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Research on Image Recognition Method of Icicle Length and Bridging State on Power Insulators

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ABSTRACT Icicle will cause serious distortion of insulator electric field, weaken its voltage strength, and easily cause insulator flashover. Previous studies have shown that the longer the length of icicles on insulator, the greater the possibility of electric flashover. Then, it is of great theoretical significance and practical value to study the image identification technology of icicle length of iced insulators. Firstly, the growth mechanism and structural characteristics of insulator icicles are discussed in this paper, and the image acquisition method of iced insulator is discussed. Secondly, the methods of saliency detection and color feature analysis are used to extract the region of icicle and insulator sheds respectively, then, the icicle structure on insulator is obtained by the difference calculation of above two images. Meanwhile, the pixel curve of the iced insulator image is processed by Fourier transform, and the reference size of insulators icicle is obtained by calculating the length of the shed spacing. Finally, a practical case about iced insulators in substations is analyzed in detail, which proves the effectiveness of the method proposed in this paper.

INDEX TERMS Power insulators, icicle, insulator bridged, image recognition method, saliency detection.

I. INTRODUCTION

Icing is an important cause of power system operation failure. Serious icing accumulation will lead to structural faults and insulation problems such as tower collapse, wire breakage, fitting damage, insulation flashover, etc, causing large-scale and long-term power interruption, resulting in huge economic losses [1]–[4]. In 2008, a severe icing disaster broke out in southern China, causing the collapse of the power grid in vast areas, causing tens of billions of economic losses to the Southern Power Grid and the State Grid corporation of China. The icing growth mechanism and safety protection issues have also become an important research topic of the power field [5]–[7]. In addition to mechanical damage, as a special surface pollution, icing will lead to a sharp drop in the electrical performance of insulators, resulting in power system flashover accidents [8]–[10]. According to a survey report of the International Grid Conference, the flashover problems caused by icing and snow occur all over the world, regardless of the transmission line or power substation [11], [12], as shown in Fig.1.

In the case of severe glaze icing, the gap of the insulator sheds will be bridged by icicles, which can cause serious electric field distortion on the surface of insulators. Especially in the process of icing growth and melting, the surface of icicles and insulators is wet, and its conductive ions can migrate freely to form conductive paths, resulting in a significant weakening of the electrical strength of insulators. So icicle growth and melting state are more likely to cause flashover accidents of insulators, which has a great impact on the safe and stable operation of the power system [8], [13]–[17]. Reference [13]–[14] found that the corona discharge intensity at the tip of insulator icicle is mainly affected by the parameters of icicle length and the conductivity of the meltwater, and there may be more prone to ice melting flashover in the critical bridging state. References [2], [4], and [8] studied the icing flashover problem of power insulators in heavily iced area., and found that the insulators structure of "combination model of big shed and small shed" can alleviate the problem of insulator bridged to a certain extent, but it is difficult to

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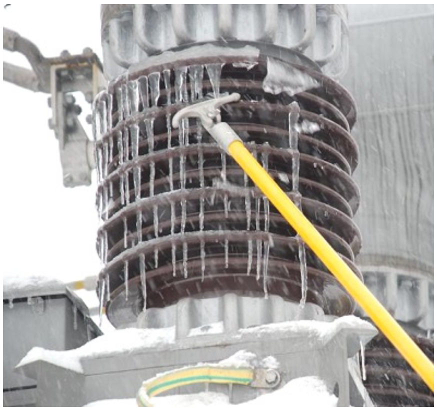


(a) Natural icing growth on substation post insulator

(b) Natural icing growth on transmission line insulator

FIGURE 1. The images of iced insulator.

completely avoid that happen. Therefore, it is of great theoretical significance and practical value to study the identification technology of icing severity and icicle length, and to remind operators of the insulator bridged status and flashover risk level in time.

The on-line monitoring and identification technology of icing growth on artificial buildings have been studied for more than ten years, and many effective methods have been proposed, such as tension sensor measurement method [18], [19], image monitoring method [7], [20]–[22], capacitive sensor measurement method [23], [24], and so on. The image monitoring method is one of the most widely used methods at present, which can analyze the icing growth on power insulators through different indicators. Based on a large number pictures of on-site iced insulator, the image processing algorithms have been extensively studied, such as image denoting, image segmentation, boundary extraction and so on [7], [20]–[22]. The research mentioned above is mainly to evaluate the overall state of iced insulators, which is effective for rime icing and wet snow, because the volume of iced insulator has a significant change after icing accumulation. However, glazed icing is a smooth and transparent structure with unobvious transverse volume change, which is difficult to identify through traditional methods. The overall division and boundary extraction cannot satisfy the length identification of insulator icicle. So, an image recognition method is proposed for icicle length and insulator bridging

TABLE 1. The grade of insulator icing.

