IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received March 6, 2021, accepted March 21, 2021, date of publication March 24, 2021, date of current version April 7, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3068464

Failure Analysis of "Lantern-Like" Composite Insulator Heating Defects and the Improved Dye Penetration Test Method

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This work was supported in part by the National Natural Science Foundation of China under Grant 51707020, and in part by the Science and Technology Project of Electric Power Research Institute of China Southern Power Grid Company under Grant 066600KK52190015 and Grant 150000202003010lJC00074.

ABSTRACT In 2019, 27 new 500 kV AC composite insulators showed a severe heating, different from the traditional heating failure reported in recent years, the heating area isn't limited in the high voltage side and 3-5 discontinuous heating area appears in the middle part. It was named "Lantern-like" heating failure according to the shape of the heating area. With the withstand voltage test, absorption test, X ray micro-CT test and SEM analysis, The 3D structural imaging of the through channels in the rod has been achieved, which would change the electric field distribution significantly. Short internal through channels will change the electrical field distribution and provide the energy to the abnormally heating. To detect these potential channels which should be responsible for the abnormally heating in the rod, the test time of dye penetration test has been extended from 15 minutes to 2 hours, and the improved test methods can find the through channels easily but won't alert for the normal ones.

INDEX TERMS Composite insulators, abnormally heating, 3D structural imaging, dye penetration test, water immerge.

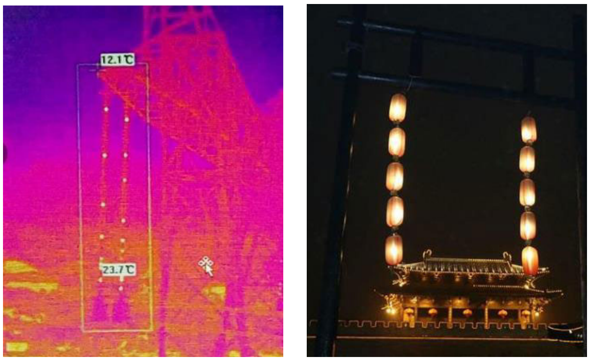
I. INTRODUCTION

Composite insulators are increasingly used in the transmission lines, especially the DC transmission grids, due to its light weight and excellent anti-pollution performance [1]–[3]. In China, the number of composite insulators has approached that of traditional ceramic or glass insulators, and they are becoming the key out-door insulation equipment for transmission projects. With the continuous improvement of composite insulator, there have been few reports on composite insulator failures such as brittle fracture [4]–[6], Composite insulators have maintained a low failure rate worldwide.

In recent years, the composite insulators in China have repeatedly experienced abnormal heating, which has attracted the attention of many scholars [7]–[9]. It was generally believed that, the polarization effect of moisture or pollution should take responsibility for the abnormal heating in area with a high humidity [10]. Take the heating failure in South China in 2011 as an example [10], 513 out of the 1327 composite insulators (in one transmission lines) can't meet the infrared (IR) measurement requirements. For most insulators which only heated under high humidity, Water polarization was believed to be the cause of abnormal heating according to the results of withstand voltage test and chemical analysis. For the few remaining insulators that also heated at lower humidity, the reason of heating still needs to be studied, however, the existing evidence suggested that the defect of rods is the key cause of heating [5], [8], [11].

In 2019, an abnormal heating failure of composite insulators occurred in southern China. Based on the current research results, it can be concluded that this abnormal heating failure was caused by water polarization. After replacing new insulators, it was surprising that the failure has not been eliminated and the new composite insulators had a severe heating in both high voltage (HV) side and the middle part. Due to the following three reasons, these new failure samples are of great research value: (1) the heating location is not limited to the HV side, and the IR images are obviously different from

The associate editor coordinating the review of this manuscript and approving it for publication was Guillaume Parent.



