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RESEARCH ARTICLE-ELECTRICAL ENGINEERING

The Application of Recurrence Plot in Tracking Characteristics of PU-Based Insulation Material

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Abstract

Cable joints are the weakest part of underground energy transmission systems due to the presence at the interface between the insulation material and the cable conductor. Underground cables serve under heavy service conditions (dust, dirt, humidity, etc.). So, the tracking resistance of polymers used in joint points of underground cables needs to be determined. In the first section of the study, equivalent samples were prepared under vacuum conditions in laboratory conditions from PU-based filling material used as filler material in low voltage underground cable joints. Prepared samples were tested in an established CTI test setup according to ASTM D5288. Samples were tested in prepared test setup under 600 V, 500 V, 400 V, and 300 V voltages. In the second section of the study, leakage currents were analyzed with the recurrence plot method, which is frequently used in nonlinear times series analysis. Later, recurrence quantification analysis was made by Recurrence Rate (RR) and Determinism (DET) parameters. The behavior of the system occurs less linear with decreased Recurrence Rate in Recurrence Quantification Analysis (RQA). RR and DET parameters increased with the decrease in voltage levels. As a result of, it is revealed that the tracking formation behavior of the PU cable joint becomes more unstable with increasing voltage. Thus, the CTI and RQA are shown to be also available to determine the tracking resistance of cable joints.

Keywords Recurrence plot (RP) · Recurrence plot quantification (RQA) · Tracking failure · Cable joints · Comparative tracking index (CTI) · Tracking characteristics

1 Introduction

The underground power transmission systems are increasing their popularity and prevalence day by day. The cables used in underground power systems are exposed to humid and dirty conditions under service. When insulation materials under wet and dirty conditions are exposed to electrical stress, leakage currents flow from the insulation surface, and surface discharges occur. These surface discharges cause the carbonized conductive paths on the insulation surface. It is a dielectric breakdown called tracking failure. Installation and maintenance costs of an underground cable system are higher than overhead power lines [1]. Therefore, underground cables should be produced against tensile strength, pressure, water absorption, and tracking failure.

Polyurethane (PU)-based filling material is commonly used as filling material in cable joints. Polyurethane consists of combining of urethane monomers. Urethane monomer formed by combining of carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) with covalent bond [2]. In the 1950s, polyurethane was introduced for electrical insulation [3]. Thermoplastic polyurethane has some properties, such as high hardness, high resistance against erosion, and chemical materials. Today, thermoplastic polyurethane is commonly used in the coating of low power cables, the coating of PCBs, and cable joints as filling material [2]. These filling materials consist of two components as resin and hardener. Because commercial energy cables are produced in a finite length, cable joints are frequently used in an underground energy transmission line. The most significant advantage of cable joints used resin is that they can be applied quickly and in a short time. If electric field distribution in cable joints is not

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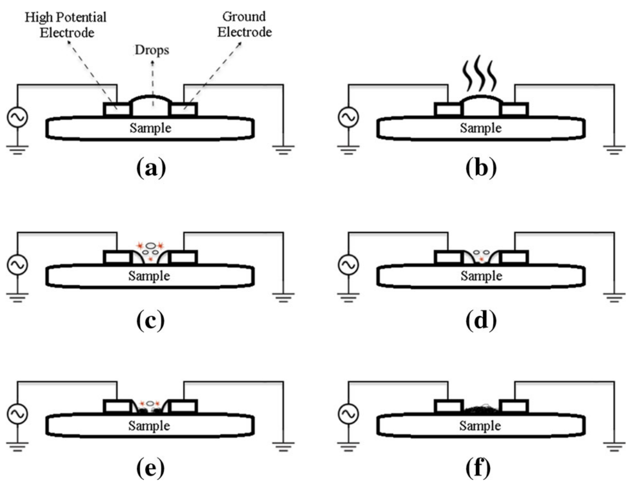

Fig. 1 The process of tracking on insulation surface **a** formation of conductive layer on material surface, **b** the beginning of the evaporation of the electrolyte, **c** formation of surface discharge due to dry-band, **d** the combustion of insulation surface and the beginning of the carbonization on the surface, **e** the developing and propagation of carbonization, **f** breakdown of insulation surface

smooth, then tracking failure probability in insulation material is increased [4, 5]. Therefore, the safety and reliability of polymer insulation materials used in cable joints should be tested.