Icing Grade	Standard disc insulator (146mm *254mm)	Uniform shed substation post insulator (300mm *50mm)
Slight	Only thin icing shell on the upper surface	Only thin icing shell on the upper surface
Mild	Mild icing layer on the upper surface. The length of icicle is between 0 and 40mm, and the icicle length is less than one third of air gap.	Mild icing layer on the upper surface, the length of icicle is between 0 and 40mm
Medium	Obvious icing layer on the upper surface, and the length of icicle is between 40 and 100mm	The air gap between sheds is bridged by icing
Serious	Completely bridged by icing, and insulator air gap is filled with icing shell	Completely bridged by icing, and insulator air gap is filled with icing shell

state in this paper, which has significant theoretical value and engineering significance for the warning of icing flashover.

II. INSULATOR ICICLE GROWTH MECHANISM AND ITS CHARACTERISTICS

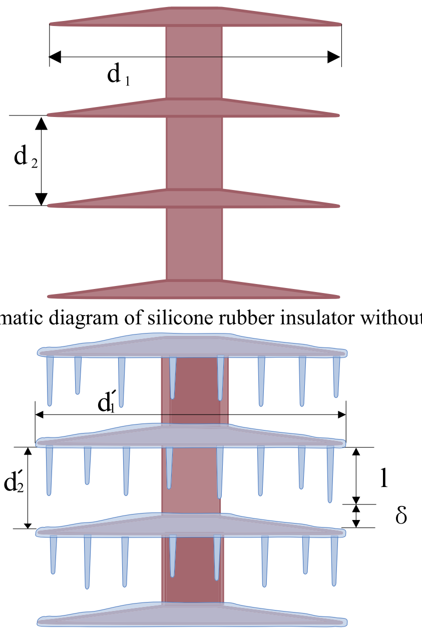
A. GROWTH MECHANISM OF NATURAL ICICLE

Icicles is the result of icing wet growth. Usually it is formed when the ambient temperature is close to 0 and the liquid water content (LWC) of airstream is high, such as freezing rain and drizzle. Since the freezing rate of the supercooled droplets is less than the collision rate, the droplets cannot be completely frozen at the collision position, and the unfrozen water will flow on the surface of the insulator shed driven by the gravity and wind. Finally, the glaze layer and icicles gradually formed with structural characteristics of smooth and transparent.

The growth mechanism of natural icing has been studied in [1], [11], and found that icicle growth is closely related to meteorological conditions and water supply rate. Under the condition of sufficient water supply rate, the vertical growth rate of icicle is much larger than that in the horizontal direction, then a hanging column icicle is formed. And it is generally considered that there are almost no bubbles in the interior of glaze icing with density ranges of 800 to 900. As a result, the glaze icing has the undesirable characteristics of strong adhesion, fast growth rate, and easy to induce insulator bridged. According to the differences of icing thickness and physical characteristics, insulators icing can be divided into four grades: slight, light, medium, and severe [8]. The icing physical characteristics and estimated thickness of each grade are shown in Table 1.

B. THE STRUCTURAL CHARACTERISTIC OF INSULATOR ICICLES

The structure diagrams of insulators before and after icing growth as shown in Fig.2. In this case, the silicone rubber insulator before icing is shown in Fig.2(a), the diameter of the insulator shed is d_1, and the shed spacing is d_2. Under certain climatic conditions, supercooled droplets driven by airstream continuously collide and adhere to the insulator surface, and gradually grow into icicles shown in Fig.2(b). Under this condition, the diameter of the iced insulator shed



(a) The schematic diagram of silicone rubber insulator without icing

(b) The schematic diagram of iced insulator

FIGURE 2. The schematic diagram of power insulators before and after icing accumulation.

is d_1', and the spacing between sheds is d_2'. Assuming the length of icicle is l, and the remaining air gap is δ, then $d_2' = l + \delta$. Moreover, when δ is 0, the iced insulators is bridged by icicles.

In the growth process of glaze icing, there are most of droplets can not freeze in time and will flow along the inclined insulator surface under the action of gravity and wind, thus forming the pendulous icicle shown in Fig.2 (b). Therefore, the insulator shed diameter of iced insulator d_1' is only slightly larger than d_1, and the shed spacing of iced insulator d_2' is slightly smaller than d_2.

It is difficult to obtain the insulator icicle length and bridging state directly by traditional edge analysis method, because the icing shell is transparent with very few bubbles, and the changes of icing insulator diameter are not significant. In addition, since the icicles generally grow overhanging along the insulator, it is difficult to identify icicles when the photographic angle is inappropriate. Therefore, for the recognition image of insulator icicle length and bridging state, it is necessary to take a photographic frontal view.

C. IMAGE ACQUISITION METHOD OF ICED INSULATORS

The image acquisition technology of electrical equipment has been studied for more than ten years, and at present, the images of iced insulator mainly come from two aspects: one is taken by mini patrol UAV(unmanned aerial vehicle), the other is acquired by image online monitoring system. Moreover, both of them have been used widely in China's Power Grid, and played a great significance in preventing and controlling the icing accident of power system.