(a) (b)

FIGURE 1. **The IR results onsite of the "Lantern-like" heating failure (a) and the picture of lantern (b).**

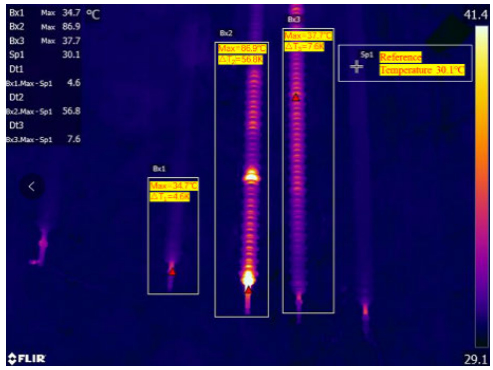
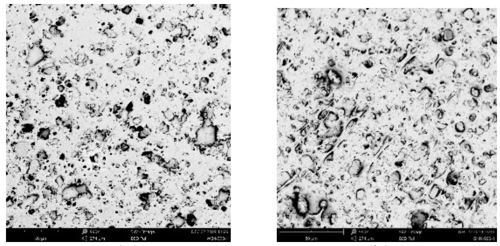


FIGURE 2. **The IR results of the withstand test in the high humidity environment.**



(a) (b)

FIGURE 3. **SEM test results of the silicone rubber: (a) heating insulators (b) reference insulators.**

that of other failure composite insulators in the past 10 years. (2) The failure insulators have passed the factory inspection and could meet the current standard for composite insulators. (3) The failure insulators were new and the aging process can be ignored. And the aging was usually a factor which was hard to be excluded in past studies.

In this article, firstly, the cause of abnormal heating was studied by withstand voltage test, dissection test and micro-structure test. Secondly, 3D image of internal defects in the rods was obtained by X-ray micro–Computed Tomography (micro-CT) technology. And based on the simulation results, the cause of abnormal heating has been further proved. Finally, according to the cause of heating, an improved dye penetration test method was proposed to detect such kind of defects in the rods.

II. BACKGROUND AND WITHSTAND VOLTAGE TESTS

In 2019, 27 new 500 kV AC composite insulators showed a severe heating. 3 failure insulators (Sample 1#, 2#, 3#) have been sent to National Engineering Laboratory of Ultra High Voltage (Kunming, China) to explore the cause of abnormally heat. The failure was repeated with the AC withstand voltage test under 318 kV, which equals to the 1.1 times of the operation voltage. The performance of these 3 insulators in the withstand voltage test is quite different from other heating insulators found in recent years [7], [10], [12]:

(1) The heating insulators are new and aging factors can be completely eliminated.

(2) The maximum temperature rise can exceed 60°C.

(3) The heating area is no longer limited to the HV end, and the middle part which has a low electrical field also show an obvious heating($>$ 10°).

(4) The heating problems still exist in a low humidity environment.

Fig.1 shows the on-site heating image of these insulators, as we can see from these pictures, the heating area is discontinuous and covers both the HV end, ground end and middles part. Since the heating area looked like the lantern, This failure is called "lantern-like" heating to distinguish it from traditional heating failure.

The results of withstand voltage test are shown in Table 1. The ambient temperature was about 30 °C. An insulator with a traditional heating (4#) and a normal one (5#) which operated for 5 years has also been taken as control groups. The withstand voltage test includes that: (1) AC test under high humidity (see Fig 2). The test voltage (Vrms) was 318 kV, and the relative humidity (RH) in the high voltage test hall exceeded 90% (The RH value was adjusted using sprayer). (2) AC test under low humidity. The test voltage (Vrms) remained 318 kV, and the insulators have been exposed to the sunlight for 72 hours before test. The test RH was 46±2%○.

The results show that: (1) The "lantern-like" heating failure could be repeated in the lab, 2 discontinuous heating area in the middle part were observed during the AC withstand test. and the maximum temperature rise in the lab was similar with that in the field (see Table 1) (2) different from the sample (4#) with traditional heating failures, the "lantern-like" samples (1#, 2#, 3#) heated under high and low humidity environment, which indicated that the water polarization in the rubber sheath was no longer the main cause of the heating [13].

III. FAILURE CAUSE ANALYSIS

A. ABSORPTION PROPERTY OF SILICONE RUBBER MATERIAL

Water polarization process was responsible for the traditional heating failure in high humidity area in recent years. To exclude the influencing of water in the sheath, the water absorption property of samples (1-3#, 5# as a control group) have been tested.