Insulating materials used in electrical insulation systems are affected by environmental conditions while working in-service conditions. Pollutants accumulate on the surface of the insulating material due to the dirty environmental conditions, and a polluted layer is formed on the insulation surface. The contaminated layer causes the formation of a conductive layer on the insulation surface under moist and wet conditions. Insulation surfaces can resist even very high voltage levels. However, layers of polluted and dust are formed on insulating surfaces with time. These layers can be hazard the safety and reliability of insulation materials under wet conditions by tracking failure [5]. These types of exposure can negatively affect the performance of insulation systems. Electrical tracking failure is a dielectric degradation phenomenon involving carbonized conductive paths on the surface of polymers. The process of tracking formation can be simulated with electrolyte drops between electrodes [6, 7]. The steps of the process of surface tracking are as follows and given in Fig. 1 [8, 9]:

(a) The conductive layer is formed on the insulation surface with pollution and humidity.
(b) Surface currents flow through the conductive layer and it is caused generation of high heating. The heating allows the evaporation of the electrolyte. So, a thin dry-band layer forms between the electrodes.
(c) Surface currents are interrupted due to dry-band. The interruption is caused by increasing electric field between dry-band region. Eventually, surface discharge begins between electrodes.
(d) Due to surface discharge, the temperature of insulation surface increases. With this high temperature on the surface, combustion occurs on the surface of the material and carbonization starts on the surface.
(e) Carbonization is developed and propagated on the insulation surface with time.
(f) The surface discharge starts to become permanent with the increase in the amount of carbonization. As a result, the insulation resistance of the surface is reduced. Finally, the resistance of the insulation is completely loss at the end of the cumulative process. Thus, the insulation surface is degraded.

Comparative Tracking Index (CTI) is an experimental method to determine the tracking resistance of solid insulating materials up to 600 V when wet and contaminants on the surface [6]. In order to determine the resistance to tracking in the polymer material, there are many methods in the literature. For example, recording the discharge quantity, time to dielectric breakdown, evaluating the dielectric loss angle, and the CTI value. The CTI value is exceptionally significant and practical for the selection of insulating materials among these methods [7]. In recent years, the CTI test method was carried out for the determination to tracking the resistance of polymers materials in many studies [7–13]. In these studies, tracking resistances of gamma-ray irradiated PBT (Polybutylene Terephthalate), PET (Polyethylene Terephthalate) and PBN (Polybutylene Naphthalate) [7], tracking resistance with energy absorption during surface discharge in polymeric materials [9], tracking resistance of HTV (High Temperature Vulcanized) and LSR (Liquid Silicone Rubber) used in insulators [10], tracking resistance of PB (Polybutylene) [11], tracking resistance of epoxy/TiO2 nanocomposites under dc voltage [12] and effects of adding nanofiller tracking failure of epoxy/MgO nanocomposites under dc voltage [13] were investigated by CTI test method.

Many various techniques can be applied for fault diagnosis of electrical equipment. Analysis of data (heat, vibration, leakage current, etc.) recorded from devices is of great importance in order to diagnose or predict malfunctions in electrical equipment [14, 15]. There are many methods in the literature for the analysis of signals. Recurrence Plot (RP) analysis is frequently used for the analysis of nonlinear systems in many different fields such as geology, finance, health, and biomedical [10–13, 16]. The leakage currents flowing as a result of deterioration on the surface of the polymers are chaotic signals. These leakage currents are signals with characteristics specific to chaotic signals such as confusion, irregularity, and nonlinearity. In many studies in recent years, recurrence plot analysis has been used to analyze leakage currents flowing from the surface of polymers during the tracking failure.

Fig. 2 The prepared sample under the laboratory conditions

In these studies, Recurrence Quantification Analysis (RQA) was used in conjunction with the recurrence plot to evaluate maps quantitatively [7, 8, 10–13, 17, 18].

In this study, equivalent samples were prepared under vacuum conditions from PU-based filling material used as filler material in low voltage underground cable joints. The surface tracking behavior of prepared samples was evaluated by (Comparative Tracking Index, CTI) test method. Thus, the experiments were applied according to ASTM D5288 test standard. The samples were followed both physically and visually throughout the experiments. After experiments, the weight loss in samples was measured. During the visual follow-up, the number of drops of formed carbonized on the sample's surface, number of drops 0.5 A and above leakage current from the sample surface for 2 s and number of drops of permanent discharge on the sample surface were recorded. Later, leakage currents collected from the ground electrode were evaluated by RP and RQA methods to understand the mechanism of tracking behavior.

