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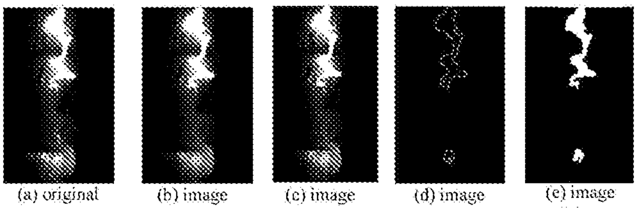
(54) METHOD FOR ANALYZING SURFACE DISCHARGE BASED ON NONLINEAR CHARACTERISTICS OF LEAKAGE CURRENT OF ICE-COVERED INSULATOR.

(57) Provided is a method for analyzing surface discharge based on nonlinear characteristics of a leakage current of an ice-covered insulator. The method is suitable for monitoring and ensuring safe operation of the ice-covered insulator. Chaos of a time series of the leakage current is checked by estimating a maximum Lyapunov exponent on the basis of an embedding space theory and a phase space reconstruction method. Then, a dynamic behavior of the leakage current is studied on the basis of a recurrence plot technique, a dynamic discharge behavior of the ice-covered insulator is clearly and visually analyzed by means of graph texture transformation, and an index to quantify regularity of the leakage current is provided on this basis. A cooperative relation between an arc length extracted by processing an image and the leakage current is quantitatively analyzed to determine a rule of variation of the leakage current.



(a) original image (b) image noise removal (c) image enhancement (d) image segmentation (e) image filling

FIG. 1

METHOD FOR ANALYZING SURFACE DISCHARGE BASED ON NONLINEAR CHARACTERISTICS OF LEAKAGE CURRENT OF ICE-COVERED INSULATOR

TECHNICAL FIELD

[01] The present invention relates to a method for analyzing ice-covered surface discharge of an insulator, and in particular to a method for analyzing surface discharge based on nonlinear characteristics of a leakage current of an ice-covered insulator.

BACKGROUND ART

[02] With vigorous development of world advanced ultra/extra-high voltage transmission and transformation projects in China, ultra/extra-high voltage transmission lines are increasingly increased, and the risk of ice flashover accidents is also increasing day by day. In severe cold weather, growth of an ice edge severely limits electrical performance of an insulator, which may cause corona discharge, arc development, and even flashover, thereby seriously endangering operation of a power grid. Although China has increased investment in manpower and scientific and technological resources to build the strong and reliable power grid, flashover accidents caused by line ice coverage are still inevitable. Therefore, it is necessary to reasonably and effectively monitor discharge of the insulator on a transmission line, and improve a capability of determining safe operation of the ice-covered insulator.

SUMMARY

[03] An objective of the present invention is to provide a method for analyzing surface discharge based on nonlinear characteristics of a leakage current of an ice-covered insulator. The method includes:

[04] 1) establishing an experimental platform, studying an arc state of a direct current ice-covered insulator in a laboratory environment, and obtaining image data by monitoring camera photographing;

[05] 2) processing a collected arc image, and extracting arc features;

[06] 3) analyzing a flashover process on a surface of the ice-covered insulator;

[07] 4) nonlinearly analyzing a leakage current waveform monitored from the previous step;

[08] 5) transforming a one-dimensional nonlinear time series of the leakage current into two-dimensional matrix data on the basis of a recurrence plot technique, and effectively extracting nonlinear characteristics of the two-dimensional matrix data;

[09] 6) on the basis of the recurrence plot technique used in 5), reflecting chaos of a time series of the leakage current by calculating a Lyapunov exponent, and providing quantitative description of a state of a chaotic system; and

[10] 7) analyzing discharge characteristics of the ice-covered insulator during surface flashover by means of the recurrence plot technique, and revealing a relation between the discharge characteristics and a nonlinear variation of the leakage current.

[11] Beneficial effects:

[12] 1. In order to improve image quality, a method for combining traditional image processing with morphological processing is used. Noise of an image is removed. Then, contrast and sharpness of the image are enhanced by means of power transformation. During edge segmentation, a closed and accurate arc profile is obtained through a mark-controlled watershed algorithm based on morphology. Finally, the image at an edge of an arc is filled by applying a filling algorithm, and then an accurate arc perimeter is extracted.

[13] 2. The chaotic time series is transformed into the two-dimensional matrix on the basis of the recurrence plot technique, to visually display phase space trajectories of an original system at different comparable time points in the phase space. When the ice-covered Insulator is subjected to surface discharge, the recurrence plot technique can analyze the discharge characteristics of the ice-covered insulator during surface flashover and reveal the relation between the discharge characteristics and the nonlinear variation of the leakage current.

BRIEF DESCRIPTION OF THE DRAWINGS

[14] FIG. 1 shows images of an image processing process.

[15] FIG. 2 is a schematic diagram of an experimental device.

[16] FIG. 3 shows schematic diagrams of a leakage current, a measured voltage and an arc length recorded at different stages.

[17] FIG. 4 is a schematic diagram of calculation of m and τ by means of a C-C method.

[18] FIG. 5 is a schematic diagram of calculation of a maximum Lyapunov exponent of a leakage current at each stage during flashover.

[19] FIG. 6 shows recurrence plots at different stages.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[20] 1. An experiment is carried out in a cold chamber having a size of 4.8 m*2.8 m*3.5 m. FIG. 2 shows a schematic diagram of an experimental device. Test steps are carried out according to an Institute of Electrical and Electronic Engineers (IEEE) 1783/2009 standard. In order to simulate an ice coverage process in a natural environment, the ice coverage experiment lasts for 60 minutes. A voltage is gradually increased at a rate of 3.0 kV/s. After an estimated flashover voltage is reached, a current-voltage level is maintained for 15 minutes. The experiment is carried out at a sampling frequency of 10 kHz. A high-speed camera capturing a 256 gray level records a phenomenon of surface discharge of an insulator at a rate of 6000 frames per second.