Firstly, internal micro-structure of silicone rubber (Fig 3a) has been observed with scanning electron microscope (SEM) method. Compare with an insulator which operate for 5 years but not heat (5#, Fig 3b), It could be found that the internal

TABLE 1. The temperature rise on site and in the withstand test.

Sample No.	Temperature rise（℃）	Temperature rise（℃）	Temperature rise（℃）
	On site	High RH>90%	Low RH=46%
1#	61	56.8	61
2#	9.7	7.6	7.4
3#	15.9	17.1	14.4
4#	7.2	4.6	0.8
5#	0.4	0.5	0.3

1#-3#: "Lantern-like" heating insulators, 4#: Traditional heating insulator, 5 #:Normal insulator (Operation for 5 years)

structure was similar in porosity which means the deficient samples had the same free volume inside with the well-behaved ones.

Then the water absorption test was conducted on the silicone rubber maters from all the 4 samples. The test setup is shown in Fig 4. 3 small rubber samples was cut from the insulators and put them into a sealed chamber with deionized water remaining in the bottom. And the samples have been placed on a shelf to avoid the directly contacting with the water [14]. The relative humidity value inside could reach 100% due to the well-sealed of the chamber. Before the test, the samples were dried under 60°C until the weight of samples won't decrease, and the initial weight has been recorded as m_0. During the test, the samples were weighed regularly, and $m(t)$ means the average of the weight of 3 samples at time point t. Then the water absorption $w(t)$ could be simply calculated with Equation (1):

$$w(t) = \frac{m(t) - m_0}{m_0} \times 100\% \tag{1}$$

For the absorption of samples would not change after 196 hours, the $w(196)$ was considered to be saturated water absorption (w_s). The results (Table 2) of absorption test showed that (1) The absorption of surficial rubber from the heating samples (1-3#) ranged from 0.36%-0.52%, while the absorption of sample 5 # was 0.76%, which was much higher than that of heating samples. Considering that the on-site temperature rises of sample 5 # was only 0.4 °C, the water polarization can't be the main cause of the abnormally heating occurred on sample 1-3#. (2) The absorption of surficial material was higher than internal material, this is because the aging process mainly affects the surface layer of the material. And this can also be proved by comparing the results between sample 1-3# with sample 5#. The samples with longer operating years (5 years) had a greater absorption than new samples.

In general, the "lantern-like" heating failure is totally different from the traditional abnormally heating, and water polarization in the silicone rubber is not the main cause of the failure.

B. DISSECTION TEST

All the end fitting of heating samples (1-4#) were dissected and the results showed that (Fig.5): Comparing with the

TABLE 2. Absorption test results for silicone rubber from insulators.

Sample No.	Absorption（%, surficial material）	Absorption（%, inner material）
1#	0.400	0.32
2#	0.52	0.38
3#	0.36	0.26
5# (refrence)	0.76	0.30

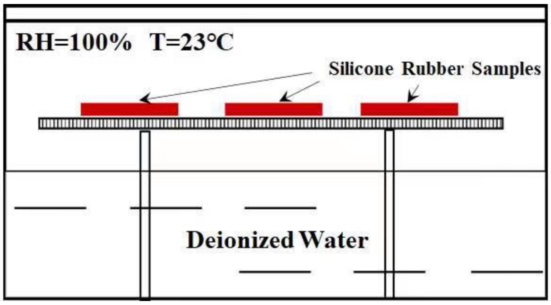


FIGURE 4. Test setup for the absorption test.

traditional heating sample 4#, the corrosion in fitting of sample 1-3# was not serious. Only a slightly corrosion had been found at the top of the ending. The dissection test results has also proved the conclusion that the water intrusion in the ending won't result in the "lantern-like" heating. In addition, the heating area of sample 1-3# covered the middle part of the insulators where the electrical field was quite low, there should be another channel for the water transporting from the HV ending to the middle part.

