the resulting powder was clumped with water on the metal flange and the insulating cylinder. The inside of the insulating cylinder was not filled with quartz sand or silicone gel, there was no compression spring and the varistor was not wrapped in a heat shrink sleeve. The metal flange was loose and obvious. No sealant was applied to the joints between the insulating cartridge and the flange, and there were obvious traces of uncured silicone rubber infiltration on the threads. The resistor tabs were separated and named in order from the bottom to top. The insulating coating on the side of the varistor No. 24-31 of the upper half of the core group was deteriorated and discolored, and the aluminum electrode showed signs of oxidation and blackening. The six aluminum conductive blocks also showed varying degrees of rust and corrosion. Comparing the arrangement of the upper and lower varistor, the color difference of the glaze layer is obvious. To sum up, the internal moisture traces of MOA A are more obvious.

3.2.4. Varistor DC reference voltage test
A total of 8 varistors of No.28-31 in the upper part and No.1-4 in the lower part are selected for testing, which consisted of U_{1mA} and $I_{0.75U1mA}$ on the resistive tabs before drying. Then, the same test was performed after drying at 150°C for 2 hours. The test data is shown in Table 3 which indicates that varistors No. 1-4 all passed the test. The U_{1mA} rose significantly for varistors No. 28-31 after drying, proving that the varistors were damped. The $I_{0.75U1mA}$ was reduced slightly but was still much greater than 50μA. To conclude, the side insulation coating of the varistor was damaged irreversibly. The No. 31 varistor was selected to remove the side insulating coating and polished, and $I_{0.75U1mA}$ was 46μA, which was reduced greatly, indicating that the side insulating coating of the varistor weakened the insulating performance.

Table 3. The test data before and after drying

Varistor	Before drying		After drying	
	U_{1mA}/kV	$I_{0.75U1mA}$/μA	U_{1mA}/kV	$I_{0.75U1mA}$/μA
31	1.13	377.8	4.16	269.2
30	1.92	308.5	4.52	218.8
29	3.22	201.4	4.83	161.2
28	2.29	182.4	4.68	169.7
4	5.31	11.1	5.26	10.7
3	5.44	12.3	5.39	11.6
2	5.28	10.9	5.24	12.0
1	5.29	10.5	5.26	11.3

3.2.5. High current impulse test
The performance of the varistor side insulation coating will determine their ability to withstand overvoltage shocks. To further verify whether the side insulation coating of the varistor of MOA A is degraded, No. 28-31of the varistor is subjected to a 4/10μs high current impulse withstand test at two intervals. If it can withstand 2 times under 100kA current without breakdown and flashover, the varistor is reliable, the side insulation coating is good [9]. The test data is shown in Table 4. There was no blowout or cracking of the varistors, but flashover was still present and all four varistor failed the test.

Table 4. The data of high current impulse test

Varistor	Impulse current value/kA	Result
31	The First 101	pass
	The second 101	flashover
30	The First 101	flashover
29	The First 100	pass
	The second 100	flashover
28	The First 100	flashover

3.2.6. Seal test
To verify the sealing of the batch of MOV, the seal test of MOA B was carried out. This paper uses the pumping and soaking method, the pressure difference in the container pumped to slightly more

than 0.02Mpa, soaking time ≥ 3min. Table 5 presents the data of seal test.During the test, no obvious bubble overflow was seen. Comparing the data before and after soaking the MOA, the U_{1mA} is basically the same, while the $I_{0.75U1mA}$ increases to 85.8μA. The change of the leakage current before and after is more than 20μA, which does not meet the requirements of the seal test.

Table 5. The data of seal test

	U_{1mA}/kV	$I_{0.75U1mA}$/μA
Before seal test	163.7	18.3
After seal test	163.5	85.8

4. Analysis of Causes of MOA Deficiencies

The internal and external screw threads of the epoxy insulating cylinder are complete, which eliminates the possibility of loosening of the screw thread slipping or other raw material quality problems. The metal flange and the insulating cylinder can be easily separated and the silicone rubber is not fully cured when it seeps into the flange gap, indicating that the flange contact surface threads are not coated with glass sealant for waterproofing. The thermal expansion coefficients of the epoxy insulating cylinder and the metal flange do not match, therefore, when the glass sealant is not applied for sealing, tiny moisture absorption channels will form at the joints, resulting in moisture inside the MOA. The coatings on the side of the varistors are discolored, the upper and lower aluminum layers are rusted and blackened.Furthermore, the U_{1mA} of the varistors increase significantly after drying. The appearance inspection and test result also prove that the varistors at the top of the MOA are affected by moisture. Therefore, the damping of the MOA leads to the deterioration of the varistor, which is the main reason for the defect.

In addition, the material of coating on the side of the varistor is epoxy resin, while the varistor itself is an inorganic material. The adhesion effect between the two is not ideal. After getting wet, the moisture will be adsorbed on the interface of the middle layer, affecting the electrical performance of the varistor. The epoxy resin is easy to crack and fall off when subjected to continuous high-temperature operation or short-term impact, so as to accelerate the deterioration of the coating. Epoxy resin insulation coating will limit the service temperature of MOA, limit the performance of varistor, and keep poor energy absorption level when subjected to high current impulse [10]. The test data also proves that the insulation coating on the side of the varistor has irreversible deterioration.