[21] 2. A gray image collected by the camera is processed, and a processing process is shown in FIG. 1. Noise of the image is removed. It is found that a median filtering effect is better than that of a smooth spatial linear filter by means of comparison of a common method, and therefore a median filtering method having a 3*3 template is selected. An image after noise removal is shown in FIG. 1(b). Since nose removal processing has a fuzzy effect on the image, a gray level is nonlinearly transformed by means of power transformation herein, an objective of which is to enhance contrast and sharpness of the image and ensure a difference of gray values between pixels. An enhanced image is shown in FIG. 1(c). Then, a mark-controlled watershed algorithm based on morphology is applied, which essentially imitates an immersion process of a topographic map. The image is segmented according to region characteristics of the image. In combination with the advantages of region growing and edge detection, a closed, connected and position-accurate contour may be obtained, which is as shown in FIG. 1(d). Finally, the image at an edge of the arc is filled by applying a filling algorithm to obtain an arc region as shown in FIG. 1(e), and arc features are extracted according to the region.

[22] 3. A flashover process of the ice-covered insulator is analyzed. FIG. 3 shows a waveform of arc features, and voltage and current changes during a period from stable discharge to flashover. In a stage I, occurrence of partial filamentary discharge results in sawtooth features of voltage and current waveforms, which are as shown in FIGs. 3(a) and 3(b). A leakage current at a direct current voltage is stably maintained at an amplitude of approximately 14 mA. In addition, a weak arc length remains stable at the stage, and average arc length values of a positive voltage and a negative voltage are 41.89 mm and 30.24 mm respectively, which are as shown in FIG. 3(c). During a stage II, a current rises from 6.97 mA to 21.15 mA, and a voltage drops from 100.78 kV to 84.95 kV, which indicates a transition from glow discharge to arc discharge. Then, the leakage current and voltage return to a normal level, which is as shown in FIG. 3(b). In a stage III, electric field intensity at an arc head is significantly increased, resulting in a spike in the leakage current and flashover. In FIG. 3(b), a leakage current is increased from 8.29 mA to 720.3 mA between 5.31 s and 5.41 s. In FIG. 3(a), a leakage current is increased from -23.89 mA to -522.1 mA between 6.20 s and 6.25 s. According to FIGs. 3(a) and 3(b), repeated discharge frequencies at a positive direct current voltage and a negative direct current voltage are 333 Hz and 833 Hz respectively during flashover, and corresponding maximum peak measured values are 720.3 mA and 522.1 mA respectively.

[23] 4. A maximum Lyapunov exponent of a time series of the leakage current is calculated. A chaotic system is a deterministic nonlinear system presenting various characteristics. A main feature is sensitivity of the characteristics to an initial condition, which results in trajectories generated by closely spaced initial values in a phase space that diverge exponentially along with time. The Lyapunov exponent may reflect the characteristic. The Lyapunov exponent is defined by taking long-term evolution of an infinitesimal n-dimensional sphere in a n-dimensional phase space as an example. Due to local instability of the system, the n-dimensional sphere is transformed into an ellipsoid. An i-th Lyapunov exponent is defined by a length of a principal axis of the ellipsoid, and is represented as $p_i(t)$,

[24]
$$L_i = \lim_{t\to\infty}\frac{1}{t}\ln\frac{p_i(t)}{p_i(0)} \tag{1}$$

[25] A magnitude of the Lyapunov exponent represents an exponential rate of convergence or divergence of a nearby trajectory in a phase space. In a direction of L_i<0, a phase volume shrinks and motion is stable. In a direction of L_i>0, a long-term behavior is sensitive to an initial condition and motion presents a chaotic state. L_i=0 corresponds to a stable boundary that is a critical case. Therefore, under the condition that a maximum L_i value of a time series is greater than 0, it is determined that the time series is a chaotic series.

[26] The maximum Lyapunov exponent of the chaotic time series is calculated by means of a small data method. Calculation steps are as follows:

[27] (1) The chaotic time series of the leakage current having delay τ and an embedding dimension m is calculated. The embedding dimension is m, and according to a Takens's phase space reconstruction theory, a reconstructed phase space of the time series of the leakage current is represented by a point X_{i}:

[28]

$$X_i=(x_i,x_{i+\tau},\dots,x_{i+(m-1)\tau}),\ X_i\in R^m,\ (i=1,2...,M) \qquad (2)$$

[29] N represents a size of a data set, where N=M+(m-1)τ. Values of τ and m are determined by means of a C-C method. Steps are as follows: a correlation integral of an embedded time series is defined:

[30]

$$C(m,N,r,t)=\frac{2}{M(M-1)}\sum_{I\le i\le j\le M}\theta(r-d_{ij}),\ r>0 \qquad (3)$$

[31] $d_{ij}=\|X_i-X_j\|$, when x<0, $\theta(x)=0$, and when x≥0, $\theta(x)=1$. Vectors in a phase space that are less than r (distance between X_i) are called as correlation vectors. A proportion of the correlation vectors in all M(M-1) possible pairs is defined as a correlation integral $C(m, N, r, t)$. The study of an C-C algorithm is related to a function S.

[32]

$$S(m,N,r,t)=C(m,N,r,t)-C^m(1,N,r,t) \qquad (4)$$

[33] In order to select an appropriate τ, the time series is divided into t sub-series:

[34]

$$S(m,N,r,t)=\frac{1}{t}\sum_{s=1}^{t}\{C_s(m,N/t,r,t)-C_s^m(1,N/t,r,t)\} \qquad (5)$$

[35] When $N\to\infty$,

[36]

$$S(m,r,t)=\frac{1}{t}\sum_{s=1}^{t}\{C_s(m,r,t)-C_s^m(1,r,t)\} \qquad (6)$$

[37] When an actual series is processed, time corresponding to a zero-crossing point of $S(m,r,t)$ or a minimum difference of $S(m,r,t)$ of different radii is selected as a local maximum time interval. A difference between a maximum value and a minimum value of r is defined as:

[38] $$\Delta S(m,t)=\max\left\{S(m,r_j,t,N)\right\}-\min\left\{S(m,r_j,t,N)\right\} \qquad (7)$$