The image acquisition system of patrol UAV has the characteristics of high definition and adjustable photographic angle, which can effectively reduce the complexity of image recognition algorithm. However, UAV image acquisition system needs human participation, which is not suitable for large-scale application in the heavy icing areas such as mountains. The image on-line monitoring system can be applied to various harsh environments without manual participation. However, the image acquisition device is fixed installation, resulting in the available of images captured are vulnerable to many factors, such as icing location, photographic angle, sediment on the camera lens, and so on.

III. IMAGE RECOGNITION ALGORITHM OF INSULATOR ICICLE

Recognition of insulator icicles by image processing algorithm is an effective way to avoid insulator flashover accident. In this paper, the identification method of icicle length and bridging state is divided into two key steps. Firstly, the icicle structure is segmented from the iced insulator image. Then the length of icicle is calculated through a reference size of shed spacing.

A. THE IDENTIFICATION ALGORITHM OF ICICLE PROFILE

1) OVERALL FLOW OF THE IDENTIFICATION ALGORITHM

The appearance of icicles is usually transparent or translucent, which is easy to integrate with the background. Especially the steel cap structure of the ceramic insulator and glass insulator, the color characteristic is very similar to icicles, which increases the recognition difficulty of insulator icicles. The identification algorithm of icicle profile includes two core modules. On the one hand, the saliency detection method [25] is used to handle the iced insulator image, which used to eliminate the influence of the background and the steel cap structure, and acquire the clear profile of the icicle and insulator shed. On the other hand, the insulator shed can be extracted through the analysis of color and brightness characteristics, thus the icicles can be identified in the iced insulator images by differential calculation. The detailed process is shown in Fig.3.

(1) As shown in Fig.4(a), the iced insulator image is processed by the pre-processing method of literatures [2], [3], which can be used to exclude the influence of environmental background.
(2) Considering the color characteristics of glass insulator, ceramic insulator and silicone rubber composite insulator, the region of insulator shed is extracted by color feature analysis method. The shed area of glass insulator obtained by green feature is shown in Fig.4(b).
(3) The Fourier transform is applied to the gray image, and the spectral data are filtered and reconstructed by the saliency analysis method. Then the saliency image of the iced insulator is extracted as shown in Fig.4(c). And, the region of icicle and the profile of insulator shed are obtained by threshold segmentation and morphological processing, as shown in Fig.4(d).
(4) Perform the differential calculation and the morphological processing on the results obtained in the

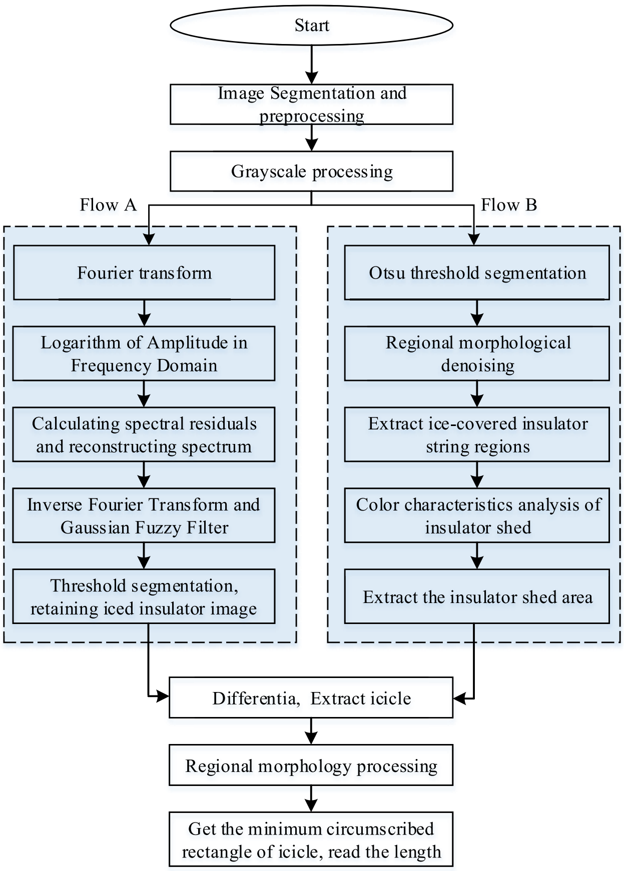


FIGURE 3. The identification algorithm flow of insulator icicle.