C. MICRO-STRUCTURE ANALYSIS FOR RODS

To investigate the microstructure of the rod and find the potential water transporting channel, a new method for the rod based on the computed tomography scan has been proposed [15]–[17]. Comparing with the traditional detecting method for rod (e.g., SEM), the new method could perform a 3D imaging of the possible internal channel. The accuracy can reach 2 μ m and the equipment type used for detection is NanoVoxel-4000.

3D imaging results have been shown in Fig.6, the blue part represent the air while the grey part represent the epoxy resin and glass fiber. Comparing with the results (Fig.6b) of traditional heating sample, there were more air gaps (Fig.6a) in the rods of "lantern-like" heating insulator (2#). The porosity of sample 2# (which equals 0.77%) was significantly higher than that of sample 4# (0.23%). Meanwhile a channel composed of many short air gap has been found in the middle of sample 2# (see Fig 6a),the diameter of the through hole is 350 μm.

When there was a through channel existed in the rods, even if a slightly water intrusion at the end fitting (it can be proved by the dissection results of end fitting) will change the electric filed distribution and cause a serious heating [[18]–[20]]. To explain the impacts of the through channel on the electrical field distribution, a 3D insulator-tower-line model has been built (Fig.7a), the length of the insulators was

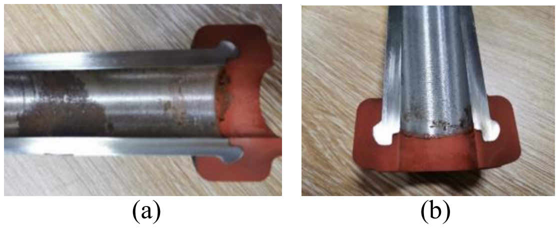


FIGURE 5. Dissection test results of the end fittings: (a) Seriously erosion, (b) Slightly erosion.

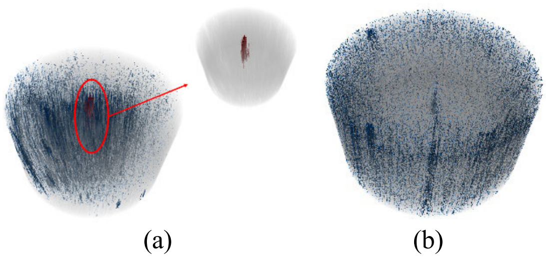


FIGURE 6. 3D images of the air gap and the through channels in the rods, obtained by the X-ray micro-CT method: (a) A through channel in rod of "Lantern-like" heating composite insulator (b) Air gaps in the rod of traditional heating insulators.

4450mm which equals the real 500kV composite insulators, the pipe diameter and the ring diameter of grading ring were 50mm and 400 mm respectively. According to the micro CT scan results, a water channel (diameter = 350 μm, length = 2100 mm) had been placed in the middle of the rod. The umbrella has been ignored in our model and only the sheath has been considered.

The electrical field distribution of the insulator model was calculated with the FEM simulation software. In the solving process, the boundary of tower, low voltage end fitting and grading ring was set to earthed; the boundary of line and low voltage end fitting and grading ring was set to constant potential 318kV, which is the 1.1 times of the operating voltage. The subdomain of the water channel was set as suspended potential, which means the potential of these mesh elements is always the same. The dielectric constant of the sheath and rod was set as 3.5 and 5 respectively. The height of the tower is 30m and the whole model was set in an air region with volume equal to a cube 100m on each side.

If there was no channel in the rod, the electrical field distribution won't change a lot in the high humidity. According to our test results, the relative dielectric constant of silicone rubber would increase from 3.5 to 4.26 after immerging in the water for 72 hours, while the maximum electrical field only decreased 4.7% (from 6.49kV/cm to 6.19kV/cm, see the red and black lines in Fig 7b).

But if there was a water channel inside, the maximum electrical field would significantly increase to 33.06 kV/cm (see the blue lines in Fig. 7(b)), and the location of the maximum electrical field shifted from the HV end to the middle.

