Improved Image Analysis Method to Evaluate Tracking Property under Successive Flashover Based on Fractal Theory

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Abstract: Successive flashover would result in carbonized tracking on insulator surface and cause deterioration to the insulation. Thus, investigation of the tracking can be beneficial in understanding flashover characteristics during long-term operation. In this paper, DC flashover was operated on the insulator, and the image of tracking after successive discharge were captured. Improved differential box-counting method (IDBM) was applied to analyze these images based on fractal theory. Weighted item was suggested during the counting procedure for rectangle image with margin covered by cut-size box. Fractal dimension of the tracking was calculated according to the suggested method. It is claimed that the suggested method could estimate the discharge propagation property and deterioration characteristics on the insulator surface. Moreover, IDBM showed advantages in image pre-processing and deterioration property revealed compared to traditional box-counting method attributing to the consideration of color depth. This image analysis method shows universality in dealing with tracking image and could provide additional information to flashover voltage. This paper suggested a potential approach for the investigation of discharge mechanism and corresponding deterioration in future research.

Keywords: fractal dimension; flashover; tracking; differential box-counting method; insulator; epoxy resin

1. Introduction

Polymer dielectrics are widely applied in gas insulated apparatus serving as insulators due to the desirable insulation, ageing and mechanical properties. However, it is speculated that flashover would occur at the gas/solid interface, for example, the SF$_6$/epoxy resin (EP) composites interface, resulting in severe operation failure [1]. Nowadays, surface flashover has been a vital concern for the development of gas/solid insulation in gas insulated substations (GIS) and gas insulated transmission lines (GIL) and attracts much attention [2–5]. During long-term operation, successive flashover would occur at the SF$_6$/EP interface and cause deterioration to the insulation progressively which will lead to the decline of surface insulation strength [6]. Thus, investigation of the discharge property and corresponding damage under successive flashover is of great importance for the application of EP composites in a gas insulated system.

In recent decades, researchers have investigated the flashover characteristics and proposed improved methods to prevent the occurrence of discharge [7–9]. Since deterioration of EP during discharge process will result in the production of carbon compounds, carbonized tracking would appear on EP surface [7,10]. The tracking performs similar radial pattern like discharge and also indicates discharge path. Thus, attention can be focused on the tracking pattern to reveal the discharge property on the EP surface. In addition, methods to analyze discharge phenomenon can be introduced to study the tracking pattern. Various image analysis methods have been applied to study the discharge phenomenon [11–13]. Among them, fractal analysis is considered to deal with the self-similarity of discharge image with acceptable result which was first introduced to analyze
the discharge phenomenon in SF\textsubscript{6} [14]. In past years, fractal analysis has already been applied to investigate the discharge at the dielectric interface or inside the transparent dielectric [15–17]. A. Beroual et al. discussed the influence of oil and pressboard on creeping discharge based on the fractal analysis of the discharge image [18]. B. X. Du et al. investigated the variation of fractal dimension (FD) of electric tree under different treeing time and pulse duration [19]. Thus, fractal analysis is considered as a potential approach to deal with the tracking pattern with satisfactory results.

Moreover, successive flashover on the same path could promote the depth of the tracking color [7]. The brown tracking would consequently lead to increasing the risk of flashover along this certain path attributing to the increasing conductivity on these traces [6]. Subsequent discharge following this path will result in additional damage to the surface and consequent depth of the tracking color. Thus, investigation of tracking along with its color characteristics is of great meaning to understand the discharge propagation and the deterioration due to discharge under successive flashover. However, previous fractal analysis preferred to convert color or gray image to binary image according to box-counting method (BCM) which neglects the depth of pixels [20]. Conversion from color to binary image for tracking will remove the property of color depth for each trace. This leads to the misunderstanding that discharge will occur following each path with the same possibility and cause the same damage on each path. Thus, an improved method needs to be applied concerning both the distribution property and the depth of each path.