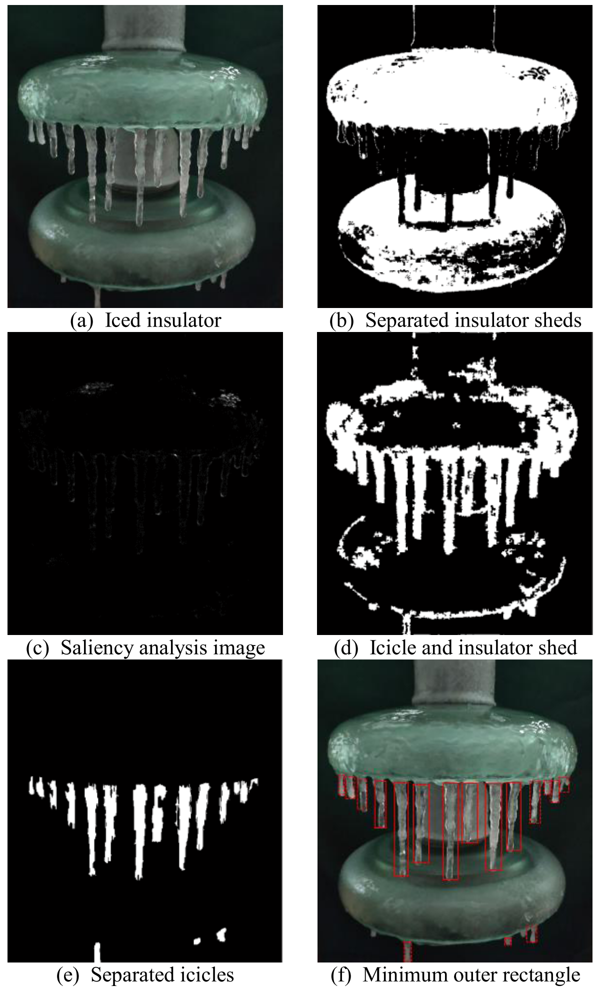


FIGURE 4. Insulator icicle recognition result.

steps (3) and (2), and the completed icicles region is shown in Fig.4(e).

(5) Get the minimum outer rectangle of each icicle in Fig.4(e), and get the pixel length of each outer rectangle in the image.

2) IMAGE SALIENCY DETECTION METHOD

The grayscale image $(I_1(x, y))$ is transformed from spatial domain to frequency domain by Two Dimensional Discrete Fourier Transform, then the amplitude spectrum $A(f)$ and phase spectrum $P(f)$ are calculated.

$$A(f) = \sqrt{(\mathrm{Re}(F(I_1)))^2 + (\mathrm{Im}(F(I_1)))^2} \quad (1)$$

$$P(f) = \arctan\left(\frac{\mathrm{Im}(F(I_1))}{\mathrm{Re}(F(I_1))}\right) \quad (2)$$

where Re is the real part of the frequency domain data, while *Im* is the imaginary part, F represents the Two Dimensional Discrete Fourier Transform, and Logarithmic spectrum $L(f)$ is obtained by logarithm of amplitude $A(f)$.

$$L(f) = \log(A(f)) \quad (3)$$

Since the logarithmic curve satisfies the local linear condition, the average spectrum is obtained by smoothing the logarithmic curve with the local average filter $h_n(f)$, where h_n is a convolution core of the $n \times n$ mean filter, then the spectral residual is the difference between the logarithmic spectrum and the mean filter.

$$R(f) = L(f) - h_n(f) * L(f) \quad (4)$$

where $*$ denotes convolution, $R(f)$ is a residual spectrum, which is reconstructed as a new amplitude with the original phase spectrum $P(f)$ to form a new frequency spectrum. The reconstructed spectrum is inversely transformed by Fourier transform and filtered by Gauss fuzzy filter.

$$s(x, y) = g(x, y) * F^{-1}(\exp(R(f) + iP(f)))^2 \quad (5)$$

$g(x, y)$ takes the Gaussian kernel of 5×5 and $\sigma = 1.5$. F^{-1} represents the inverse Fourier transform. After the inverse Fourier transform and the Gauss fuzzy filter, the salient region image of iced insulator is shown in Fig.4(c), and then the image processing results shown in Fig.4(d) are obtained by the threshold segmentation again.

B. THE IDENTIFICATION ALGORITHM OF ICICLE LENGTH

1) THE CALCULATION METHOD OF ICICLE REFERENCE SIZE

In order to accurately analyze the length of insulator icicles, it is necessary to give a reference size of pixel point.

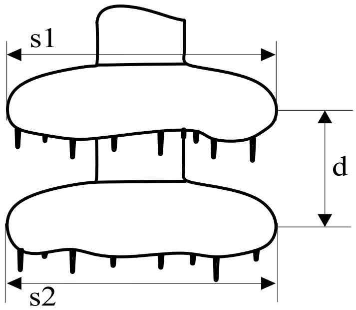


FIGURE 5. The front view of the iced glass insulator.

Because the shed spacing is known for a specific insulator, which can be chosen as the reference size. And it means that the actual length of a single pixel can be determined by the ratio of actual shed spacing to its pixel length. Moreover, the AC withstand voltage of insulator will decrease with the increase of ice length[8].

The front view of the iced glass insulator is shown in Fig.5, in which the lower edge of iced insulator shed is uneven due to the existence of the non-uniform icing layer and hanging icicle. Then, there will be a big error when the distance between two lower shed edges is chosen as the reference size. For this reason, the pixel distance of maximum diameter between two insulator sheds is defined as center distance (d), which is also the actual pixel shed spacing and be used as the reference size in this paper.

