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Research on corrosion mechanism of suspension insulator steel foot of direct current system and measures for corrosion inhibition

He Chen[1], Yueguang Yang[1], Guolei Su[1], Xiaoqing Wang[1], Hourong Zhang[1], Xiaoyu Sun[2]*, Youping Fan[2]

1.CSG EHV Power Transmission Company, Guangzhou 510663, China;
2. School of Electrical Engineering, Wuhan University, Wuhan 430072, China

Abstract. There are increasingly serious electrocorrosion phenomena on insulator hardware caused by direct current transmission due to the wide-range popularization of extra high voltage direct current transmission engineering in our country. Steel foot corrosion is the main corrosion for insulators on positive polarity side of transmission lines. On one hand, the corrosion leads to the tapering off of steel foot diameter, having a direct influence on mechanical property of insulators; on the other hand, in condition of corrosion on steel foot wrapped in porcelain ware, the volume of the corrosion product is at least 50% more than that of the original steel foot, leading to bursting of porcelain ware, threatening safe operation of transmission lines. Therefore, it is necessary to conduct research on the phenomenon and propose feasible measures for corrosion inhibition. Starting with the corrosion mechanism, this article proposes two measures for corrosion inhibition, and verifies the inhibition effect in laboratory conditions, providing reference for application in engineering.

1. Introduction

Extra high voltage direct current transmission has advantages such as long transmission distance, large transmission capacity, saving transmission space and low comprehensive cost. It effectively solves the problem of the reverse distribution of resource reserve and energy consumption in western and eastern China, playing an important role in promoting reasonable optimal configuration of energy resources and improving national economic level in our country[1-3].

The ±800kV Chusui direct current transmission engineering put into operation in June 2009 is the first ±800kV direct current transmission engineering in the world independently designed and researched by our country[4-6]. It is a main line connecting the power transmission of the whole power system in south China, starting from Yunnan to the west and to Guangdong to the east. The V series structure is adopted in large quantity for the ±800kV Chusui direct current transmission line, in order to improve mechanical performance and ensure transmission safety. However, this structure may lead to local corrosion in operation sections with damp weather conditions and large precipitation because it is easy to accumulate moisture on lower edge of the insulator hardware, which composites electrolyte together with surface contaminant and forms conducting loop with the function of additional direct voltage.

There are frequent phenomena of insulator corrosion on various direct current transmission lines. In some operation sections with extremely high corrosion ratio, insulator hardware corrosion may lead to the degradation of mechanical performance and electrical performance of the insulator to different

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degrees, and the degradation of mechanical performance may result in serious transmission accidents such as flashover or breakdown, threatening the safe and stable operation of power system. Therefore, it is necessary to conduct further research on corrosion mechanism of the insulator and propose targeted inhibition measures for sections with serious corrosion, in order to ensure safe operation of power system.

2. Analysis on Mechanism of Steel foot Corrosion

2.1 Analysis on Typical Inducing Environment for Corrosion

Fig.1: Typical Inducing Environment for Steel foot Corrosion

According to comprehensive analysis on typical topographic conditions and meteorological environment in regions with serious insulator steel foot corrosion, the following typical characteristics shown in Fig.1 can be acquired: (1) on shaded side of plateau mountainous regions; (2) large air humidity and plentiful rainwater; (3) frequent continuous heave fog weather, difficult to disperse.

2.2 Galvanic Corrosion of along Service Leakage

It refers to the corrosion caused by leakage current circulation path formed along with the surface of the insulator, with the basic principle of electrochemical corrosion, as shown in Fig.2 External direct current power supply, positive and negative metal electrodes and conducting solution form the electrolytic tank circuit. The metal electrode connected to the positive pole of the direct current power supply generates the oxidizing reaction under the effect of the direct electromotive force, and loses electrons; at the same time, corresponding positive ions are formed and broken away from the surface of metal material. This process is known as anodic corrosion[7-9].