[39] According to a statistical conclusion, m=2, 3, 4, 5, $r_j=\frac{i\sigma}{2}$, i=1, 2, 3, 4 are set. Formulas are as follows:

[40] $$\overline{S}(t)=\frac{1}{16}\sum_{m=2}^{5}\sum_{j=1}^{4}S(m,r_j,t) \qquad (8),$$

[41] $$\Delta\overline{S}(t)=\frac{1}{4}\sum_{m=2}^{5}\Delta S(m,t) \qquad (9), \text{ and}$$

[42] $$S_{cor}(t)=\Delta\overline{S}(t)+\left|\overline{S}(t)\right| \qquad (10)$$

[43] FIG. 4 shows three curves corresponding to equations (8)-(10). Leakage current data of a third stage under a positive voltage is taken as an example, time τ=14 s corresponding to a first zero point $\overline{S}(t)$ or a first local minimum point $\Delta\overline{S}(t)$ is appropriate delay time. A minimum point of $S_{cor}(t)$ is τ_w=28 s, and is also a selected time window value, from which m=3 may be obtained. For a first stage and a second stage at a positive direct current 75 kV, corresponding values of t are 15 s and 10 s, and values of m are 3 and 4.

[44] (2) A phase space is reconstructed: a phase space is reconstructed on the basis of τ and m$\{X_j, j=1, 2\ldots, M\}$.

[45] (3) Nearest neighbor points are searched: a nearest neighbor point for each point X_j in the phase space is found, and a constraint is applied to transient separation, i.e.

[46] $$d_j(0)=\min\left\|X_j-X_{\hat{j}}\right\|,\ \left|j-\hat{j}\right|>T \qquad (11)$$

[47] (4) A distance between neighboring points is calculated: for each point X_j in the phase space, a distance between neighbor point pairs after an i-th discrete time step is calculated:

[48] $$d(j)=\left|X_{j+i}-X_{\hat{j}+i}\right|,\ i=1,2,\ldots,\min(M-j,M-\hat{j}) \qquad (12)$$

[49] For each i, an average value of $\ln d_j(i)$ for all j is calculated as $y(i)$:

[50]
$$y(i)=\frac{1}{ph}\sum_{j=1}^{p}\ln d_j(i) \tag{13}$$

[51] In (13), p represents the number of nonzero $d_j(i)$. A regression line is fitted by least square method. A slope of the line represents $Lmax$ of an ice coverage flashover process. FIG. 5 shows that L_{max} is greater than 0 at each stage of the ice coverage flashover process, which means that an LC time series of the ice-covered insulator during flashover has a chaotic behavior, which may be analyzed by chaos analysis. FIG. 5 shows a downward trend of L_{max} from a first stage to a second stage, and then an upward trend of $\mathrm{L}_{\mathrm{max}}$ from the second stage to a third stage. The change indicates that the most obvious chaotic feature of surface discharge appears on the ice-covered insulator in the second stage, which is mainly due to ubiquitous existence of glow discharge. However, with increase in the leakage current, a transient and unstable phenomenon appears on partial arc discharge, thereby intensifying nonlinear features of the time series of the leakage current.

[52] 5. Recurrence plot analysis of the leakage current is carried out. In step 4, it has been proved that the leakage current in the flashover process has chaotic characteristics. In order to effectively extract nonlinear characteristics from the leakage current, the chaotic time series is transformed into a two-dimensional matrix on the basis of a recurrence plot technique. Matrix elements (recurrence points) correspond to combinations of time points associated with similar states in a power system represented by an original time series. The recurrence plot visually shows phase space trajectories of various comparable time instances of an original system in the phase space. When the ice-coverage insulator is subjected to surface discharge, the recurrence plot technique may analyze the surface discharge characteristics of the ice-covered insulator and reveal a relation between the surface discharge characteristics and a nonlinear variation of the leakage current. Moreover, leakage currents of a negative arc and a positive arc during arc discharge have similar relations to arc features, and therefore only positive characteristics are selected to analyze the flashover process. FIG. 6 shows recurrence plots at different stages of a positive direct current. Typical waveforms T1 and T4 are extracted from a stage I and a stage III respectively. Due to the long duration of the second stage, two time intervals exhibiting significant arc discharge, i.e. T2 and T3, are selected. Each time section includes 100 ms of leakage current data. On the basis of calculated values of m and τ, a recurrence plot is generated for each time period.

[53] A topological structure of recurrence is changed significantly at different time periods. Gradual changes of the topological structure and texture of the recurrence plot from the stage Ⅰ to the stage Ⅲ provide a valuable research method for studying the characteristics and changes of surface discharge of the insulator. Distribution of dense dots on the recurrence plot is related to continuous arc burning, which indicates a continuous behavior of surface discharge of the ice-covered insulator. On the contrary, a blank region corresponds to stop of discharge, which represents transition between different discharge modes.

[54] FIG. 6 shows a unique pattern of alternating a large white region and a block region consisting of recurrence points, which indicates a significant change in the dynamic system, and reflects a transition in the pattern of surface discharge of the ice-covered insulator.

[55] FIG. 6(a) shows a surface condition of an insulator during transition from corona discharge to arc discharge at a second stage. The existence of a wide range of vertical and horizontal segments indicates that the state of the leakage current is changed slowly in a certain time range, which indicates that the surface discharge on the insulator is not significant.

[56] FIG. 6(b) reflects a situation that a coarse and bright white arc appears on a surface of an insulator. The number of scatter points is reduced, and time points are densely distributed along a main diagonal. A frequency of alternation between a blank region and dense recurrence points is increased. The feature effectively demonstrates alternative formation and extinction of an arc discharge channel.

[57] FIG. 6(c) reflects further development of an arc. A radius of an arc root and a radius of an arc head in an arc channel are increased, resulting in an increase in discharge energy. Recurrence points are further increased along an accumulation region of a main diagonal.

