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A New Evaluation Method of Aging Properties for Silicon Rubber Material Based on Microscopic Images

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ABSTRACT In recent years, composite insulators have been widely applied in transmission lines; however, deterioration of insulation properties caused by aging may cause power supply's large-scale outage and badly impact the social economy development. Therefore, in this paper, an entirely new method for evaluating aging properties of silicon rubber for composite insulators based on microscopic images was proposed. The microscopic images were collected by portable digital microscope-B011, and defective area proportion (k) was extracted by calculating and comparing the defective area pixel with the background pixel. Thus, the salt fog flashover experiments were conducted in a multifunction artificial climate chamber to indicate aging properties of silicon rubber material; then, the equations for calculating silicone rubber flashover voltage (U_{50}) by k were established. The value of U_{50} can even decrease by 57.3% with the increase in the value of *k*. Moreover, a complete aging evaluation procedure of silicone rubber composite insulators was obtained. Taking a city as an example, the critical failure *k* ($k1 = 19.6$) value of composite insulators in the area was obtained. Finally, the future research directions of this paper were clarified; besides, future usage scenarios of this paper were clearly displayed.

INDEX TERMS Evaluation method, aging properties, silicon rubber composite insulators, microscopic images, non-contact detection.

I. INTRODUCTION

Composite insulators have been widely applied in transmission lines for their anti-pollution property, light weight and sufficient mechanical strength [1]–[4]. However, after long-term exposure of composite insulators in complex environments, electrical, mechanical and chemical failures of the silicon rubber based HV composite insulators have been occurring contingently in different parts of the world [5]–[7]. It will cause power supply's large-scale outage, and badly impact the social economy development. The primary cause of bad influence is aging of silicone rubber materials. As a result, plenty of researches [8]–[22] have been done through simulation, natural and artificial test to reveal aging properties of silicone rubber insulators as well as influencing factors of it.

Nowadays, many methods have been proposed to detect the aging properties of silicone rubber insulators. Surface roughness tests [8], scanning electron microscopy (SEM) [9], hydrophobicity tests [10] and electrical test [11], [12] such as salt fog flashover test, leakage current test and thermally stimulated current(TSC) test are used to test the physical performance of the silicone rubber material. Fourier Transform Infra-Red (FTIR) test [13] is mainly used to study changes in the main groups within composite insulators. FTIR test can reflect the aging state of the material from the angle of the microcosmic composition changes as a chemical measuring method.

Aging influencing factors of silicone rubber insulators has been widely concerned, therefore many researchers have studied the aging influencing factors through simulation and experiment [14]–[18]. FTIR, energy dispersive X-ray (EDX), X-ray diffraction (XRD), and surface roughness test were carried out in literature [14], then the results that the aging of composite insulators along the line is gicaused by the arc discharge of dry-banded surface were proved. The related test and the electric-field simulation were studied in literature [15], the research found that the long-time corona discharges would result in serious degradation of composite insulators. Study in [16] showed that the heat and ozone produced by the discharge are the causes of hydrolysis, pyrolysis, crosslinking, oxidation, and condensation on the silicone rubber surface. Hydrophilic silanol was produced on the silicone rubber surface, then the symmetrical structure of the methyl was destroyed, and oxygen content was increased, which could decrease the hydrophobicity of silicone rubber.

Besides, researchers [17], [18] found that the higher the corona voltage is and the longer the corona action is, the higher the density of trap charge is and the deeper the trap level is.

What's more, salt contamination can also cause more corona discharge, corona arcing, as well as a loss of hydrophobicity, which results in silicone rubber material damage [19], [20]. In literature [21] an entirely new and highly transformative model of silicone rubber aging caused by aqueous salt was suggested, they have also shown that the aqueous salt solutions environments are highly damaging to the silicone rubber polymer network. Besides, it [22] was found that the long-term field exposure yielded weaker insulator deterioration than the salt fog chamber aging which shows that salt fog in coastal environments is an identified cause of damage to silicone rubber materials.

From the foregoing contents, it is generally accepted that the aging problem of silicone rubber composite insulators is a worldwide problem. Although many methods have been adopted to detect the aging properties of silicone rubber insulators, these methods are almost based on contact measurement methods, and the equipment is relatively expensive. These methods need to take composite insulators off the transmission line for measurement, which is a very time-consuming work. Therefore, this paper proposed a non-contact method for evaluating insulation properties of silicon rubber for composite insulators based on digital microscope, where insulation properties were represented by the salt fog flashover voltage. It is found that this non-contact method can be used to evaluate insulation performance very well. The research in this paper is of great significance to the transmission lines routing inspection and the evaluation of silicon rubber insulation properties.