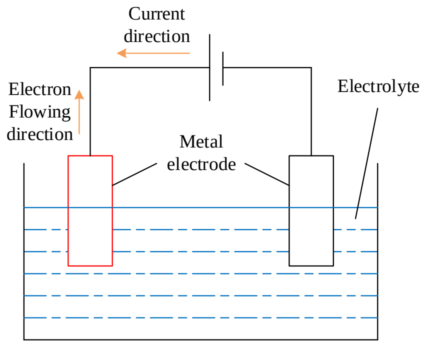


Fig.2: Schematic Diagram for Direct Current Electrolytic Action

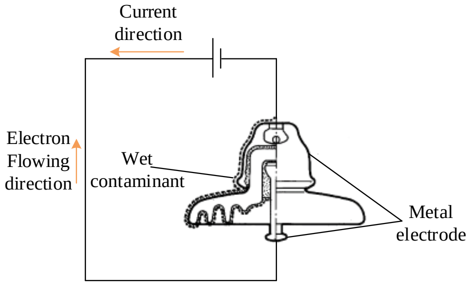


Fig.3: Schematic Diagram for Steel foot Corrosion

The metal on the positive polarity side of the power supply in Fig.3 is the positive pole, and the metal on the negative polarity side of the power supply is the negative pole. When the. The leakage current path is formed in condition that the porcelain ware is affected with damp on the surface and the contaminant is dissolved in moisture. At this time, the metal in the positive electrode generates corresponding oxidization reaction and loses electrons, and changes to high valence positive ions at the same time.

$$F_e \to F_e^{2+} + 2e^-$$

The metal in the negative electrode generates corresponding reduction reaction, and acquires electrons while forms negative ions at the same time.

$$O_2 + 2H_2O + 4e^- \to 4OH^-$$

The positive and negative ions combine in the electrolyte, and generate water insoluble hydroxide.

$$F_e^{2+} + 2OH^- \to F_e(\mathrm{OH})_2 \downarrow$$

The hydroxide is further oxidized with the function of oxygen and water.

$$4F_e(\mathrm{OH})_2 + O_2 + 2H_2O \to 4F_e(\mathrm{OH})_3$$

It is available to acquire the rust products of different element proportions with the combined action of factors such as temperature, PH value and oxygen content in moisture. The composition of rust can be expressed as follows:

$$mF_e\mathrm{O} + nF_{e2}O_3 + pH_2O$$

The values of m, n and p here vary with different conditions. The insulator with steel foot corrosion on direct current transmission line is on the positive polarity side. Considering that the steel foot side of the insulator on the positive polarity side is connected to the transmission line, the steel foot is in high potential compared with the iron hat. In condition that the insulator is exposed to rain or affected with damp on the surface, the contaminant accumulated on surface of the insulator is combined with moisture to form an electrolyte environment, leading to the electrolytic tank conditions due to the positive and negative electrodes of iron hat and steel foot. The steel foot as the positive electrode changes to bivalent cation dissolved in the electrolyte by losing electrons due to oxidation reaction, leading to positive electrode steel foot corrosion.

3. Analysis on Accelerated Corrosion Test

The simulation test methods used for research on insulator electrolytic corrosion at present are mainly divided into two categories: one category includes long term field simulation method, and the other category includes accelerated simulation methods by establishing test platforms in laboratory conditions, mainly including water spray method, salt fog method, electrolytic bath method, solid dirt layer method, etc. It is obvious that field simulation methods cost too much time and leads to large time span, adverse to practical engineering application. The accelerated corrosion methods satisfy the requirements on time, but indexes such as field fitting performance shall be taken into consideration. Several methods are introduced in the following, and comparisons on advantages and disadvantages among them will be made, in order to select the optimal test method.

3.1 Water spray method

The water spray method suspends the insulator according to the actual operation method in the field, and sprays NaCl solution to the position of corrosion on steel foot. It then adds direct current voltage to form conductive path, and connects the steel foot end to the positive electrode of the power supply, to generate positive electrode corrosion and forms the accelerated corrosive environment. In which the flow rate and the conductivity of the conducting solution have large influence on corrosion rate. The flow rate is determined by adjusting the water spray rate of the sprayer, and the conductivity is acquired by calculating the concentration of the NaCl solution.