[58] FIG. 6(d) shows proximity of flashover on a surface of an insulator. During this time, an arc may cross 2-3 insulator single umbrella skirt, and the blank region in the recurrence plot is further reduced, which indicates intensification of the discharge phenomenon, which means that flashover is imminent. During flashover, due to unstable discharge of an electric spark, an instantaneous high current may be accompanied by obvious pulse features.

CLAIMS:

1. A method for analyzing surface discharge based on nonlinear characteristics of a leakage current of an ice-covered insulator, comprising:

1) establishing an experimental platform to manually simulate a glaze ice coverage flashover experiment, studying an arc state of a direct current ice-covered insulator in a laboratory environment, and obtaining original image data by monitoring camera photographing;

2) processing a collected arc gray image, and extracting arc features;

3) analyzing a flashover process on a surface of the ice-covered insulator, and analyzing an arc and a time waveform of voltage and current changes detected during a period from stable discharge to flashover on the surface of the ice-covered insulator;

4) nonlinearly analyzing a leakage current waveform monitored from the previous step;

5) transforming a one-dimensional nonlinear time series of the leakage current into two-dimensional matrix data on the basis of a recurrence plot technique, and effectively extracting nonlinear characteristics of the two-dimensional matrix data, which is configured to detect outdoor insulator performance;

6) on the basis of the recurrence plot technique used in 5), reflecting chaos of a time series of the leakage current by calculating a Lyapunov exponent, and providing quantitative description of a state of a chaotic system; and

7) analyzing discharge characteristics of the ice-covered insulator during surface flashover by means of the recurrence plot technique, and revealing a relation between the discharge characteristics and a nonlinear variation of the leakage current.

2. The method for analyzing surface discharge based on nonlinear characteristics of a leakage current of an ice-covered insulator according to claim 1, wherein a magnitude of the Lyapunov exponent represents an exponential rate of convergence or divergence of a nearby trajectory in a phase space in step 6); in a direction of $L_i<0$, a phase volume shrinks and motion is stable; in a direction of $L_i>0$, a long-term behavior is sensitive to an initial condition and motion presents a chaotic state; $L_i=0$ corresponds to a stable boundary that is a critical case; and therefore, under the condition that a maximum L_i value of a time series is greater than 0, it is determined that the time series is a chaotic series.

REVENDICATIONS

1. Procédé d'analyse de la décharge sur une surface sur la base des caractéristiques non linéaires du courant de fuite de l'isolateur recouvert de glace, caractérisé en ce qu'il comprend les étapes suivantes consistant à :

1) construire une plate-forme expérimentale afin de simuler artificiellement une expérience de contournement sous la pluie, le givre et la glace, effectuer une étude sur l'état de l'arc électrique d'un isolateur à courant continu recouvert de glace dans un environnement de laboratoire, et prendre des photos à l'aide d'une caméra de surveillance, afin d'obtenir des données brutes de l'image ;

2) procéder à un traitement de l'image et à une extraction des caractéristiques de l'arc électrique à partir de l'image en niveau de gris acquise de l'arc électrique ;

3) analyser un processus de contournement de la surface de l'isolateur recouvert de glace, et analyser l'arc électrique pendant la période allant de la décharge stable sur une surface de l'isolateur recouvert de glace au contournement ainsi que des formes d'ondes temporelles des variations détectées de tension et de courant ;

4) effectuer une analyse non linéaire des formes d'ondes du courant de fuite obtenues lors de la surveillance à l'étape précédente ;

5) à l'aide de la technique du graphique récursif, transformer une série temporelle non linéaire unidimensionnelle du courant de fuite en données matricielles bidimensionnelles, et extraire efficacement ses caractéristiques non linéaires, afin de tester des performances de l'isolateur extérieur ;

6) sur la base de la technique du graphique récursif adoptée à l'étape 5), refléter la nature chaotique de la série temporelle du courant de fuite par calcul de l'exposant de Lyapunov, et fournir une description quantitative de l'état d'un système chaotique ;

7) à l'aide de la technique du graphique récursif, analyser des caractéristiques de décharge de l'isolateur recouvert de glace pendant le processus de contournement le long de la surface, et révéler sa relation avec la variation non linéaire du courant de fuite.

2. Procédé d'analyse de la décharge sur une surface sur la base des caractéristiques non linéaires du courant de fuite de l'isolateur recouvert de glace selon la revendication 1, caractérisée en ce que, à l'étape 6), la taille de l'exposant de Lyapunov indique le taux exponentiel de convergence ou de divergence d'une trajectoire proche dans l'espace des phases ; dans la direction $L_i<0$, le volume de phase se contracte et le mouvement est stable ; dans la direction $L_i>0$, le comportement à long terme est sensible aux conditions initiales et le mouvement présente un

état chaotique ; L_i=0 correspond à la limite stable, qui est une situation critique ; ainsi, si la valeur maximale de L_i d'une série temporelle est supérieure à 0, on peut déterminer qu'il s'agit d'une série chaotique.

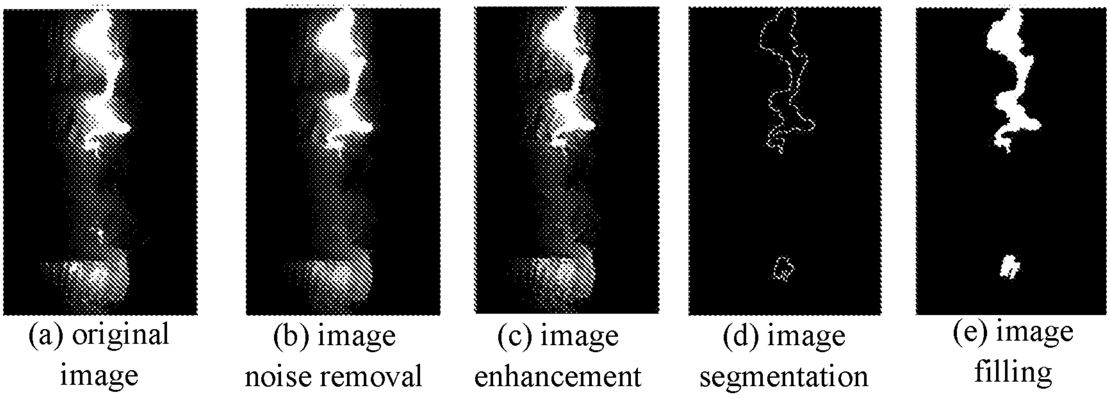

(a) original image
(b) image noise removal
(c) image enhancement
(d) image segmentation
(e) image filling