II. MICROSCOPIC IMAGES CHARACRERISTICS OF AGED SILICONE RUBBER MARERIAL SAMPLE

In this section, methods of microscopic images collection and defective area extraction of silicon rubber samples were expounded. The microscopic images were collected by digital microscope-B011 and defective area is extracted by Matlab in this paper.

A. AGED SILICONE RUBBER MATERIAL SAMPLES

The samples were silicone rubber sheets cut from the typical suspension composite insulators arranged in different operating transmission lines in China. The service time of composite insulators is 1-22 years. The length and width of silicone rubber sheet cut from composite insulators are 400 mm and 300 mm respectively. In order not to destroy the state of the surface, the surface of the rubber sheet should not be touched when cutting.

B. MICROSCOPIC IMAGES COLLECTION OF AGED SILICONE RUBBER MATERAIL SURFACE

The microscopic images were collected by digital microscope-B011 as is shown in Fig. 1. Then, the surface of the samples were magnified by 10, 100, 1000 and 2000 times respectively. It is found that the cracks and depressions on the insulator surface caused by aging can be clearly seen in the magnified images by 1000 and 2000 times. The acquisition distance of magnified 2000-fold pictures is closer, about 1.5-2.0mm, the clarity is not as good as that of magnified 1000-fold pictures, and the acquisition area is small, so the method of magnifying 1000-fold was taken to collect pictures, and some of the collected pictures are shown in the Fig. 2. In this study, 80 samples were collected. The surface defect of specimens is mainly divided into two types, namely, cracks and dents.

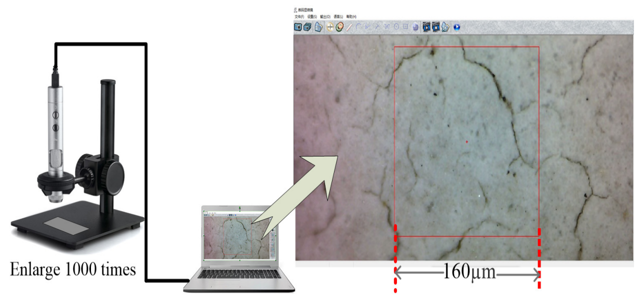

FIGURE 1. Digital microscope and microscopic images.

As is known to all, the reason for better performance of the composite insulators is the hydrophobicity on the surface of its synthetical material and the hydrophobicity transfer. The aging of composite materials will greatly reduce the performance of the material. From the figure, it can be seen that there are different kinds of surface defect and different defective areas on different silicon rubber surfaces. Speculating that the aging degree of silicone rubber is related to the degree of surface defect, the defective area of materials will try to be quantified.

C. MICROSCOPIC IMAGES ANALYSIS OF AGED SILICONE RUBBER MATERIAL SURFACE

In this paper, the defective area is extracted by Matlab. The way of Matlab processing an image is to operate the RGB value of each image pixel. By calculating and comparing the defective area pixel with the background pixel, the effective defective area can be easily extracted. The processing flowchart is shown in Fig. 3.

As shown in Fig. 3, firstly color images obtained from digital microscope are composed of 3-channel pixels. Each of these channels corresponds to the intensity value of one

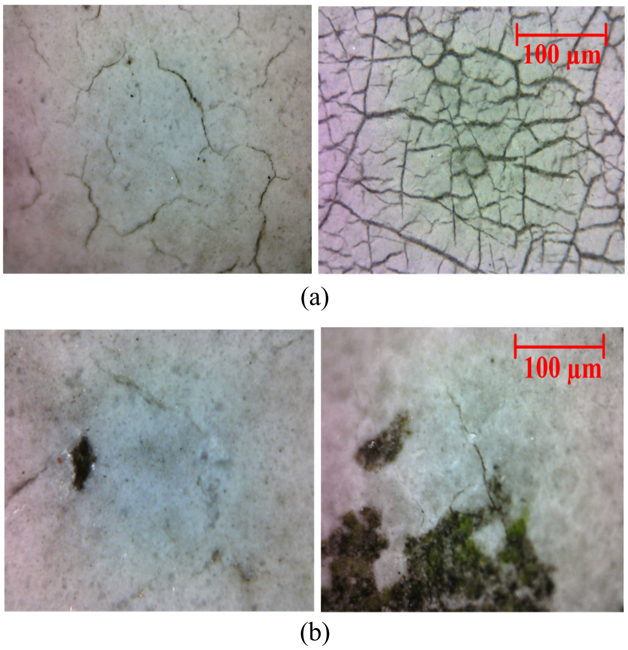

FIGURE 2. Microscopic images. (a) Silicon rubber surface with cracks. (b) Silicon rubber surface with dents.