The calculation method of icicle reference size is as follows:

(1) The image of iced insulator is grayed and segmented by threshold. The results are shown in Fig.6(a) and Fig.6(b).
(2) Fig.6(c) is processed morphologically to remove the influence of non-coherent areas and burrs on the calculation results.
(3) The number of transverse pixels in Fig.6(c) is counted from top to bottom, which can be drawn as pixel distribution curve, as shown in Fig.7.
(4) The pixel center distance d of the iced insulator shed can be obtained by the method in Section 3.2.2, and the result is shown in Fig.6(d).
(5) According to the known structural parameters of insulators, the actual distance between two insulator sheds is divided by the pixel center distance d, then the actual size corresponding to each pixel is calculated.

2) CALCULATING METHOD OF CENTER DISTANCE

Due to the non-uniform icing layer and hanging icicle, the transverse pixel distribution curve of the iced insulator image is not smooth. It is necessary to eliminate the interference of extreme points. The main process is as follows:

(1) Sliding filter is applied to the pixel distribution curve of the iced insulator image to avoid data fluctuation. And the coordinate sequence $M = \{(x_1, y_1), (x_1, y_1), \cdots, (x_m, y_m)\}$ of the curve

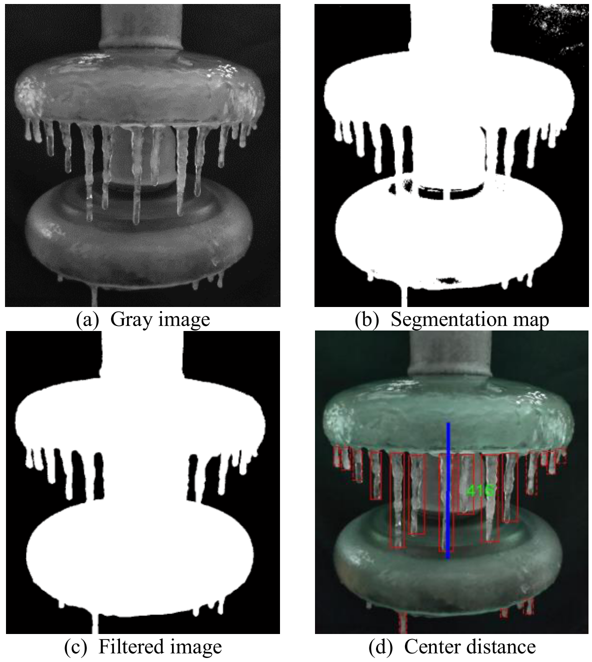


FIGURE 6. The reference size analysis of iced insulator.

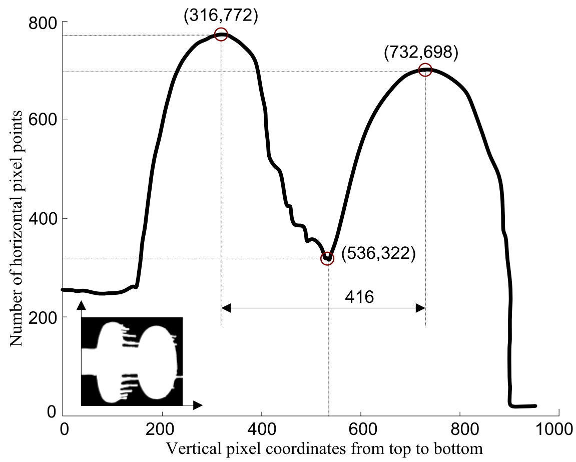


FIGURE 7. Pixel distribution curve of iced insulator image.

is obtained, where the total number of elements in sequence M is m.
(2) The maximum ordinate point $(x_k, y_{k,\max})$ of pixel data is found, where $y_{k,\max}$ is the maximum value of the ordinate and x_k is the abscissa corresponding to the point.
(3) Considering that the size change of insulators is not significant before and after icing accumulation, the reduction factor β of the maximum ordinate is chosen as the threshold, and the initial value of β is defined as 0.75. Subsequently, all maximum points whose ordinates are greater than $\beta \times y_{k,\max}$ are extracted and formed discontinuous sequences $N = \{(x_i, y_i), \cdots, (x_n, y_n)\}$, where $i \geq 1, n \leq m$.
(4) If the number of elements in the sequence N is less than 2, then $\beta = 0.95\beta$ and return to step 3.

Otherwise, on the basis of i and n in sequence N, the continuous data segments in sequence M are intercepted and form a continuous coordinate sequence $W = \{(x_i, y_i), (x_{i+1}, y_{i+1}), \cdots, (x_n, y_n)\}$.

(5) A new sequence $W_y = \{y_i, y_{i+1}, \cdots, y_n\}$ is composed of ordinates in sequence W. Fourier transform of sequence W_y, and a complex sequence $F(W_y) = \{(a_1, b_1), (a_2, b_2) \cdots (a_w, b_w)\}$ is obtained, where a_k and b_k represent real part and imaginary part respectively, $w = n - i + 1$.