3.2 Salt fog method

The NaCl solution is adopted for the salt fog method. Different from the water spray method, it forms salt fog by utilizing high pressure electric spray gun, to develop the conductive film on the surface of the insulator directly, to generate certain leakage current with the function of the external direct voltage. The test is needed to be conducted in special fog room equipped with special fogging device.

3.3 Solid dirt layer method

This method coats a layer of solid dirt layer on the surface of the porcelain insulator, with available solid dirt layers shown in Table 4.2. Artificial damping is conducted after the coating of the dirt layer, to generate the leakage current of certain value under the direct voltage, which shall be continued for a while, to achieve the purpose of the accelerated electrolytic corrosion of the test object. The adopted solid dirt layer material shall form a conductive film on the surface of the porcelain insulator after the damping with strong adhesiveness, in order to avoid too early loss after moisture.

Table 1: Comparisons on Materials of the Solid Dirt layer Method

Material of the dirt layer	Leakage current	Length of time	Setting time	Coating effect
Water glass and graphite powder	25mA	<0.5h	Comparatively long	Ordinary
Water glass and NaCl solution	30mA	<0.25 h	Comparatively long	Poor
Epoxy resin and graphite powder	25mA	<0.25 h	Long	Poor
Bone paste water and water and NaCl	>70mA	1h	Comparatively long	Good
Bone paste and tap water	70mA	1h	Ordinary	Good

According to existing research findings, only about 3C leakage electric charge quantity can be simulated in each smearing; therefore, over ten thousands of times of smearing are needed for the insulator with operation time of more than 15 years.

3.4 Electrolytic bath method

Add 3% NaCl solution in the electrolytic bath as the electrolyte, and adopt a copper bar as the negative electrode, and connect the steel foot test object to the positive electrode. Well wrap the positions not applied with corrosion of the steel foot test object with insulation material before soaking the steel foot test object into the electrolyte, in order to achieve consistence between the simulated steel foot position and the actual corroded position on the steel foot of the suspension insulator. Then adjust the direct current power supply and keep the constant current of 5A, and record the ampere hour value accumulated in the electrolytic process, and measure the corresponding corroded depth and corrosion volume of the steel foot and the zinc cover.

3.5 Comparisons among different schemes

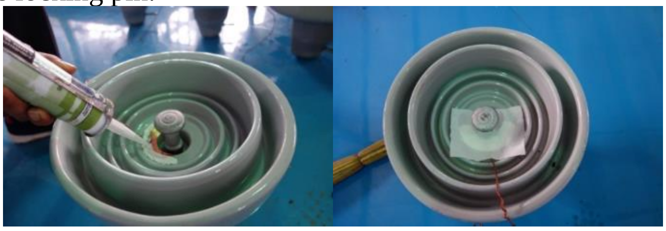
According to existing research findings, in the four above schemes, the water spray method has comparatively low requirements on equipment; it is easy to set up the test platform, coinciding with field operation conditions. The salt fog method is also coinciding with field operation conditions, but it has comparatively high requirements on test platform, and special fog room and supporting fogging device are required. The solid dirt layer method does not have high requirements to test equipment, but ten thousands of times of smearing are required, which is only applicable to the tests with small electric charge leakage quantity. The electrolytic bath method has simple requirements on equipment, but with simulation effect different from the actual field corrosion condition of the insulator. According to the comprehensive comparisons among the above test methods, this article selects the water spray method for the accelerated corrosion test.

4. Sample Treatment

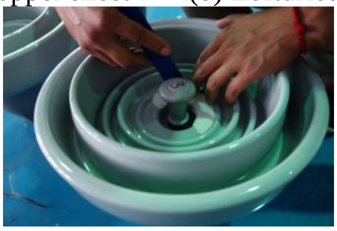
4.1 Sample Pretreatment

Make a semi-circular arc copper sheet electrode with inner diameter of 1.5 cm, outer diameter of 3.5 cm and width of 2 cm. Weld a metal wire on the middle part of the outside of the copper sheet.