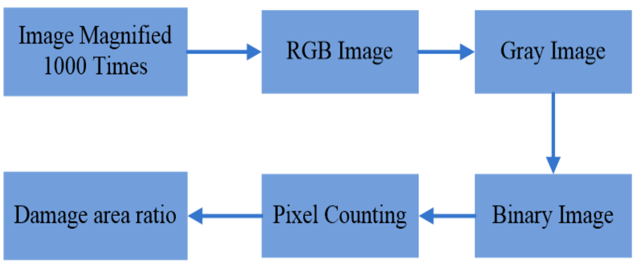

FIGURE 3. Flow chart of image processing.

of the three primary colors (Red, Green, and Blue). Then the color images are transformed into gray images. It is necessary to adjust the contrast of the gray images in order to make the spots brighter than background pixels. After adjusting the contrast, the threshold segmentation algorithm is used to convert the gray image to binary images. After the binary images are gained, the defective area pixels and all the pixels of binary images will be calculated, and then the area proportion of the defective part will be obtained.

The detailed key steps of image processing are as follows:

(a) Converting of image type

The silicon rubber surface images are JPG format RGB color pictures. In the image processing tool box of Matlab, four image types (RGB, indexed, gray and binary image) are supported. Of all the image types above, RGB, gray and binary images are used in this paper.

RGB image is presented as an M×N×3 matrix in Matlab and it is read by the function imread in image processing tool box. Every pixel in RGB images have three channels, representing intensities in ranges of wavelengths corresponding

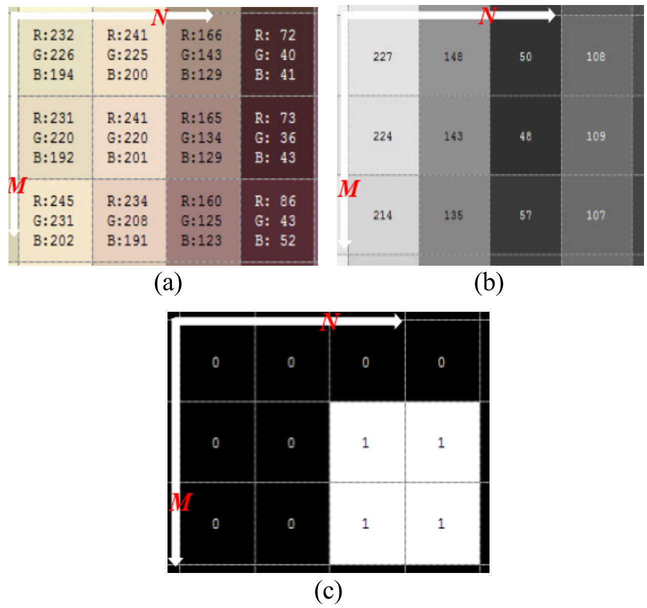

FIGURE 4. Data structure of different image types. (a) RGB. (b) Gray. (c) Binary.

to red, green and blue. The data structure of RGB image is shown in Fig. 4(a).

Gray image is a matrix with size of M×N as is showed in Fig. 4(b). Every block in the figure is the pixel of gray image that enlarged many times. Every value center marked in the pixel represents the brightness of every pixel and the value range between 0 and 255.

Binary image is also an M×N matrix but only with the value logical 0 and logical 1. Value 0 is black and value 1 is white, as shown in Fig. 4(c).

(b) Contrast adjusting

In this paper, the contrast of gray image is adjusted in order to make the bright spot more identifiable from the background. The calculation expression is in Eq. (1).

$$g(x, y) = \frac{\max - \min}{f_{\max} - f_{\min}}[f(x, y) - f_{\min}] \quad (1)$$

where, I is the original image matrix, J is the output matrix, low_in and high_in means the dynamic range in the source image, low_out and high_out means the target dynamic range in output image.

(c) defective area proportion calculating

The binary image is finally used to count the defective area proportion of silicon rubber surface. The whole image is composed of value 0 and 1, the defective area is black with the value 0, and the background is completely white with the value 1. In this paper, the defective area is defined as the number of white pixels with value 1. Because the binary image is essentially M×N matrix whose elements is 0 or 1 alternatively, it is easy to use function sum to count the defective area. Then, defective area proportion can be calculated in Eq. (2).

$$k = \frac{N_{black-pixel}}{N_{black-pixel} + N_{white-pixel}} \tag{2}$$

where, K is the defective area proportion, $N_{black-pixel}$ is the number of defective area pixels, $N_{white-pixel}$ is the number of background pixels.