FIG. 1

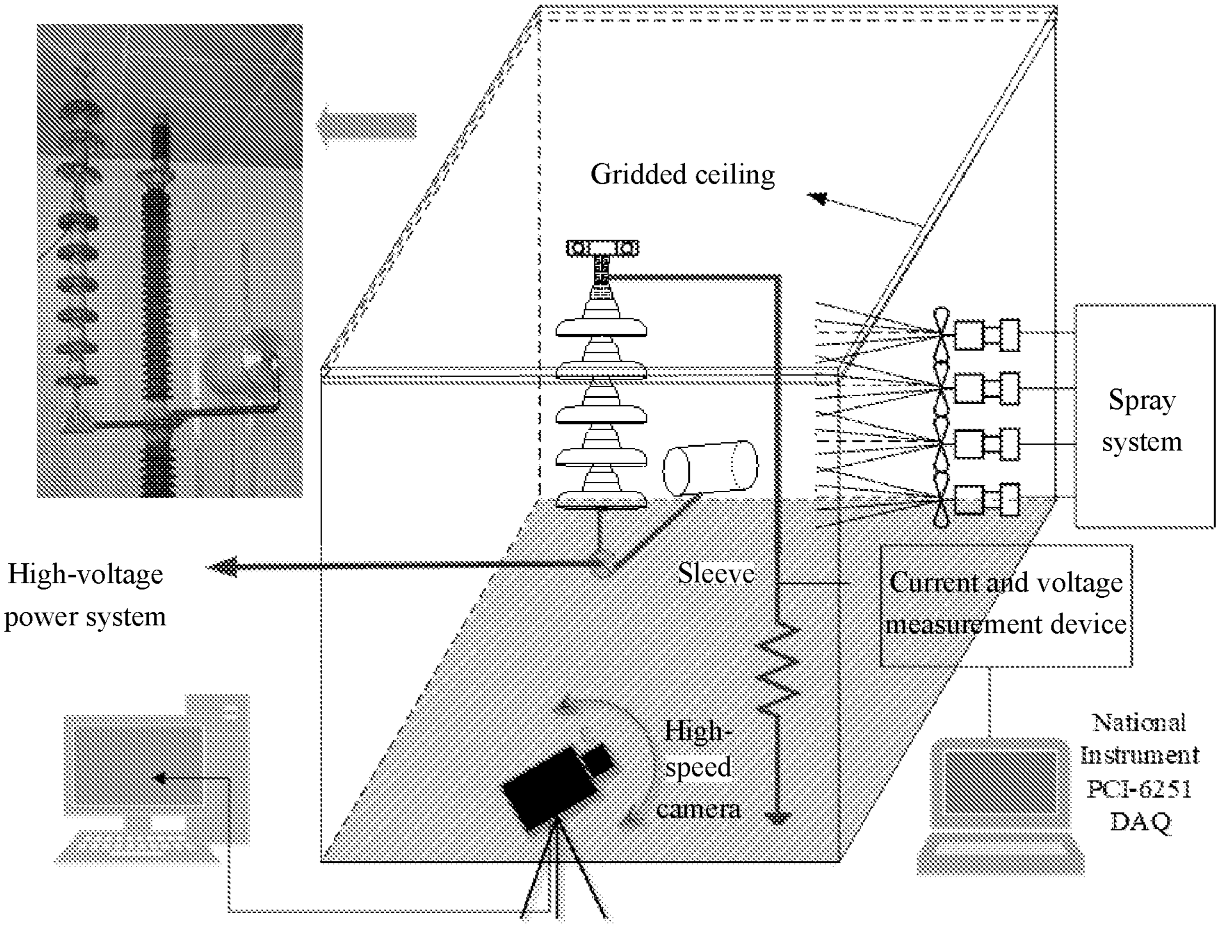