(6) Exclude the latter half of the sequence $F(W_y)$, each complex number can represent the characteristics of the signal at a certain frequency, as follows:

$$f_k = (k-1) \times \frac{f_s}{w} \tag{6}$$

where f_k is the signal frequency, k is the k-th complex point, w is the total number Fourier transform data, f_s is the sampling frequency, in this case $f_k = w$. The amplitude characteristic at specific frequency can be calculated as

$$A_k = \frac{\sqrt{a_k^2 + b_k^2}}{w/2} \tag{7}$$

The first element point represents the signal amplitude with the frequency of 0. In addition to the first data, the maximum $A_{k,\max}$ can be obtained. Where $k-1$ is the cycles number of the sequence W, corresponds to $k-1$ insulator sheds.

(7) If the insulator shed is a unified structure, the calculation formula of the pixel center distance is

$$d = w/(k-1) \tag{8}$$

Moreover, if the insulator is "combination pattern of big shed and small shed", the pixel center distance should be adjusted according to the structural characteristics. For example of Fig. 1(a), the shed spacing can be calculated as $2d$.

C. ALGORITHM VALIDITY ANALYSIS

In order to verify the effectiveness of this method, some measurement results of key icing parameters are extracted for glass insulator and silicone rubber insulator, such as distance of sheds (d), maximum icicle length ($l_{\max}$), and the number of icicle length over $^{d}/_{3}(n)$, as shown in Table 2. The test results show that the image analysis results will be affected by the irregular icing and the image shooting angle, and there is a certain calculation error. Among them, the shed thickness of composite insulator and post insulator is very thin, and the maximum insulator shed diameter change is very little and easy identify before and after glaze icing growth. So the shed spacing recognition accuracy of composite insulator and post insulator is high with relative error about 5%. For ordinary suspension glass insulator and ceramic insulator, the diameter of insulator shed edge changes little. Under the influence of uneven icing layer and shooting angle, the position of the maximum diameter will change significantly. In this paper, the average length of shed spacing is calculated by Fourier transform, which can improve the accuracy to a certain extent, with the maximal error about 10%. Moreover, the recognition error of the icicle length on glass insulator and silicon rubber insulator are less than 10%, and the number of icicle with the length more than $^{d}/_{3}$ is proved more accurate.

TABLE 2. The grade of insulator icing.

N	Image Processing Results		Image results	Actual results	Relat -ive error	Icing Grade
1		d (mm)	146.4	136.2	7.49	Medium
		$l_{\max}$ (mm)	92.6	98.4	5.89	
		n	7	7	0	
2		d (mm)	124	122.2	1.47	Serious
		$l_{\max}$ (mm)	125.2	119.6	4.68	
		n	4	4	0	
3		d (mm)	116.2	121.5	4.36	Mild
		$l_{\max}$ (mm)	39.9	36.7	8.72	
		n	0	0	0	

IV. RECOGNITION ANALYSIS OF NATURAL ICICLE ACCUMULATED ON SUBSTATION INSULATOR

In order to verify the effectiveness of the recognition method described in this paper, the image of iced post insulator in substation is selected as the analytical example. The original image and pre-processed image are shown in Fig.8(a) and Fig.8(b), respectively. The identification result of icicle region and its minimum outer rectangle is shown in Fig.8(c) and Fig.8(d), respectively. In which, the maximum icicle length is 78 pixels, and the diameter of the icicle root up to 12 pixels.

The identification result of insulator shed area is shown in Fig.8(e). Analyzing the pixel points of binary image shown in Fig.8(e), the transverse pixel distribution curve is shown in Fig.9, in which the maximum value of longitudinal coordinates is $y_{k,\max} = 234$. Taking $\beta = 0.75$, then the threshold of the longitudinal coordinates is 175.5, and the discontinuous coordinate sequence composed of maximum points on the curve can be written as $N = \{(48, 188), (68, 151), (87, 211), (107, 194), (126, 234), (149, 215)\}$. The continuous data sequence corresponding to abscissa coordinates 48-149 is selected, which can be written as $W = \{(48, 188), (49, 186), \ldots\ldots, (148, 212), (149, 215)\}$. Moreover, the sequence W_y composed of the ordinates in sequence W is transformed by Fourier transform. Then the $F(W_y)$ curve in Fig.9 is obtained, and the pixel