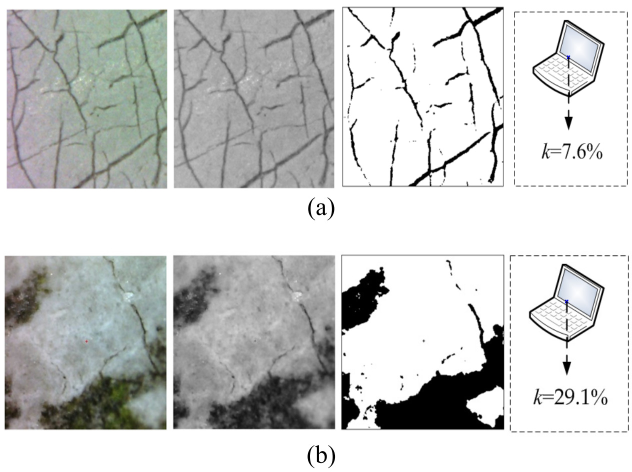

FIGURE 5. Example of defective area quantification. (a) Silicon rubber surface with cracks. (b) Silicon rubber surface with dents.

Fig. 5 is the example of image processing using the methods mentioned above. The threshold of binarization is obtained by the function graythresh of Matlab system. Defective area proportion of a and b are 7.6% and 29.1% respectively. Four points of each sample were taken for photographic acquisition, and then the k values of four points were averaged.

III. RELATIONSHIP BETWEEN ELECTRIC PERFORMANCE AND *k* OF AGED SILICONE RUBBER SAMPLES

A. EXPERIMENTAL SETUP

The methods for evaluating the aging properties of silicone rubber materials has described in introduction. As mentioned above, salt fog in coastal environments is an identified cause of damage to silicone rubber materials, besides, silicone rubber insulators are particularly prone to flashover accidents in salt fog environment. In order to obtain the specific values of aging degree of silicone rubber materials related to electrical insulation performance, salt fog flashover method was selected to test the aging properties of the samples.

The salt fog flashover experiments were conducted in a multifunction artificial climate chamber which has a length of 3.8 m and a diameter of 2.0 m. The artificial tests on complex climate atmospheric environments can be carried out in the climate chamber, such as ice, rain, fog, and low barometric pressure. The test circuit is shown in Fig. 6. In the test circuit, T is the YDJ-5/50 ac testing transformer, R0 is a current limiting resistor, C1 and C2 are the capacitors of the capacitor divider D, H is a wall bushing, r (1Ω) is a current sampling resistor, G is a protective discharge tube,

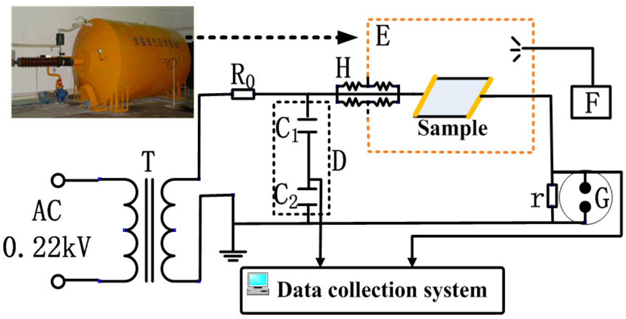

FIGURE 6. Schematic diagram of the ac test circuit.

E represents the artificial climate chamber, F is an ultrasonic water fog generator (YC-G030T). The power supply meets the requirement of the artificial pollution test [23].

B. TEST PROCEDURE

1) PREPARATION

In order to simulate the real scene, it is not necessary to clean the samples (79 specimens were used in total), just put it between the electrodes made of copper foil and wire according to the experimental flow chart. 500μS/cm Nacl solution (After correction to 20°C) is configured and placed in a beaker. Note: The purpose of this paper is to explore whether the electrical properties of silicone rubber materials are related to their surface defect. Therefore, only 500μS/cm salt fog is selected as an example to test.

2) WETTING AND FLASHOVER TEST

When the sample was ready, the ultrasonic water fog generator was activated to simulate the natural salt fog. The flashover test was conducted simultaneously when the surface of samples were fully wetted to prevent water on the skirt of silicone rubber sheet from dropping into ground.