Differential box-counting method (DBCM) as an improved BCM can evaluate the roughness of surface dealing with gray image compared to traditional BCM which can only be applied in binary image [21]. Considering the depth of each pixel as its height, DBCM can be used to evaluate the distribution of the color depth in a gray image [22], [23]. Thus, in this article, tracking pattern referring to successive flashover was investigated and improved differential box-counting method (IDBCM) was suggested to quantize the tracking pattern on EP surface. DC flashover was conducted on EP sample surface and the tracking was captured. Pre-processing was introduced and improvement on traditional DBCM was applied considering the irregular shape of the sample and tracking. Tracking pattern and corresponding fractal dimension were investigated. Advantages of the suggested image analysis method were discussed compared to BCM referring to the universality of algorithm and information deriving from FD result.

2. Experimental Method

2.1. Characteristics of EP Sample

In this test, basin-type insulator consisting of EP composites was prepared as EP sample. The height was 190 mm, and the radius was 251 mm at the bottom. The center and the circle at bottom were prepared with electrodes. Bisphenol-A epoxy resin (Type of CT-5531, produced by Huntsman) formed as the matrix with aluminum oxide micro-particles as the filler at the mass fraction of 30%. The average surface roughness of the EP sample is 0.12 \( \mu \)m. SF\textsubscript{6} gas with the purity of 99.99% was prepared to provide an insulating environment.

Conducting particle was adhered on sample surface to induce discharge in certain direction attributing to the field distortion at the tip, since flashover will propagate in random direction without particle leading to dispersive tracking [24]. Particles at various locations can provide various field distribution which can help to investigate the influence of field distribution on flashover property. The copper particle with the diameter of 0.5 mm was cut into 25 mm in length and placed at 19, 71, 123 and 175 mm respectively away from HV electrode providing a quartered location along the surface. The diagram is illustrated in Figure 1 in which the particles corresponding to different locations are marked as Case A, Case B, Case C and Case D, respectively.
2.2. Surface Flashover Test

DC voltage was applied by a HVDC source via a SF$_6$ filled bushing. The sample was cleaned by absolute ethyl alcohol and dried before placing it into a sealed chamber. The setup was vacuumed to 30 Pa and then filled with SF$_6$ gas up to 0.06 MPa. Then the whole setup was standing for 30 min before voltage was applied. Positive DC voltage was increased at the speed of 1 kV/s until flashover occurred. Flashover voltage was recorded through a voltage divider. 20 times of successive flashover was required for each set of tests with the same location of particle, then the tracking on EP surface was captured by an HD camera after the sample was taken from sealed subsection. The schematic diagram for the test is illustrated in Figure 2 and a typical image of the sample with tracking on the surface is shown in Figure 3.

Figure 1. Illustration of EP sample with electrodes and surface particle. Particle corresponding to Cases A to D distributes quarterly along the insulator surface.

Figure 2. Schematic diagram of experiment circuit. The insert figure on upper right illustrates the inside view of the chamber.

Figure 3. Typical image of tracking on EP sample surface. Only the upper half of the insulator with tracking is shown.
3. Improved Differential Box-Counting Method

As can be seen in Figure 3, the depth of tracking varied with traces. Thus, image analysis based on fractal theory needs to consider the distribution of depth to evaluate the tracking pattern. According to the algorithm of DBCM, the color image is converted to gray-level, and each pixel in the image is assigned with a value corresponding to gray level in the FD calculation procedure [22]. The calculated FD varies from 2 to 3 and the value indicates the fluctuation of pixels in the image.

The EP sample in this test was shaped in basin-type and the tracking distributed on the three-dimensional (3D) surface. Considering the perspective effect, the height of the sample was neglected in the captured image, thus resulting in the inaccuracy of tracking location compared to the real object. Particularly, the radius shown in the image is smaller than its actual radius. Before fractal analysis, preliminary image processing was applied to convert to flat the captured image considering perspective effect and reduce the calculation error as little as possible.

Most previous investigations of FD concerning the discharge phenomenon were applied on the image with square shape [18–20]. In particular, the size of these images is usually $M \times M$ pixels, where $M$ is equal to $2^n$, here $n$ is an integer larger than 1. In calculation procedure for both BCM and DBCM, if the length of the covering square box is set as $2^r$, where $r$ is an integer larger than 1, then all the pixels can be covered with varying the length of the box. However, for the captured image in this article, it was preferred to extract the minimum rectangle area containing the entire tracking from the image. This area is usually of random width and height. It cannot ensure coverage of all the pixels in the image of $M \times N$ with the box of $2^r \times 2^r$ which then leaves margin with the size smaller than the box to be covered. Thus, IDBCM was suggested to deal with the potential margin. According to the algorithm in [25], weight factor was added considering the contribution of margin to total value during the counting procedure.