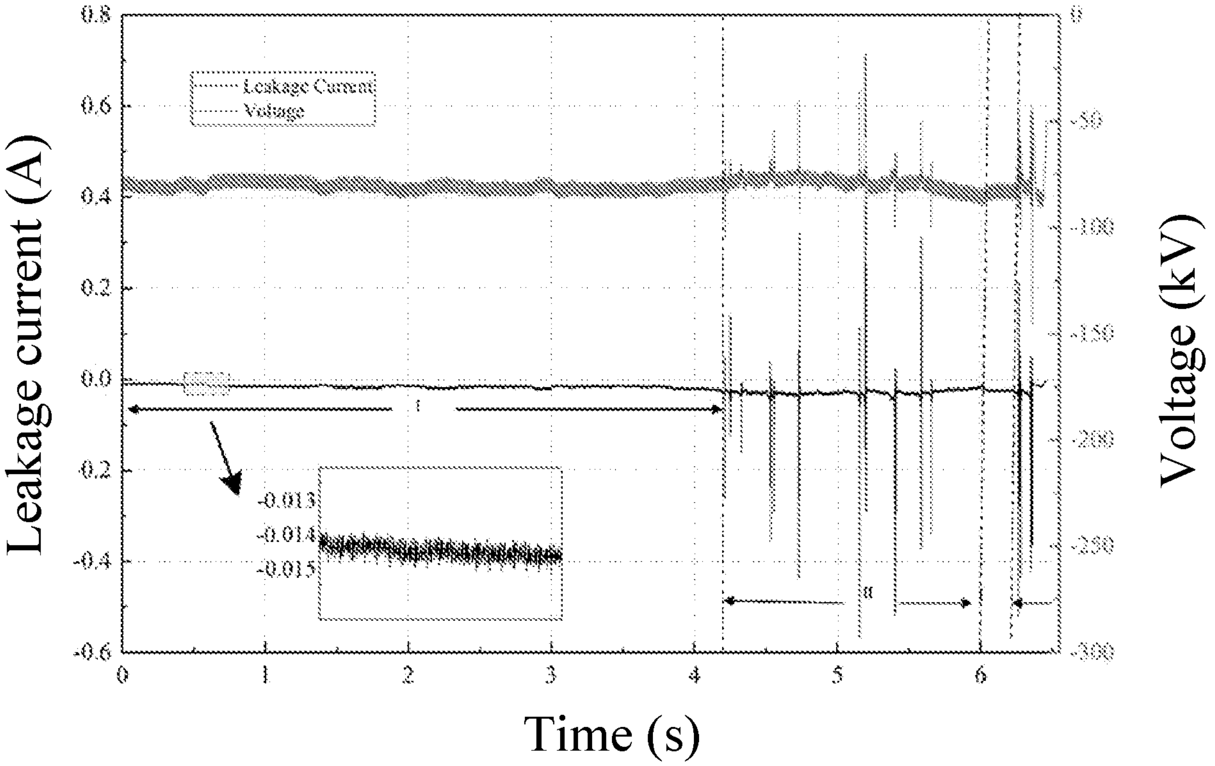
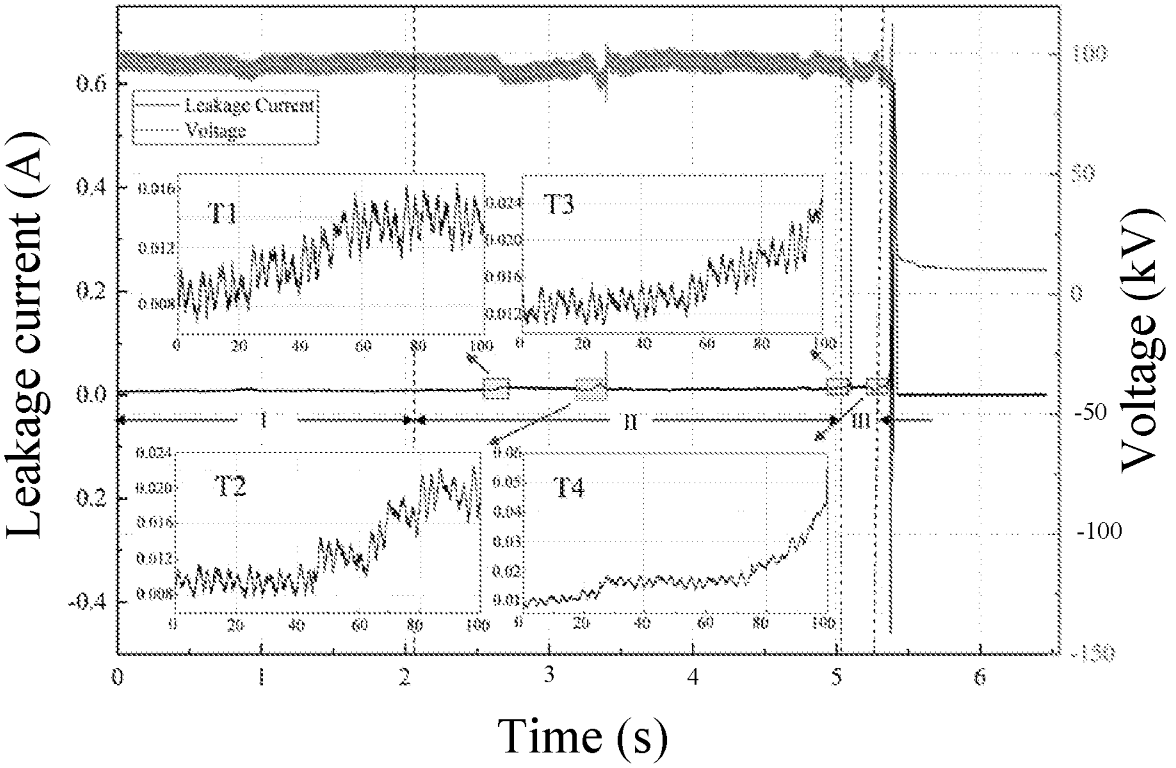