During the tests, the up and down method was adopted [23], which mean that at least 15"valid" tests were carried out on the same defective sample (taken from the similar position of silicone rubber insulators). The flashover voltages changed based on the up and down method. And the voltage step was set at about 5% of expected U_{50}. U_{50} was calculated by the individual test and the following 14 individual tests. The U_{50} and relative standard deviation error (σ) were calculated by the equation as follows:

$$U_{50} = \frac{\sum(U_{\rm i} n_{\rm i})}{N} \tag{3}$$

$$\sigma = \sqrt{(\sum_{\rm i=1}^{N}(U_{\rm i} - U_{50})^2)/(N-1)}/U_{50} \times 100\% \tag{4}$$

where $U_{\rm i}$ is an applied voltage, $n_{\rm i}$ is the number of tests which were carried out at the applied voltage $U_{\rm i}$, and N is the number of the number of the whole "valid" tests. U_{50} tested following above procedure and k calculated following methods in section 2 are shown in table 1 and 2, where U_{50C}

TABLE 1. U_{50} and *k* (cracks area proportion).

No.	1	2	3	4	5	6	7	8	9	10
k	0.4	0.4	0.6	0.6	0.6	1.2	3.4	4.2	4.5	4.5
U_{50C}(kV)	8.31	8.43	8.35	8.2	8.21	8.12	7.21	6.75	6.83	6.74
No.	11	12	13	14	15	16	17	18	19	20
k	4.6	5.7	7.5	7.6	7.6	8.6	9.3	9.3	9.8	12.5
U_{50C}(kV)	6.7	6.56	5.61	5.6	5.48	5.45	5.4	5.35	5.3	4.91
No.	21	22	23	24	25	26	27	28	29	30
k	12.5	12.9	12.9	14.2	14.3	14.6	14.6	14.8	18.1	18.1
U_{50C}(kV)	4.85	4.74	4.85	4.71	4.72	4.69	4.65	4.5	4.12	4.09
No.	31	32	33	34	35	36	37	38	39	40
k	18.2	18.2	18.5	18.5	18.9	18.9	19.3	19.6	19.6	21.5
U_{50C}(kV)	4.05	4.08	4.07	4.1	4.11	4.06	4.04	3.99	3.95	3.89
No.	41	42	43	44	45	45				
k	23.5	27.5	27.6	28.1	28.5	28.5				
U_{50C}(kV)	3.88	3.75	3.72	3.59	3.68	3.55				

TABLE 2. U_{50} and *k* (dents area proportion).

No.	1	2	3	4	5	6	7	8	9	10
k	0.2	0.2	0.3	0.4	0.6	1.8	2.9	3.1	3.6	4.5
U_{50D}(kV)	10.35	10.45	10.17	10.7	10.3	10.4	10.21	10.02	9.95	9.83
No.	11	12	13	14	15	16	17	18	19	20
k	4.9	5.1	5.2	5.6	5.6	5.8	5.9	6.8	7.5	7.5
U_{50D}(kV)	9.61	9.54	9.56	8.89	9.1	8.75	8.71	8.06	7.48	7.45
No.	21	22	23	24	25	26	27	28	29	30
k	7.6	7.8	8.5	10.1	11.5	12.1	14.8	15.2	20.4	21.1
U_{50D}(kV)	7.48	7.46	7.12	6.5	6.31	6.18	6.1	6.11	5.81	5.69
No.	31	32	33	34						
k	25	25.3	28.8	32.5						
U_{50D}(kV)	5.75	5.64	5.59	5.61						

is U_{50} under cracks defect type condition, U_{50D} is U_{50} under dents defect type condition.

The following conclusions can be drawn from the above results:

(1) The surface defect area proportion of different silicone rubber specimens varies greatly. For cracks defect type, the *k* value ranges from 0.4 to 28.5. For dents defect type, *k* value ranges from 0.2 to 32.5.

(2) The defective area proportion has a great influence on the electrical characteristics of silicone rubber specimens. Whatever type the defect is, the flashover voltage decreases with the increase of the defective area proportion. For cracks defect type, the flashover voltage decreases by 57.3% when the *k* increases from 0.4% to 28.5%. For dents defect type, the flashover voltage decreases by 45.8% when the area increases from 0.2% to 32.5%.

(3) The flashover voltages of different defect types silicone rubber specimens vary greatly, for example, when k=0.4, U_{50C} is about 8.4kV, while U_{50C} is about 10.7 kV.