In the simulation model, the most extreme case was considered that the through channel was continuous from HV side to the middle part. But in real situation, the channel could be shorter and discontinuous which resulted in more electrical field peaks along the insulators and lead to separately heating

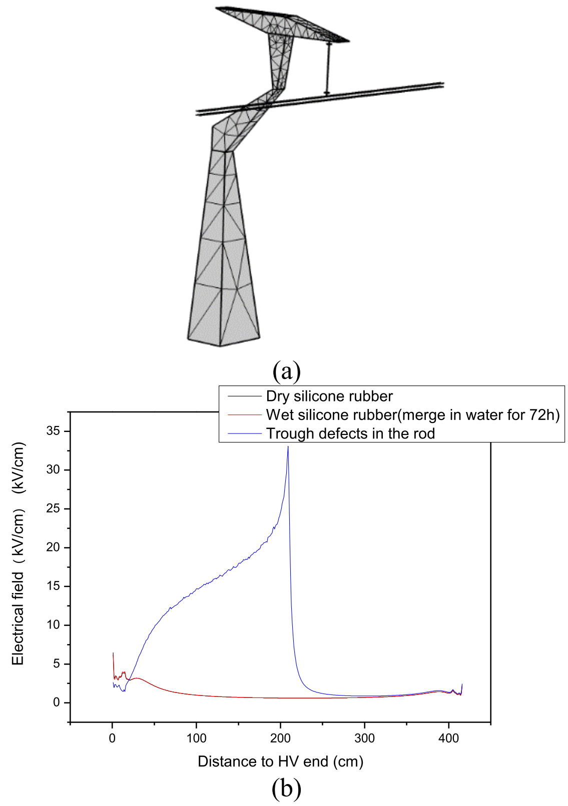


FIGURE 7. 3D models and simulation results of the electrical field distribution: (a) 3D tower-line-insulators models (b) Electrical field distribution on the surface of insulators.

part. In Fig 8, 4 shorter channels (channel 1 = 355mm, channel 2-4 = 400mm) has been placed in the rod to replace the previous long channel. The maximum electric field has decreased to 24.3kV/cm (see Fig. 8), but more peaks could be found in the electrical field distribution which lead to the discontinuous heating area.

According to the results of withstand voltage test, micro-structure test and simulation test, the process of the "Lantern-like" heating failure could be obtained: The moisture could invade the end fitting during the long-term operation and cause the erosion to the end fitting (Fig 5b). If there were through channels in the rod (Fig 6a), the water will diffuse due to the capillary action and change the electrical field distribution significantly (Fig.7, Fig.8). It's well known that the polarization power is proportional to the square of the electric field strength, the increase of the electrical field will subsequently cause the abnormally heating in the corresponding area. In addition, considering that the unit in thermal conducting equations is Kelvin (K), the polarization power of 1# is only 1.17 times of that in 2# insulators(assuming that the ambient temperature is 20°C), which means there is a smaller difference in electrical field (only 1.08 times), it's difficult to distinguished the "Lantern-like" heating from other heating failure simply by temperature rise.

IV. EXTENDED DYE PENETRATION TEST METHOD

Dye penetration test is a method to check the performance of rod material against the water which has been recommended

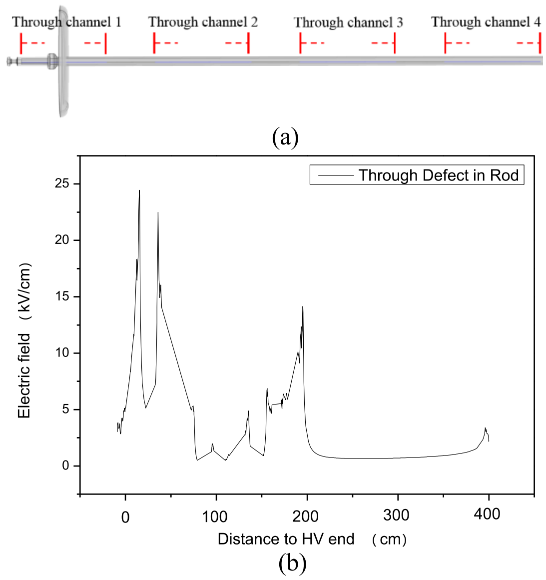


FIGURE 8. **The models and results of electrical field distribution of the insulators with 4 separate channels inside: (a) The size and the location of the 4 short channels in the models (b) The electrical field distribution of the insulators with 4 separate channels.**