Gridded ceiling
Spray system
High-voltage power system
Sleeve
Current and voltage measurement device
High-speed camera
National Instrument PCI-6251 DAQ

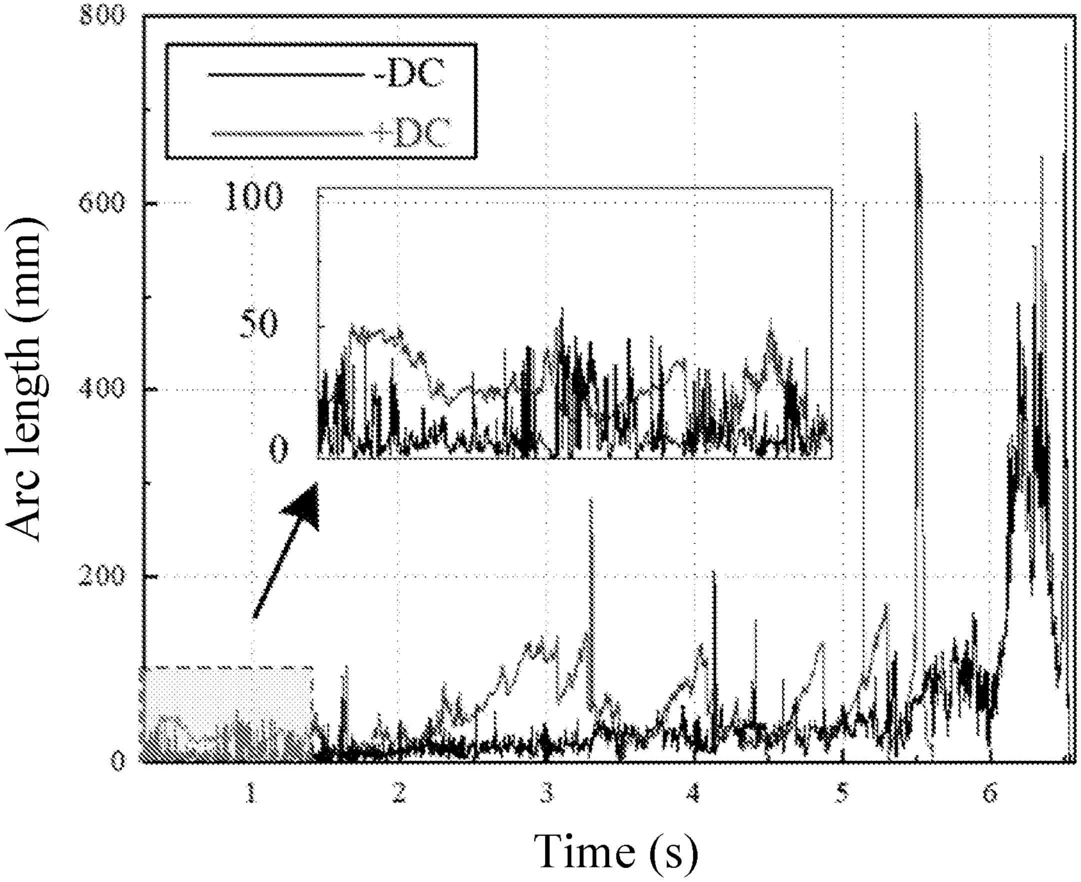
FIG. 2


Leakage Current
Voltage
Leakage current (A)
Voltage (kV)
Time (s)
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
0
-50
-100
-150
-200
-250
-300
0
1
2
3
4
5
6
I
II
-0.013
-0.014
-0.015

(a)


Leakage Current
Voltage
Leakage current (A)
Voltage (kV)
Time (s)
0.6
0.4
0.2
0.0
-0.2
-0.4
100
50
0
-50
-100
-150
0
1
2
3
4
5
6
I
II
III
T1
0.016
0.012
0.008
T3
0.024
0.020
0.016
0.012
T2
0.024
0.020
0.016
0.012
0.008
T4
0.06
0.05
0.04
0.03
0.02
0.01
0
20
40
60
80
100

(b)



(c)
FIG. 3

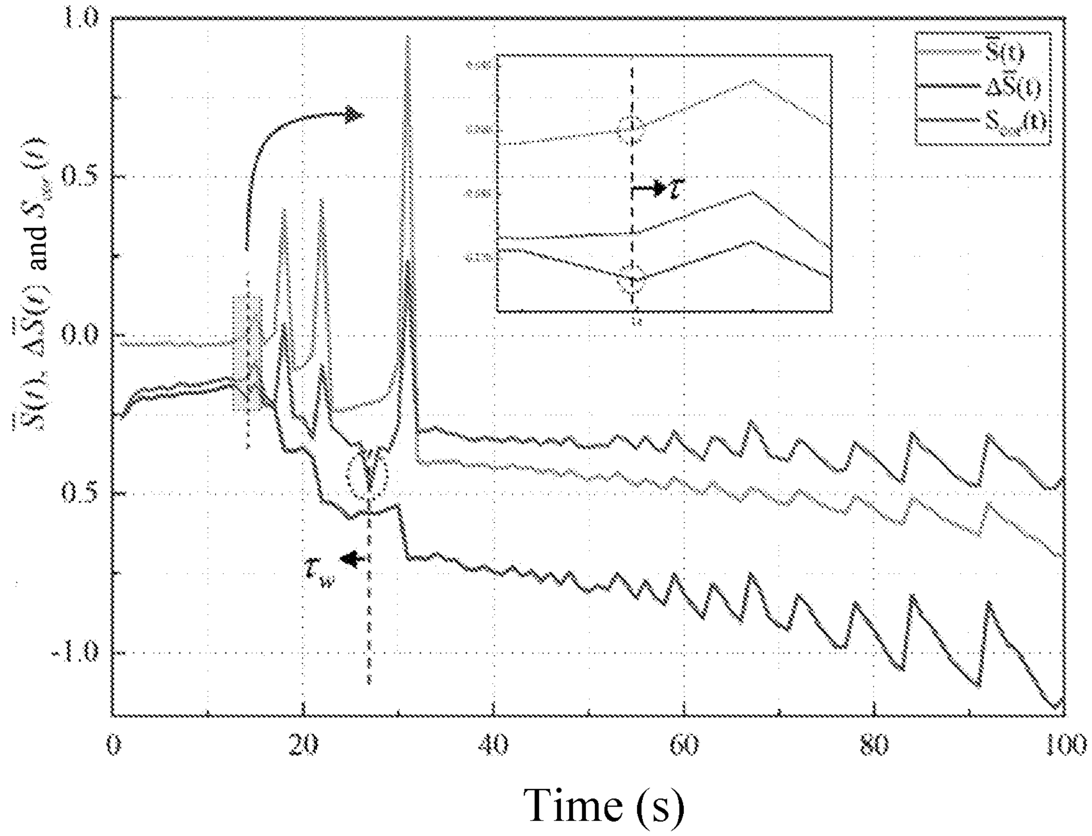

1.0
0.5
0.0
0.5
-1.0
0
20
40
60
80
100
Time (s)
$\bar{S}(t)$, $\Delta\bar{S}(t)$ and $S_{sw}(t)$
$\bar{S}(t)$
$\Delta\bar{S}(t)$
$S_{sw}(t)$
τ
τ_w