In order to establish the relationship between the electrical performance of silicone rubber and the proportion of defective area, Matlab was used to fit the above data, then the following fitting equations, as well as experimental and calculated results in Fig. 7 were obtained.

$$U_{50C} = 5.529 \times e^{-9.939k\%} + 3.343 \quad 0.4 \le k \le 28.5 \tag{5}$$

$$U_{50D} = \begin{cases} 10.4 & 0.2 \le k < 1.8 \\ 10.4 \times e^{(\frac{k-1.88}{9.939})^2} & 1.8 \le k < 7.6 \\ 15.93 \times e^{-29.04\%} + 5.698 & 7.6 \le k < 32.5 \end{cases} \tag{6}$$

As shown in Fig. 7, the calculated U_{50} are almost in agreement with the experimental U_{50}. But it is worth noting that the limit condition of cracks defect type is that *k* is between 0.4 and 28.5, thus, the limit condition of dents defect type is that *k* is between 0.2 and 30.5. Besides, for dents defect type, the fitting function is 3 piecewise function. When k is between 0.2 and 1.8, the U_{50D} is a constant, which means that when the dents defect area is small, it has little effect on U_{50}.

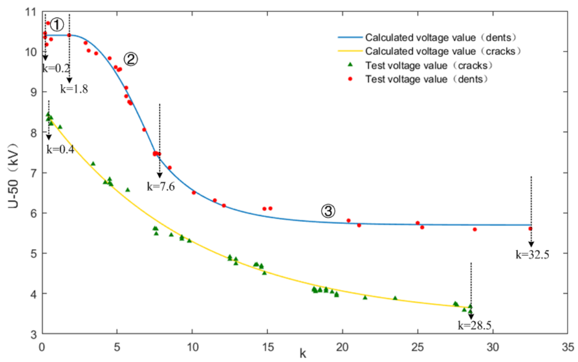

FIGURE 7. Experimental and calculated results.

IV. DISSCUSSION

A. EVALUATING PROCEDURE FOR AGED SILICON RUBBER MATERIAL

Based on above research, the following flow chart for evaluating aged silicon rubber properties by non-contact method can be obtained. In Fig. 8, E-U_{50C} means that calculating k of cracks defect silicon rubber, E-U_{50D} means that calculating k of dents defect silicon rubber. $k1$ and $k2$ are critical values of insulator failure.

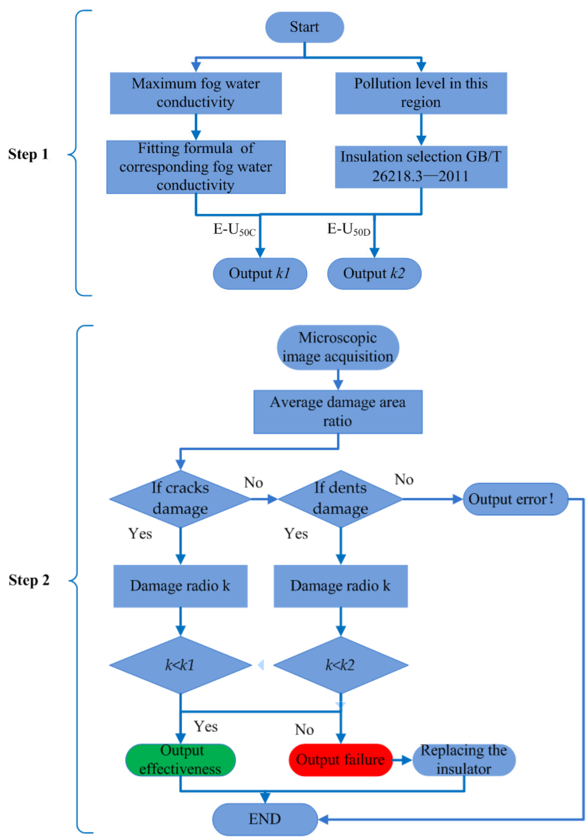

FIGURE 8. Procedure for evaluating insulation properties of silicon rubber.

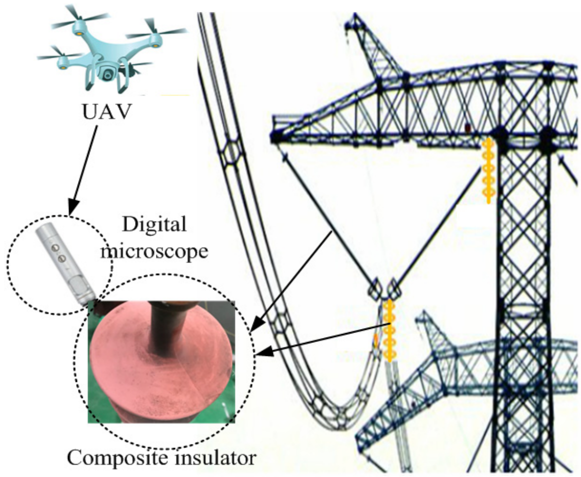

FIGURE 9. Future usage scenarios.