2 Materials and Methods

2.1 Material

The mold was kept under a vacuum of 0.01 atm for 1 h in the vacuum chamber using a 5.5hp vacuum pump. After 24 h, the sample was left from molded and cut to size 120 × 50 × 9 mm. All samples were prepared under the same laboratory conditions. The photograph of the prepared sample is shown in Fig. 2. The surface of prepared samples was cleaned with ethyl alcohol at least 24 h before the experiment and dried at room temperature in the oven. The samples were prepared from two-component commercial product used in low voltage underground cable joints. It is a PU-based filling material.

2.2 Surface Tracking Tests

The aim of CTI is to evaluate of tracking resistance of used insulation material in wet and dirty environments at low voltages levels. It was developed by the American Society for Testing and materials (ASTM) and International Electrotechnical Commission (IEC). These test methods are IEC 60112, ASTM D3638, and ASTM D5288. These test methods are known as "Comparative Tracking Index (CTI)" in literature. Firstly, CTI was published in 1959 by IEC [19, 20]. CTI test method was re-approved in 2003 and 2014 by IEC and ASTM, respectively [6, 21].

The surface between the electrodes is tested until the overcurrent relay is activated or until a persistent flame occurs on the sample surface. In this study, the experimental setup is established according to ASTM D5288 standard in Istanbul University High Voltage Laboratory. In the CTI, electrodes with a rectangular cross section of 5 ± 0.1 mm thickness 2 ± 0.1 mm are used and shown in Fig. 3a. Electrodes must have a minimum length of 12 mm [6]. According to ASTM D5288, the length of the electrodes must be at least 20 mm [21]. In order to ensure the reproducibility and accuracy of the obtained results, the electrodes should be grinded to maintain the desired geometric conditions after each test [21]. The electrodes should be placed symmetrically with 60 ± 5° on the sample and shown in Fig. 3b. The gap between electrodes must be 4 ± 0.2 mm in this test method. The photograph of used electrodes is shown in Fig. 3c. The ambient temperature must be 25 ± 5 °C during the experiments. This test does not apply above 600 V. The tracking failure can be determined when a persistent flame occurred on the sample surface or the amplitude of discharge current rose to 0.5 A and has persisted for 2 s [6, 21].

In some samples, tracking failure does not occur even at the highest voltage value. But consecutive electrical discharges may cause erosion on the insulation surface. In order to determine the amount of erosion, the weight loss and depth of tracking formed on the surface can be measured. In this study, the weights of the prepared samples were measured before and after the experiment by analytical balance with 0.1 mg readability.

In the test, a 0.1% NH_4Cl electrolyte should be dropped at most 40 mm above the electrodes with a suitable device. The drops should be dropped on the sample at intervals of 30 ± 5 s. The resistivity of the test electrolyte must be 385 ± 5 Ω.cm at 23 ± 0.5 °C (ambient temperature) [21].

The block diagram and photograph of experimental setup are shown in Fig. 4. Variac was used to adjust the applied voltage. 1 kV single-phase test transformer is used in the experimental setup. It has turned ratio of 220/1000 V. For the short-circuit current to be 1 ± 0.1 A, a pre-resistance with variable resistance is prepared. During experiments, the leakage current was measured and recorded with 48 kHz from the sample surface by an A/D converter.

2.3 Recurrence Plot Analysis

In this study, RP and RQA were used in the analysis of leakage current in order to reveal the dynamics of the system better visually. The recurrence plot is a method used