To evaluate the tracking pattern of different images, the uniform size of the selected area for tracking should be defined since the size affects the calculation. In this paper, selected rectangle area was defined as the minimum area covering the entire tracking of a certain image which was selected referring to the tracking covering the maximum area among all the images for all conditions. Since flashover propagation should perform symmetric possibility around the particle along radius direction considering the symmetric field distribution, selected area was symmetric around the particle as well.

The calculation procedure of IDBCM can be detail as follows:

1. Captured image is first flatted in radius direction and enlarged to reduce perspective effect based on sample structure as illustrated from Figure 4a,b. Then, the flatted image is converted to gray-level and cut to $M \times N$ pixels as illustrated in Figure 4c. The dashed line in Figure 4c represents the location of particle and the symmetry axis. In the following steps, this gray-level image with the size of $M \times N$ is applied to calculate FD.

![Figure 4](image)

Figure 4. Conversion of tracking from original image to flatted gray-level image. (a) is the original image. (b) is the flatted image based on the original image. (c) is the grey-scale image which is converted and cropped based on the flatted image.

2. According to DBCM, square boxes with the length of $z$ are applied to cover the entire gray-level image. Covering procedure can be conducted from upper left to lower right block by block as shown in Figure 5a. Considering each pixel inside the box with
height corresponding to its gray-level, boxes of $s \times s \times s'$ are columned to cover the total height, where $s'$ is the height of the covering box defined by $G/s' = P/s$, here $G$ is the total number of gray levels and $P$ is the length of the image with $P \times P$ pixels [22]. Since the image in this paper was sized to $M \times N$ instead of square shape, the equivalent length of the image corresponding to square shape is defined as $L = (M \times N)^{0.5}$ considering the immutability of area. Thus, the height of the box can be obtained according to Equation (1).

$$s' = \frac{G \times s}{L},$$  \hspace{1cm} (1)

![Figure 5](image)

**Figure 5.** Illustration of differential box-counting method for tracking by full-size box. (a) illustrates the covering procedure from upper left to lower right. (b) shows the counting procedure of differential height for a certain block covered by full-size box.

For a given box with the size of $s \times s$, each of the pixels with a certain gray-level has a height corresponding to $s'$. The ceil value of the difference between maximum and minimum height in this box is defined as the count of this box $N_f(i, j)$ as illustrated in Figure 5b. This count can be calculated according to Equation (2), where $i$ and $j$ are the indexes of the box in covering procedure, $h_{k,q}(i, j)$ represents the height of each pixel in this box, $k$ and $p$ are the corresponding indexes in this box. ‘int’ in this equation means to obtain the nearest integer which is not larger than this value. If all the pixels possess the same height, the count is defined as 1. Total count $N_f(s)$ corresponding to the image covered by the full-size box $s$ is the sum of the differential value in each box as in Equation (3) [21].

$$N_f(i, j) = \text{int}\left\{ \max(h_{0,0}(i, j), \ldots, h_{k,q}(i, j), \ldots, h_{s-1,s-1}(i, j)) - \min(h_{0,0}(i, j), \ldots, h_{k,q}(i, j), \ldots, h_{s-1,s-1}(i, j)) \right\} / s' + 1,$$  \hspace{1cm} (2)

$$N_f(s) = \sum_{i=q=1}^{i=q} N_f(i, j),$$  \hspace{1cm} (3)

(3) If the height $M$ or width $N$ could not be exactly divided by $s$, then the margin will remain and need to be covered with a cut-size box. Differential value is calculated as usual, and then weight factor is suggested as the ratio of area between cut-size and full-size box expressed in Equation (4), where $S(i, j)$ represents the area of cut-size box, $N_c(i, j)$ represents the count of this cut-size box with covering index of $(i, j)$. Equation (5) defines the total count of entire margin $N_c(s)$ for a certain box length summing the counts of right margin, bottom margin and right down corner. Total differential count $N_c(i, j)$ is the sum of the counts in both full-size and cut-size covering procedures as described in Equation (6).