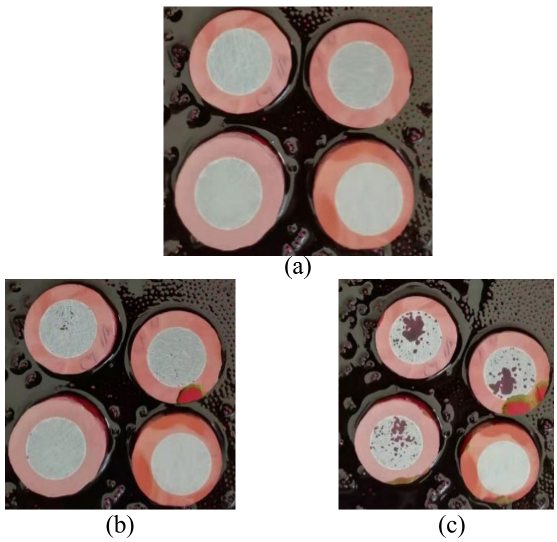


FIGURE 9. **The top face conditions of samples in dye penetration test: (a) 15min (recommended in current standards) (b) 1 h (c) 2 h.**

by IEC 62217 [21]. Unfortunately, these new insulators suffered a serious heating failure (temperature rise > 60°C) at the very beginning even they have meet the requirement of current standard. In this section an extended penetration test had been proposed to detect the "Lantern-like" insulators.

According to the IEC 62217, insulators (1-3#, 4# as control group) had been cut into four 10 mm samples and placed in a plate on a layer of glass balls. The top face conditions of samples in dye penetration test were shown in Fig. 9a. Within the first 15 minutes (existing test method recommended in standards), no dye rises through the whole specimens which means they have passed the current dye penetration test. But according to our micro-CT test and withstand voltage test, there should be a through channel in the rods. And dye spots started to appear after 1 hour on specimens from sample 1# and 2#, and the sheath began to change color due to the penetration process in the silicone rubber. (Fig.9b). For two-hour penetration test, more dye spots have been found on the top surface of the samples (see fig 9c), however, still no dye spots can be found in sample 4# (the traditional heating insulator).The dye penetration test has been repeated 4 times by different samples from the same set of insulators (1-4#), and the results is similar with that in Fig 9.

Extended dye penetration test seems more sensitive to the micro through channels in the rods which can be seen by micro-CT method, and if there was no channels in the rod, for instance sample 4#, it can also pass the two-hour penetration test. But the test time can't exceed 2 hours for the dye would go through the silicone rubber and reach the top surface of the specimens. The Lantern-like heating insulators can be detected by the extended 2 hours dye penetration test.

V. CONCLUSION

•In this manuscript, a new type of heating failure on composite insulators from Southern China is reported. Different from the traditional heating failure, this heating failure has a higher temperature rise, and a discontinuous heating area covering both HV end and middle part. It is called "Lantern-like" heating failure according to the shape of heating area.

•The "Lantern-like" heating insulators would heat in a relative low humidity environment. And its absorption and porosity of silicone rubber sheath were not inferior to well-behaved insulators, which demonstrated that the polarization of water in silicone rubber was not the main cause for the new type of failure.

•To observe the 3D structure of the potential micro channels in the rod, we developed a new detect method based on the micro CT technology. More micron-size air gap and through channels had been found in the rod of "Lantern-like" heating insulators. And the through channel affected the electric field distribution significantly, and brought high discontinuous high field stress area to the middle part of the insulators which leads to the "Lantern-like" heating.

•With the extended 2 hours penetration test, defects existed in rods of the "Lantern-like" heating insulators could be detected.

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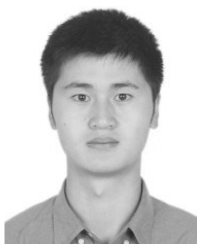

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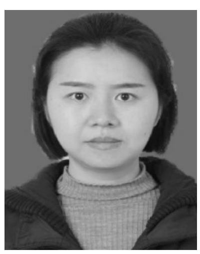

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