The method for the creep distance of the short circuit part is as follows: Fix the manufactured copper sheet electrode with waterproof glue on 1cm away from the steel foot, and the other end of the metal wire is fixed on the locking pin.



(a) Fixation copper sheet (b) Loftdried glass cement



(c) Treated glass cement

Fig.4: Creep Distance of the Short Circuit Part

4.2 Treatment of the Inhibition Corrosion Sample

This article selects the XZP2-300 model porcelain insulator as the test sample, and the structure of the insulator steel foot with nonmetal protective hat zinc cover is as follows:

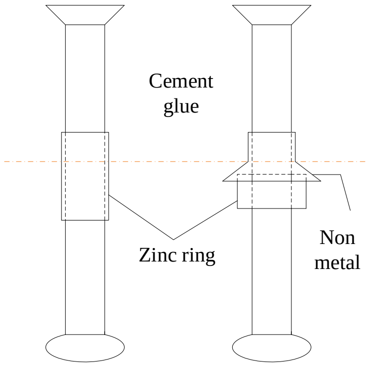


Fig.5: Schematic Diagram for Treatment of Steel foot Corrosion Inhibition Measures

5. Test Process

5.1 Development of the Test

Select 5 brand new porcelain insulators and conduct creep distance treatment to the short circuit part with metal copper sheet, with the same suspension method of V shape series in field operation (with the included angle between the axis of the insulator and the horizontal plane of 76°), in which samples 1#, 2#/ and 3# are not conducted with any treatment, and sample 4# is covered with RTV hydrophobic painting in the region without short circuit, and sample 5# is added with umbrella type nonmetal protective hat on the zinc cover part.

Prepare the electrolyte with certain conductivity. Conduct test during the preparation process with conductivity tester, with electrolyte solute of refined salt sodium chloride with purity higher than 99%, targeted conductivity of 3mS/cm, and flow of 12.5L/h.

The accelerated corrosion test aims to accelerate the steel foot corrosion. According to the electrochemical corrosion principle, the positive electrode connected with positive electrode of the power supply will have corresponding oxidizing reaction; therefore, the steel foot is connected to high potential, and the iron hat (the copper sheet used for the short circuit creep distance) is connected to low potential.

Start the test units according to the following operation sequence: check wiring – inlet the electrolyte – disconnect the ground connection – enable the power supply – boost to designated value with the target voltage of 400 V. Measure the displayed reading of the units according to leakage charge, and record the accumulated leakage electric charge quantity in every 1 h and the real-time value of the leakage current within a period.

According to the result of the hardware dissection test to the XZP_2-300 model operation insulator taken down from ±800kV Chusui direct current transmission line: the annual average maximum leakage electric charge quantity on steel foot position is 1479C, which is taken as the benchmark electric charge quantity of the test.

Record the data as per step (4) after the start of the test. Suspend the test in condition of the occurrence of rust on 1# insulator for the first time. Take down 1# insulator after the outage operation, and record the time node, including operating time and the leakage electric charge quantity of the node. Take down the sample at the leakage electric charge quantity of 8135C on 2# insulator (equivalent to the field operation of 5.5 years). Take down 3# and 4# samples at the leakage electric charge quantity of 44370C on 3# (equivalent to the field operation of 30 years). Take down 5# sample when the leakage electric charge quantity of 5# sample is the same as that of 1# sample, and record corresponding time point and leakage electric charge quantity.

5.2 Analysis on Test Result

1. The leakage electric charge quantity of 2# sample is 8135C (equivalent to the field operation of 5.5 years). Make comparisons with the insulator (6#) taken down from Chusui direct current line with actual operation length of 5.5 years.

Fig.6: Samples of Corroded Insulators 2# (left) and 6# (right)

According to preliminary observation, the corrosion state of the samples of corrosion test conducted in laboratory accelerated simulation conditions is more serious than the state of field operation, in line with the selection of the annual average leakage electric charge quantity in the worst conditions as the base value. Both of them have similar corrosion regions and shapes, indicating that there is preferable equivalence between the accelerated corrosion test in laboratory conditions and that of field operation.