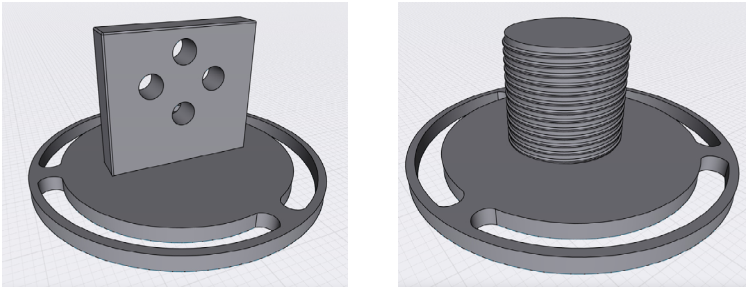
Combined with the on-line test of 42 MOAs, more than 40% have serious heating, after various tests of MOA A and the seal test of MOA B, it can be considered that this batch of MOAs have family defects of poor sealing.

5. Process Improvement

The lack of sealant on the contact surface between metal flange and epoxy insulating cylinder flange is the direct cause of this defect. Besides, there are deficiencies in the overall structure design of the MOA and the process of varistor . The article proposed improvement suggestions from three perspectives .

5.1. Optimization of metal flange and wiring structure

The wiring terminal of the original MOA is a bolt type wiring board, and it's easy for water vapor to enter the metal flange along the screw hole. When fastening the bolt type wiring board or connecting with transmission lines, it may drive the metal flange, resulting in the failure of the sealant. The design structure is shown in Fig.4. The top of the metal flange is designed as a disc structure with movable fixing holes, the bottom of the earth terminal is the same structure as the top of the metal flange and both are fixed by bolts, nuts, flat gaskets and spring gaskets. Such a split structure can eliminate the passage of moisture into the MOA and avoid damaging the cured sealant.



(a) Top of the metal flange (b) Bottom of the metal flange

Fig.4 The improved connection construction of metal flange

5.2. Filling process improvement

The MOA's epoxy-insulated cylinder has a hollow cavity structure inside, with hidden problems such as partial discharge, poor heat dissipation and ageing of the varistor side coating. To solve these problems, the operational reliability of the MOA can be improved by filling with quartz sand, liquid resin glue, and wrapping the varistor column with a heat-shrinkable sleeve and other processes.

Quartz sand has good insulation ability, which can delay the deterioration process of the varistor and improve the service life of the MOA. In addition, good thermal conductivity can solve the problem of heat dissipation of the varistor to a certain extent, to ensure its industrial frequency withstand capability and inhibit resistive current power loss [11]. However, different particle sizes of quartz sand pile up after the arc elimination capacity and thermal conductivity is different, the MOA manufacturer should choose the right particle size of quartz sand according to the actual production needs, seeking to strike a balance between arc elimination and heat dissipation performance requirements. Filling glue can eliminate the air space inside the MOA from moisture and partial discharge and improve the heat dissipation inside the MOA. This is a more demanding process than filling with quartz sand. Therefore,when carrying out the silicone gel infusion process, the intermediate cores should be stacked neatly and ensure that the tightening force of the spring should be greater than the infusion pressure to prevent the silicone gel from being injected between the varistors. The filling gel should be able to cure in time and fill the internal void of the MOA. The heat shrinkable sleeve wrapped around the varistors makes it difficult for water moisture to attach, protecting the insulation of the side coating.

This paper investigates the information of manufacturers of gapless MOAs for transmission lines of 110kV and above in Zhangzhou, and counts the reliability of MOAs taking different structures, as shown in Table 6. It can be seen that the highest reliability of the MOA using quartz sand filling, the highest probability of defects occurring in the MOA of the cavity, and the varistor column can improve the reliability of the MOA after wrapping the bundle by heat shrinkable sleeve.

Table 6. The defect rate of MOAs with different fillers

Filler	Total MOAs	Number of defects	The defect rate
Quartz sand	108	0	0%
Silicone gel	549	1	0.18%
Cavity + Heat shrinkable sleeve	177	2	1.13%
cavity	912	44	4.82

5.3. Material selection optimization of varistor side coating

The top and bottom parts of the varistor in the MOA are generally aluminum layers, and sides are mainly inorganic insulating coatings and organic insulating coatings. Inorganic insulating coatings, although more difficult and costly to apply, have been proved to be a better option when used in conjunction with MOV. The main component of the inorganic insulating coating of the existing MOA is generally PbO or B_2O_3, and other inorganic oxides are added. In this way, the purpose is to reduce the coefficient of thermal expansion and improve the thermal stability, insulating properties, and crystallization properties of the glaze layer. On the premise of ensuring the quality of the coating process, the side of the varistor adopts an inorganic insulating coating, which can improve the MOA's overall electrical performance and service life.

6. Conclusion

This paper presented A MOA experimental protocol,that can identify the nature of defects in MOA accurately and judge them for the presence of familial defects. Furthermore, an improved approach to the manufacturing process of MOA is proposed. Specifically, the following points are included:

(1) The sealant is applied between the metal flange and the insulating cylinder, and optimizing the structure of the MOA terminals can reduce the probability of the MOA being affected by moisture.

(2) Taking measures such as filling quartz sand or sealant inside the MOA, or wrapping the varistor core group in a heat shrink sleeve can improve the operational reliability of the MOA.

(3) The coating of the sides of the varistor with inorganic materials such as vitreous enamel layers prevents the insulation layer from ageing. It also improves the electrical properties of the varistor and reduces the probability of defects.

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