FIG. 4

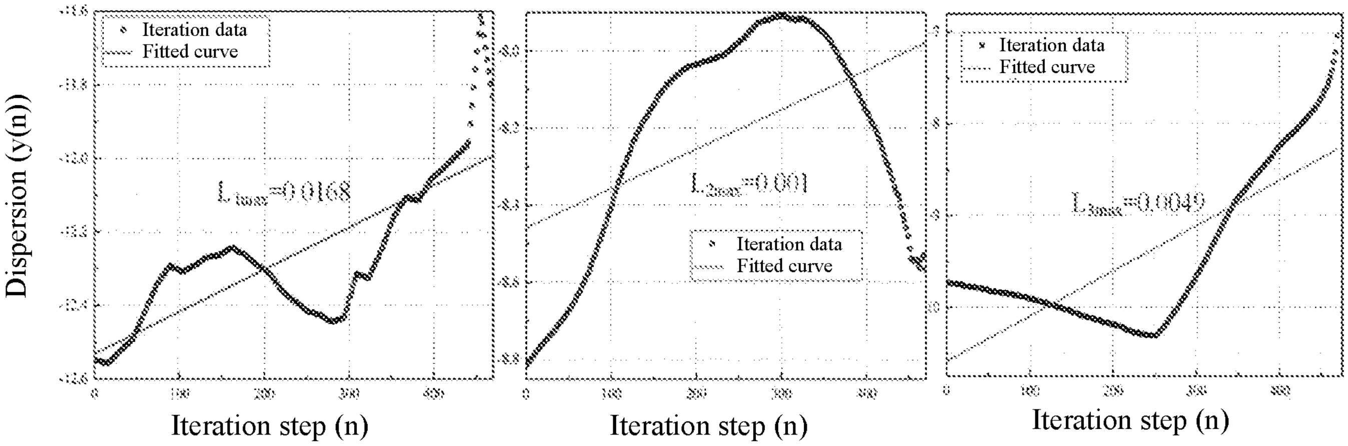
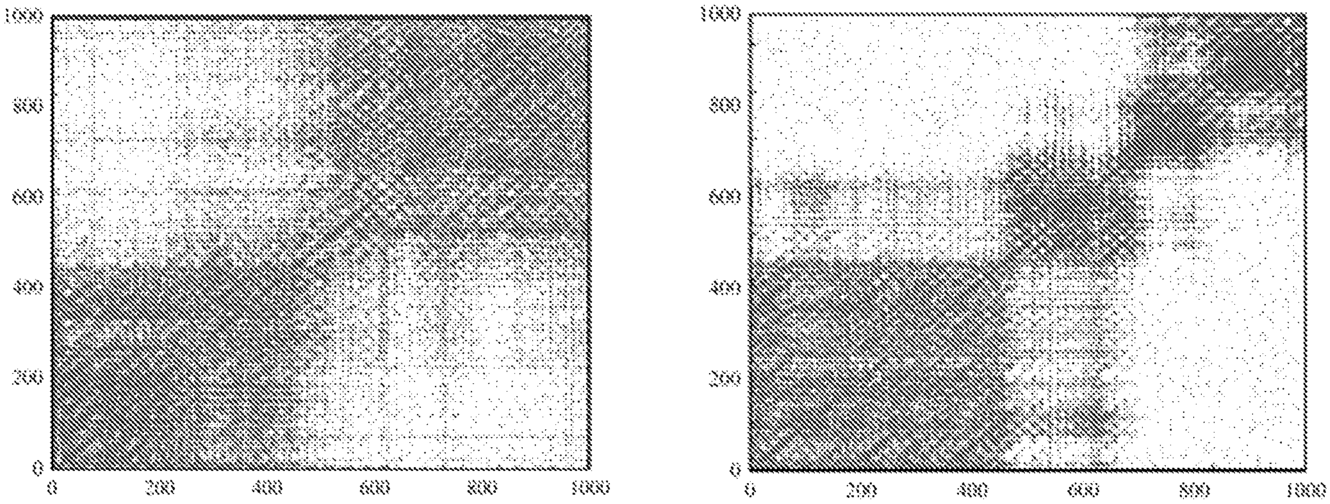
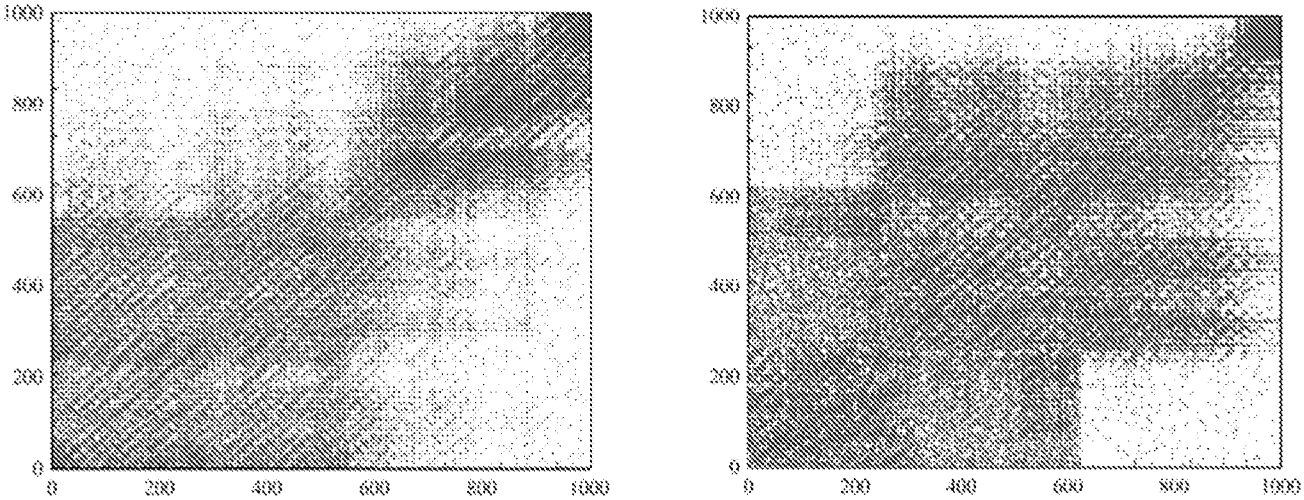

Dispersion (y(n))
Iteration data
Fitted curve
L_{1max}=0.0168
Iteration step (n)
Iteration data
Fitted curve
L_{2max}=0.001
Iteration step (n)
Iteration data
Fitted curve
L_{3max}=0.0049
Iteration step (n)

FIG. 5



(a) T1 (b) T2



(c) T3 (d) T4

FIG. 6