Next, an example based on this procedure will be briefly described. Firstly, to investigate the maximum fog water conductivity and pollution grade in a certain area. Then the fitting formula between the corresponding fog flashover voltage and the defective area proportion can be obtained according to the steps in Chapter 3. Besides, the reference uniform creepage ratios corresponding to pollution grades a, b, c, d and e are 22.0 mm/kV, 27.8 mm/kV, 34.7 mm/kV, 43.3 mm/kV and 53.7 mm/kV, respectively [24]. According to the fitting formula and insulation selection, the critical failure k value can be calculated. For instance, in a city in eastern China, the maximum fog water conductivity is 2235μS/cm and the pollution grade is a. According to the above method, it can be got that $k1 = 19.6$, while k 2 is larger than the maximum experimental value 32.5.

Secondly, the defective area proportion of silicon rubber surface can be obtained by following the above procedures. Take the above areas for example, when $k1$ is greater than 19.6, it means that the silicon rubber material has already failed due to aging, and the aged composite insulator needs to be replaced.

B. FUTURE RESEARCH DIRECTIONS

This paper presents a new method, but if it is to be used in transmission line inspection, further research is needed. Firstly, a complete composite insulator should be taken as the test sample for further study, and the relationship between the insulation characteristics of the complete insulator and the surface defect should also be explored. Secondly, field experiments should be carried out to try to use UAV to carry digital microscope and collect on-site microscopic images. Future usage scenarios are shown in the following figure.

V. CONCLUSION

This paper presents a new non-contact procedure for evaluating insulation properties of silicon rubber for composite insulators based on digital microscope, where insulation properties were represented by the salt fog flashover voltage. The microscopic images were collected by digital microscope-B011 and defective area was extracted by Matlab. The maximum values of k can reach 28.5 and 32.5, respectively. The salt fog flashover experiments were conducted in a multifunction artificial climate chamber, For cracks defect type, the flashover voltage decreases by 57.3% when the k increases from 0.4% to 28.5%. For dents defect type, the flashover voltage decreases by 45.8% when the area increases from 0.2% to 32.5%. Then the relationship between the electrical performance of silicone rubber and the proportion of defective area were established. In addition, a complete aging evaluation procedure of silicone rubber composite insulators was obtained. Taking a city as an example, the critical failure$k$ $(k1=19.6)$ value of composite insulators in the area was calculated. Finally, the future research directions of this study are clarified, besides, future usage scenarios of this study was clearly displayed. The method described in this paper is a new non-contact method based on micro-image, which provides great convenience for the evaluation of silicone rubber aging.

REFERENCES

[1] A. M. Madi, Y. He, and L. Jiang, "Design and testing of an improved profile for silicone rubber composite insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 5, pp. 2930–2936, Oct. 2017.

[2] G. Kone, C. Volat, H. Ezzaidi, and L. Duvillaret, "Experimental investigation of internal defect detection of a 69-kV composite insulator," in *Proc. IEEE Elect. Insul. Conf.*, Montreal, QC, Canada, Jun. 2016, pp. 206–263.

[3] Z. Zhang, X. Qiao, S. Yang, and X. Jiang, "Non-uniform distribution of contamination on composite insulators in HVDC transmission lines," *Appl. Sci.*, vol. 8, no. 10, p. 1962, 2018.

[4] Z. Zhang, X. Qiao, Y. Zhang, L. Tian, D. Zhang, and X. Jiang, "AC flashover performance of different shed configurations of composite insulators under fan-shaped non-uniform pollution," *High Voltage*, vol. 3, no. 3, pp. 199–206, 2018.

[5] M. Kumosa, H. S. Narayan, Q. Qiu, and A. Bansal, "Brittle fracture of non-ceramic suspension insulators with epoxy cone end-fittings," *Compos. Sci. Technol.*, vol. 57, no. 7, pp. 739–751, 1997.

[6] M. Kumosa and Q. Qiu, "Failure analysis of composite insulators (failure investigation of 500 kv non-ceramic insulators for pacific gas & Electric company)," Pacific Gas Electr. Company, San Francisco, CA, USA, Final Rep., 1996.