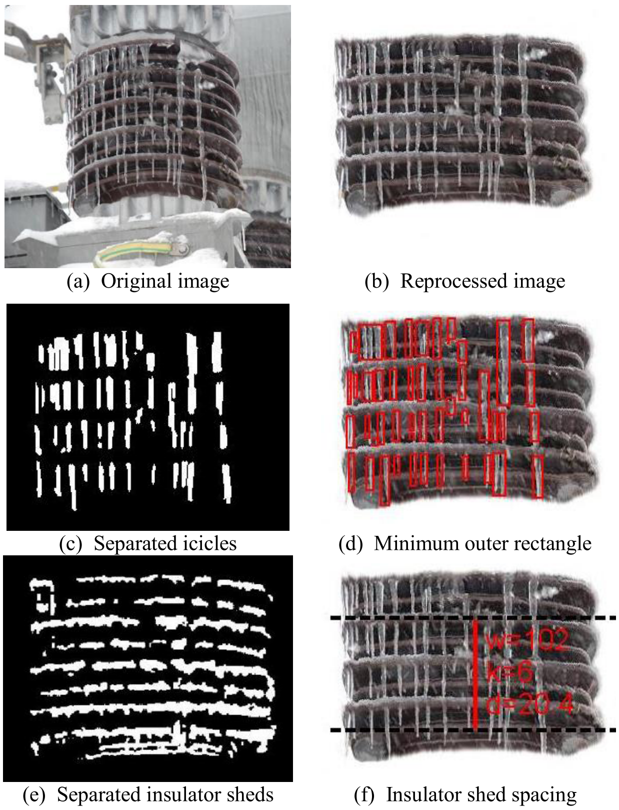


FIGURE 8. Icicle identification results of substation post insulators.

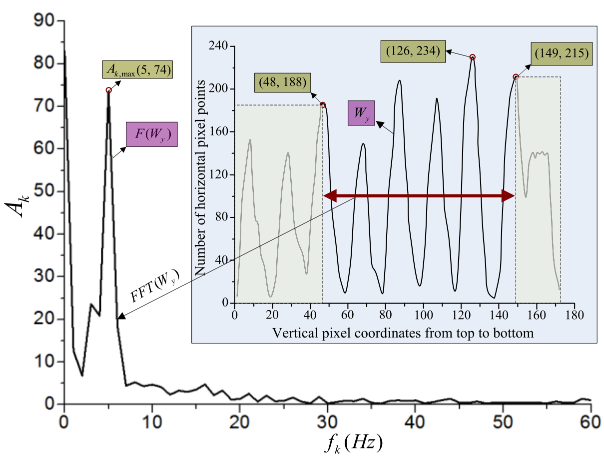


FIGURE 9. Transverse pixel distribution curve and spectrum curve of iced insulators image.

center distance d and other parameters can be written as

$$\begin{cases} w = 102 \\ k = 6 \\ d = 20.4 \end{cases} \tag{9}$$

As shown in Fig.8(a), the post insulator is composed of two different sheds, and the small umbrella shed is embedded in the middle of two large umbrella sheds. For insulators with structural characteristics shown in Fig.8(a), the shed spacing is $2d$ with 40.8 pixel points. It can be seen from the above analysis that the maximum length of the insulator icicle reaches 78 pixels in Fig.8, which is about twice of the insulator shed spacing, and there may be three large insulator sheds are bridged by icing. In addition, there are 28 icicles with a length more than 30 pixels in Fig.8(d), accounting for about 60% of the total number of detected icicles. If the thickness of the iced insulator shed is taken into account comprehensively, it can be considered that the insulator shed spacing has been bridged or critically bridged by multiple icicles. Therefore, it can be judged that the icicles have affected the electrical performance of the insulator, and the icing grade is identified as 'Serious'. The icing bridge alarm and de-icing operation of the insulator should be carried out.

V. CONCLUSION

(1) In this paper, a recognition method of insulator icicle based on image processing is proposed, which can detect the icicle length and insulator bridging state. It is of great significance for icing flashover prediction of power system.

(2) A saliency analysis algorithm is used in image recognition of insulator icicle in this paper, which can eliminate the influence of background and insulator steel cap, and get the region of icicle and insulator shed. Subsequently, the shed region of iced insulator can be extracted by image segmentation method based on color and brightness characteristics. And finally, the icicle and its minimum outer rectangle can be obtained by differential calculation.

(3) In order to measure the length of the insulator icicle, a calculation method of reference size based on Fourier transform is introduced. By this method, the pixels number of shed spacing can be determined by Fourier transformation of the pixel distribution curve, and it can be considered as reference size.

(4) The method discussed in this paper can clearly identify the icicle length in the image of iced insulator, but it is limited by image clarity and photographic angle. In addition, the accuracy and generality of the method will be further improved with the increase of the number of insulator images of natural icicles.

REFERENCES

[1] L. Makkonen, "Models for the growth of rime, glaze, icicles and wet snow on structures," *Phil. Trans. Roy. Soc. London A, Math., Phys. Eng. Sci.*, vol. 358, no. 1776, pp. 2913–2939, 2000.
[2] X. Jiang, X. Han, and Y. Hu, "Model for ice wet growth on composite insulator and its experimental validation," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 3, pp. 556–563, 2017.
[3] M. Farzaneh, "Insulator flashover under icing conditions," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 21, no. 5, pp. 1997–2011, Oct. 2014.
[4] S. M. Ale-Emran and M. Farzaneh, "Experimental design of booster-shed parameters for post insulators under heavy icing conditions," *IEEE Trans. Power Del.*, vol. 30, no. 1, pp. 488–496, Feb. 2015.
[5] X. Huang, H. Li, and Y. Zhu, "Short-term ice accretion forecasting model for transmission lines with modified time-series analysis by fireworks algorithm," *IET Gener., Transmiss. Distrib.*, vol. 12, no. 5, pp. 1074–1080, 2018.
[6] F. Yin, X. Jiang, M. Farzaneh, and J. Hu, "Electrical performance of 330-kV composite insulators with different shed configurations under icing conditions," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 6, pp. 3395–3404, Dec. 2015.