2. Stop the test at the leakage electric charge quantity of 44370C on 3# sample (equivalent to field operation of 30 years), then take down the 3# and 4# samples. The scene drawings of the two insulator samples are as shown in Fig.8, and the corresponding relationship between leakage electric charge quantity and time is as shown in Fig.9.

According to the comparisons on the corrosion state and the leakage electric charge quantities of 3# and 4# insulators:

(1) The corrosion state of the two are serious, in which the outermost zinc cover of 3# insulator totally falls off, with the most serious corrosion state near to the cement junction. The surface layer of the zinc cover of 4# insulator is also basically corroded; there are large quantities of zinc hydroxide products attached on surface of the zinc cover away from the cement junction;

Fig.7: Samples of Corroded Insulators of 3# (left) and 4# (right)

(2) According to the comparisons made on the leakage electric charge quantity at the taking down and the corrosion rate during the test process, the existence of hydrophobic material plays certain role to corrosion delay, but not significant enough.

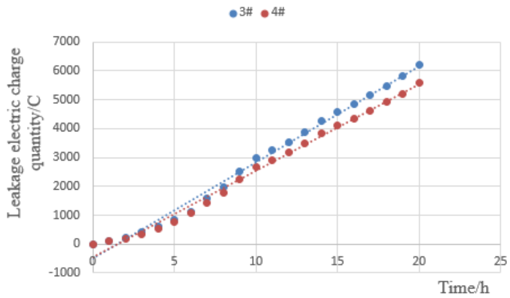


Fig.8: Comparisons on Corrosion Rate of Samples of 3# and 4# Insulators

3. When the leakage electric charge quantity of 5# insulator is equivalent to that of 1# insulator during taking off, take off 5# insulator, and record corresponding time point and leakage electric charge quantity, with corresponding time node of 108.8h and corresponding leakage electric charge of 20795C. Refer to Fig.9 for comparisons between sample drawings and Fig.10 for comparisons between corrosion rates.

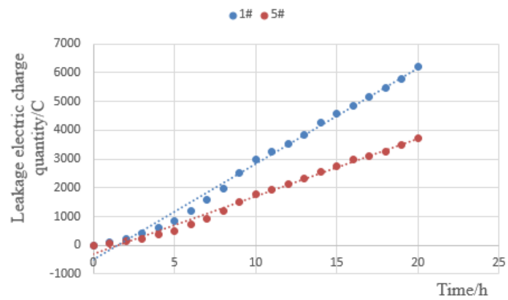


Fig.9: Samples of Corroded Insulators of 1# (left) and 5# (right)

Fig.10: Comparisons on Corrosion Rates of Samples of 1# and 5# Insulators

Make comparison on corrosion state between samples of 1# and 5# insulators, to acquire the following conclusions:

(1) The insulator corrosion regions are junctions among steel foot, air and cement (protective cover); i.e., the installation of umbrella shape protective cover can effectively change the corrosion positions of the insulators;

(2) According to the relation scheme between the leakage electric charge and time, the installation

of umbrella shape protective cover can effectively delay corrosion rate by reducing the corrosion rate to 0.6% of the original rate;

(3) The samples in the figures are conducted with equivalent treatment; the thickness of the exposed zinc layer shall be further increased compared with the steel foot treatment method in ideal state, in order to further delay the corrosion rate to the iron base.

6. Conclusion

1. According to the comparisons among various accelerated corrosion test methods, the water spray method has significant advantages on comprehensive consideration of various indexes such as field fitting performance, operability of the test and economy, applicable to the development of continuous test of large leakage electric charge quantity;

2. As for the XZP2-300 model porcelain insulator, when the leakage electric charge achieves 20795C, the zinc cover loses the protective function, and the insulated steel foot iron base is corroded, leading to direct influence on the mechanical strength of the insulator;

3. The coating on the surface of the insulator porcelain ware with hydrophobic material plays certain role in delaying the corrosion on the steel foot of the insulator, but not significant enough;

4. The installation of the umbrella shape protective cover can effectively change the corrosion position and delay the corrosion rate by reducing the corrosion rate to 0.6 times of that of the original rate.

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