$$N_c(i, j) = \left\{ \text{int}\left\{ \max(h(i, j)) - \min(h(i, j)) \right\} / s' \right\} + 1 \times \frac{S(i, j)}{s \times s},$$  \hspace{1cm} (4)
\[ N_c(s) = \sum_{i=1,j=\text{int}(\frac{s}{2})+1}^{i=M} N_c(i,j) + \sum_{i=\text{int}(\frac{M}{s})+1}^{i=N} N_c(i,j) + N_c(\text{int}(\frac{M}{s})+1, \text{int}(\frac{N}{s})+1), \]  

(5) \[ N_t(s) = N_f(s) + N_c(s), \]  

(6)

(4) The length of box is limited as \( \sqrt{L} \leq s \leq L/2 \). With varying \( s \), Step (2) and (3) are repeated until the length reaches limitation. Scatters of \( (G/s', N_t(s)) \) representing the ratio and corresponding differential value are plotted in double logarithmic axes. Then, linear fitting is conducted, and the slope of the fitting line is the FD.

4. Result and Discussion

4.1. Characteristics of Tracking

Tracking on the surface for particles at various locations is shown as Figure 6a–d corresponds to the results of 19, 71, 123 and 175 mm respectively. Obvious brown tracking remains on the surface attributing to the carbon element in epoxy resin which results in carbonized tracking on the surface. The tracking region could lead to increasing possibility of discharge propagation in this certain area.

\( \text{(a)} \) \hspace{1cm} \( \text{(b)} \) \hspace{1cm} \( \text{(c)} \) \hspace{1cm} \( \text{(d)} \)

Figure 6. Images of tracking with particle at various locations. In (a), the particle is located at 19 mm. In (b), the particle is located at 71 mm. In (c), the particle is located at 123 mm. And in (d), the particle is located at 175 mm from HV electrode.

Tracking on the surface is divided into two parts i.e., HV part covering the region from HV electrode to the tip of particle and ground part covering the region from the tip of particle to ground at bottom circle. For ground part, with moving the particle from HV electrode to ground electrode, the area of tracking decreases and the region of tracking shows an increasingly centralized tendency indicating that flashover preferred to occur in a certain direction. There is obvious dark brown tracking in the middle region in Figure 6b,c indicating that most of flashover propagated through this path and high
possibility of discharge for this path. To evaluate the tracking pattern quantitatively, fractal analysis was applied and fractal dimension was calculated for each image in this figure.

4.2. FD Result Based on IDBCM

Figure 7 shows the gray-level images cut and converted from original images corresponding to Figure 6. According to IDBCM, fitting results corresponding to the four tracking in Figure 7 are shown in Figure 8a–d, respectively. It is obvious that the calculation method suggested in this article has a considerable linear tendency while varying the length of the covering box which means IDBCM could be applied to evaluate the self-similarity of the tracking pattern. Slope of the fitting line was calculated and corresponding FD is illustrated in Figure 9. Fractal theory has been widely applied to analyze roughness and fluctuation of solid surface [26,27]. Higher value of FD indicates more fluctuating surface, for example serious protuberance, while lower value claims smoother surface or surface with stable wave [27]. When introduced to evaluate the gray distribution in a gray-level image, high value means abnormal gray values in this image including exceptional dark pixels in white background or light pixels in dark background.

![Figure 7](image-url)

_Figure 7._ Gray-level tracking image applied in calculating FD with particle at various locations. Each sub-figure has been flattened and is in accordance with the images in Figure 6. In (a), the particle is located at 19 mm. In (b), the particle is located at 71 mm. In (c), the particle is located at 123 mm. And in (d), the particle is located at 175 mm from HV electrode.
Figure 8. Fitting results of tracking according to IDBCM with particle at various locations. In (a), the particle is located at 19 mm. In (b), the particle is located at 71 mm. In (c), the particle is located at 123 mm. And in (d), the particle is located at 175 mm.