[7] M. Kumosa, L. Kumosa, and D. Armentrout, "Failure analyses of nonceramic insulators. Part 1: Brittle fracture characteristics," *IEEE Elect. Insul. Mag.*, vol. 21, no. 3, pp. 14–27, May 2005.

[8] A. Tzimas and S. M. Rowland, "Asymmetrical ageing of composite insulators: Effect on water dripping behaviour and electrical performance," in*Proc. IEEE Int. Symp. Elect. Insul.*, Jun. 2010, pp. 1–5.

[9] Y. Xiong, S. M. Rowland, J. Robertson, and R. J. Day, "Surface analysis of asymmetrically aged 400 kV silicone rubber composite insulators," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 15, no. 3, pp. 763–770, Jun. 2008.

[10] T. Sorqvist and A. E. Vlastos, "Performance and ageing of polymeric insulators," *IEEE Trans. Power Del.*, vol. 12, no. 4, pp. 1657–1665, Oct. 1997.

[11] H. Su, Z. Jia, Z. Guan, and L. Li, "Durability of RTV-coated insulators used in subtropical areas," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 3, pp. 767–774, Jun. 2011.

[12] Y. Tu, H. Zhang, Z. Xu, J. Chen, and C. Chen, "Influences of electric-field distribution along the string on the aging of composite insulators," *IEEE Trans. Power Del.*, vol. 28, no. 3, pp. 1865–1871, Jul. 2013.

[13] H. Zhang, Y. Tu, Y. Lu, Z. Xu, C. Chen, and L. Xie, "Study on aging characteristics of silicone rubber insulator sheds using FTIR," in *Proc. IEEE Int. Symp. Elect. Insul.*, Jun. 2012, pp. 83–86.

[14] R. S. Gorur, G. G. Karady, A. Jagota, M. Shah, and A. M. Yates, "Aging in silicone rubber used for outdoor insulation," *IEEE Trans. Power Del.*, vol. 7, no. 2, pp. 525–538, Apr. 1992.

[15] A. J. Phillips, D. J. Childs, and M. H. Schneider, "Aging of nonceramic insulators due to corona from water drops," *IEEE Trans. Power Del.*, vol. 14, no. 3, pp. 1081–1089, Jul. 1999.

[16] W.-X. Sima, Z.-Y. Liu, X.-L. Jiang, and Q. Yang, "Effects on surface performance of partial discharges due to discrete water droplets on the silicone rubber," *Chin. Soc. Elect. Eng.*, vol. 25, no. 6, pp. 113–118, 2005.

[17] G. F. Ying, "Research on the corona aging properties of silicone rubber material based on orthogonal test method," Ph.D. dissertation, Dept. Elect. Eng., North China Electr. Power Univ., Beijing, China, 2010.

[18] Y. Liang, "Study on the corona aging characteristics and mechanism of HTV silicone rubber," Ph.D. dissertation, Dept. Elect. Eng., North China Electr. Power Univ., Beijing, China, 2008.

[19] M. Bleszynski and M. Kumosa, "Silicone rubber RTV-1 aging in the presence of aqueous salt," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 2822–2829, Oct. 2016.

[20] B. Allen, M. Bleszynski, M. Kumosa, and E. Willis, "Investigation into the effects of environmental stresses on RTV-1 silicone-based caulk materials," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 5, pp. 2978–2986, Oct. 2015.

[21] M. Bleszynski and M. Kumosa, "Silicone rubber aging in electrolyzed aqueous salt environments," *Polym. Degradation Stability*, vol. 146, pp. 61–68, Dec. 2017.

[22] M. A. R. M. Fernando and S. M. Gubanski, "Ageing of silicone rubber insulators in coastal and inland tropical environment," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 2, pp. 326–333, Apr. 2010.

[23] J. Sun, G. Gao, L. Zhou, and G. Wu, "Pollution accumulation on rail insulator in high-speed aerosol," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 20, no. 3, pp. 731–738, Jun. 2013.

[24] *Selection and Size Determination of High Voltage Insulators Used under Contaminated Conditions Part 3: Composite Insulators for AC Systems*, Standard GB/T 26218.3-2011, China Standards Press, Beijing, China, 2011.

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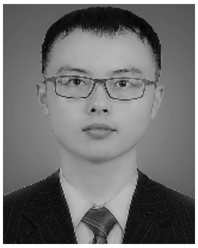

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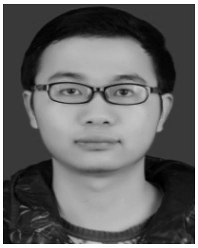

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