[7] Y. Hao, J. Wei, and X. Jiang, "Icing condition assessment of in-service glass insulators based on graphical shed spacing and graphical shed overhang," *Energies*, vol. 11, no. 2, p. 318, 2018.
[8] M. Farzaneh and W. A. Chisholm, *Insulators for Icing and Polluted Environments*. Hoboken, NJ, USA: Wiley, 2009.
[9] M. Farzaneh and W. A. Chisholm, "50 years in icing performance of outdoor insulators," *IEEE Elect. Insul. Mag.*, vol. 30, no. 1, pp. 14–24, Feb. 2014.
[10] Y. Deng, Z. Jia, J. Zhou, and L. Sun, "Ice flashover performance and its characterization parameter of composite insulator with booster sheds," *IEEE Trans. Dielectrics Electr. Insul.*, vol. 23, no. 2, pp. 1021–1029, Apr. 2016.
[11] M. Farzaneh, *Atmospheric Icing of Power Networks*. Berlin, Germany: Springer, 2008.
[12] S. Yoshida and K. Naito, "Survey of electrical and mechanical failures of insulators caused by ice and/or snow," *CIGRE WG B*, vol. 2, pp. 22–26, Jan. 2005.
[13] Y. Deng, Z. Jia, and H. Jiang, "Effect of icicle bridge conditions on the melting time distribution and flashover probability," (in Chinese), *High Voltage Eng.*, vol. 40, no. 11, pp. 3626–3635, 2014.
[14] X. Jiang, Y. Hu, L. Shu, Z. Zhang, J. Hu, Q. Hu, and Q. Wang, "Crystallisation effect of conductive ions in freezing water during phase transition and its effect on ice flashover voltage," *IET Gener., Transmiss. Distrib.*, vol. 10, no. 9, pp. 2147–2154, 2016.
[15] Y. Liu, M. Farzaneh, and B. Du, "Investigation on shed icicle characteristics and induced surface discharges along a suspension insulator string during ice accretion," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 5, pp. 1265–1269, 2016.
[16] S. Taheri, M. Farzaneh, and I. Fofana, "Electrical performance evaluation of EHV post insulators covered with ice under different air gap configurations," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 21, no. 6, pp. 2619–2627, Dec. 2014.
[17] A. Takei, T. Mizuma, and M. Akatsuka, "Large-scale numerical electrostatic analysis for performance evaluation of insulators with accreted icicles," *Int. J. Appl. Electromagn. Mech.*, vol. 60, no. 2, pp. 187–207, 2019.
[18] X. Jiang, Z. Xiang, Z. Zhang, J. Hu, Q. Hu, and L. Shu, "Predictive model for equivalent ice thickness load on overhead transmission lines based on measured insulator string deviations," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1659–1665, Aug. 2014.
[19] J. Wei, Y. Hao, and Y. Fu, "Detection of glaze icing load and temperature of composite insulators using fiber Bragg grating," *Sensors*, vol. 19, no. 6, p. 1321, 2019.
[20] X. B. Huang, F. Zhang, H. Li, and X. Liu, "An Online technology for measuring icing shape on conductor based on vision and force sensors," *IEEE Trans. Instrum. Meas.*, vol. 66, no. 12, pp. 3180–3189, Dec. 2017.
[21] L. Yang, X. Jiang, and Y. Hao, "Recognition of natural ice types on in-service glass insulators based on texture feature descriptor," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 1, pp. 535–542, Feb. 2017.
[22] D. Pernebayeva, A. James, and M. Bagheri, "Live line snow and ice coverage detection of ceramic insulator using Gabor image features," in *Proc. IET Int. Conf. Resilience Transmiss. Distrib. Netw.*, 2017, pp. 1–3.
[23] Y. Zhu, X. Huang, and Y. Tian, "Experimental study on the icing dielectric constant for the capacitive icing sensor," *Sensors*, vol. 18, no. 10, p. 3325, 2018.
[24] K. P. Owusu, D. C. Kuhn, and E. L. Bibeau, "Capacitive probe for ice detection and accretion rate measurement: Proof of concept," *Renew. Energy*, vol. 50, pp. 196–205, Feb. 2013.
[25] X. Hou and L. Zhang, "Saliency detection: A spectral residual approach," in *Proc. IEEE Conf. Comput. Vis. Pattern Recognit.*, Jun. 2007, pp. 1–8.

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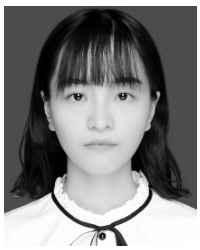

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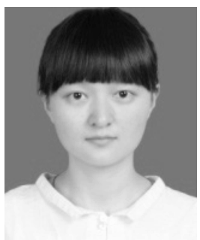

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