Figure 9. Fractal dimension of tracking and corresponding flashover voltage of EP sample with particle at various locations.

With moving the particle from the center electrode to the ground electrode, FD of tracking increases firstly and then decreases. It is obvious that there is a “main path” in the middle region in Figure 7b,c. For the tracking in Figure 7a,d, although the tracking covers much area along the sample surface, tracking shows more uniform distribution and less centralized pattern. There is no obvious “main path” among these traces whose depth and corresponding gray-level shows a uniform distribution pattern. All these traces seem to show even frequency for discharge during successive flashover. Main path with deep color
and low gray value functions as abnormal gray value to background which can lead to obvious fluctuation to gray value distribution and finally result in high value of FD. Thus, FD of Figure 7a,d shows a lower value compared to Figure 7b,c due to the obvious “main path” in these two images.

Main path with deep color as the consequence of severe discharge indicates high possibility of discharge propagation along this direction during successive flashover. Considering the variation of particle location on the surface, particle at the middle region may cause flashover propagating along particle direction in high frequency and possibility. Meanwhile, particle in the region near the center electrode or ground electrode would lead to flashover to occur in radius direction under successive conditions confirmed by the tracking pattern. Since successive discharge along the same path can cause serious deterioration to EP surface, particle in the middle region may lead to more severe damage to the sample or the insulator operating in a gas insulated system.

Flashover voltage corresponding to Figure 6 is illustrated in Figure 9. It is obvious that with moving particle from center to outer in radius direction, flashover voltage increases leaving the lowest value for particle at 17 mm which is the nearest to center electrode. This means the particle on the surface near the HV electrode would cause flashover in high possibility during operation. According to the calculation of electric field distribution, the electric field strength at the tip of the particle is extremely high. This will cause serious ionization in the SF$_6$ gas near the tip under high voltage. Charged particles will be generated near the tip and diffuse to the surroundings. The path consisting of the charged particles shows excellent electric conductivity compared with the insulating gas. Once the path bridges the metallic particle and the electrode, the metallic particle can be regarded as the prolongation of the electrode attributing to the high conductivity path. Thus, the metallic particle can be regarded as a protrusion of the electrode. This will lead to an obvious decrease in flashover voltage. When the metallic particle is placed away from the electrode, for example in the middle region along the surface, it is difficult to obtain the high conductivity path consisting of charged particles. Since the path is too long for the charged particles to bridge the electrode and the metallic particle under diffusion effect. Thus, the flashover voltage is lower when the metallic particle is placed near the center electrode.

Compared with the results of FD and flashover voltage, it can be seen that there is an inconsonant tendency with varying the particle location. It can be claimed that besides voltage, tracking pattern may help to estimate flashover characteristics and provide information different from voltage which may be of great importance for long-term operation of the insulator. Analysis of tracking pattern shows an advantage in investigating successive flashover and can deal with the estimation of damage to the dielectric surface during long-term operation. As discussed in the reference [6,7], single discharge will cause slight damage to EP surface while accumulative consequence due to flashover can result in severe deterioration on surface which will lead to reduction of insulation strength. Therefore, tracking property is important to evaluate flashover characteristics, and in this paper, IDBCM indicates a potential approach to estimate this matter with a reasonable result and considerable discrimination.

Once a new kind of structure is designed or a new kind of material is applied, the surface flashover property of the insulator may need to be discovered. Thus, experiments with respect to flashover can be conducted. The tracking images can be gathered with an HD camera after disassembling the setup as mentioned in this paper. Then, the tracking and discharge characteristics can be analyzed. While for the insulator in an operating GIS, optical fiber image bundles can be inserted inside the GIS enclosure pipe. Thus, the images inside the GIS can be transferred to the outside. With the help of the imaging device outside the GIS, the images of the insulator can be gathered. In this way, the tracking property can be obtained without disassembling the GIS.

It is noted that standard visual inspection can provide an approach to discover whether there is tracking on the sample surface and whether the flashover has happened. While if
the degree of surface degradation needs to be discovered, the standard visual inspection may not be enough. The IDBCM can provide an approach to discover the degree of surface degradation quantitatively which may be beneficial in the design of structure and selection of material with respect to the insulator. Since the method can help to evaluate the degree of surface degradation during successive flashover, it also may be beneficial in the analysis of other equipment, for example, the silicone rubber outdoor insulators.

4.3. Comparison between BCM and IDBCM

To have a deep insight of the suggested method based on DBCM, fractal analysis result according to traditional BCM in two-dimension (2D) mode was discussed. Figure 10 shows the binary images converted from original color images by directly compared with threshold. In detail, the color image was first converted to gray-level image. Then, optimal gray value was set as the threshold. The pixel with gray value higher than threshold was set as white, while the pixel with gray value lower than threshold was set as black. Finally, binary images corresponding to Figure 7 were obtained and illustrated in Figure 10a–d. As can be seen, this conversion displayed an unsatisfactory result since it fails to extract tracking from the background perfectly. Actually, attempts have been made to achieve the optimal threshold, and the images shown in Figure 10 were the relative most desirable results. This can attribute to the gradient background along the image as shown in Figure 6 in color mode. It confuses the difference between tracking and background referring to threshold value. Images in Figure 10 cannot be applied to calculate FD based on BCM since it cannot provide information with reasonable accuracy.

![Figure 10. Conversion of tracking image from color mode to gray-level by directly compared with threshold. The images in this figure are in accordance with the images in Figure 7. In (a), the particle is located at 19 mm. In (b), the particle is located at 71 mm. In (c), the particle is located at 123 mm. And in (d), the particle is located at 175 mm from HV electrode.](image-url)

Therefore, a compensable algorithm was suggested for the purpose of extracting tracking from the background entirely. As shown in Figure 11, it is obvious that most of...
the tracking was extracted. Thus, BCM could be conducted as detail in [20], and the result is displayed in Figure 12.

![Figure 11. Conversion of tracking image from RGB to gray-level by compensable algorithm. In (a), the particle is located at 19 mm. In (b), the particle is located at 71 mm. In (c), the particle is located at 123 mm. And in (d), the particle is located at 175 mm from HV electrode.](image)

![Figure 12. FD of tracking calculated according to BCM with particle at various locations.](image)

With varying the location of particle, FD of tracking shows corresponding variation. However, FD based on BCM provided ambiguous regularity with this variation indicating unproper application of BCM in dealing with tracking pattern in this condition. As depth will be neglected during conversion from gray-level or color mode to binary mode, fluctuation of color for each pixel will be neglected in evaluation. This will lead to the neglection of “main path” especially for the particle at 71 and 123 mm compared to
IDBCM. Moreover, it is too strict and difficult to ensure the captured image with a uniform background, especially when the experiment is conducted in complex conditions. This will result in the mission hard to complete that extracting tracking from the background perfectly and finally lead to the decrease in accuracy based on BCM. Considering these disadvantages of BCM, the improved DBCM in this paper indicates a potential approach to analyze flashover characteristics concerning tracking property with proper accuracy and well adaption.

5. Conclusions

Polymer dielectrics applied in a gas insulated system would suffer surface flashover which will restrain its application in high voltage apparatus. This article investigated the successive flashover at SF$_6$/EP interface concerning tracking property and applied IDBCM to evaluate the tracking pattern. The conclusions can be summarized as follows:

1. DC flashover was conducted at SF$_6$/EP interface and obvious brown tracking remained on EP surface as the consequence of successive discharge. Tracking showed obvious main path for particle in the middle region which indicated severe damage due to successive flashover.

2. Weight factor was applied in covering potential margin with cut-size box during counting procedure to improve DBCM for rectangle image with arbitrary height and width. FD of tracking based on IDBCM showed high value for particle in middle region which can attribute to the fluctuation of color depth in the region of main path.

3. IDBCM showed advantages compared to BCM in evaluating successive discharge referring to propagation path and corresponding deterioration on the surface since it considered the depth of tracking color. Meanwhile, IDBCM showed universality for the required image quality and could provide additional information to flashover voltage.

4. This suggested image analysis method proposes a potential approach to reveal flashover characteristics including deterioration property based on fractal analysis of tracking pattern in future research.

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