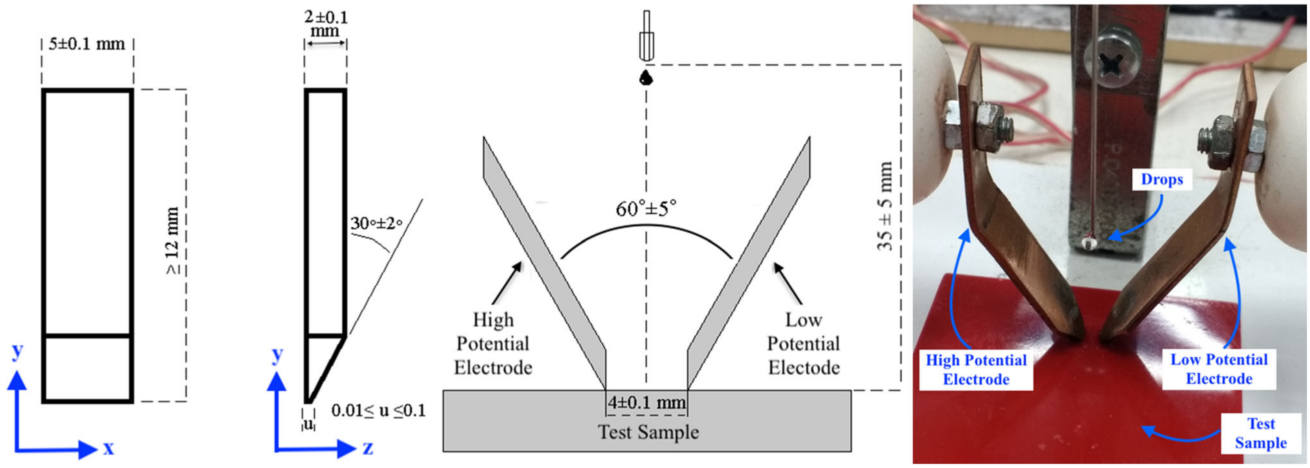

Fig. 3 **a** Electrodes dimensions, **b** electrode/specimen arrangement,**c** photograph of used electrodes

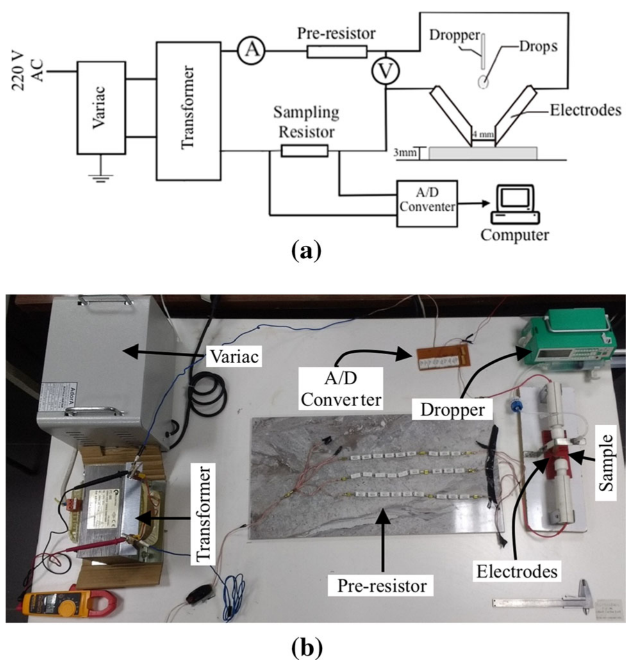

Fig. 4 **a** Block diagram of the experimental setup, **b** established experimental setup

to define the periodicity of time series [7]. This method is graphically revealed repeated conditions in a time series. The recurrence in the dynamics in the structure of dynamic systems can be visualized in a useful and straightforward way by RP. For analysis of a dynamic system, RP was presented by Eckman et al. in 1987 [22]. The aim of RP is to quickly identify nonlinear and chaotic behaviors in dynamic systems with high-dimensional phase space [22, 23]. RP method has advantages over many other methods such as simple cross-correlation in the time domain, or its equivalent in the frequency domain, spectral coherence [23].

In the modeling of dynamic systems, the general characteristic of the system can be defined from the time series containing a single variable. It is called "Takens' embedding theorem" [24]. In Takens' embedding theorem, the time series containing a single variable is used to determine the general characteristic of the system. The basis of RP is based on the Embedding Theorem presented by Takens in 1981 [24]. Based on Takens' Embedding Theorem, a time series can be reconstructed as follows [7]:

$$X(i) = [x(i), x(i+\tau), \ldots, x(i+(m-1)\tau)], \quad i = 1, 2, 3, \tag{1}$$

In this equation; $X_{(i)}$: Embedding Vector, $x(i)$: Times series, m: Embedding Dimension, τ: Delay time.

The selection of m and τ is critical when the embedding vector is obtained with the reconstruction of a time series. While mutual information can be utilized in the selection of delay time, false nearest neighbors can be utilized in the selection of embedding dimension [23]. After the calculation of embedding dimension (m) and delay time (τ), a vector is obtained by reconstruction of the time series. Finally, RP is drawn by the matrix expressed as follows:

$$R_{i,j} = H\left(\varepsilon - \left\|X_{(i)} - X_{(j)}\right\|_2\right),\ X_i,\ X_j,\ R^m,\ i,\ j(1, M) \tag{2}$$

In this equation;

ε: Predefined threshold value, ||. ||: Maximum, Euclid or Manhattan norm, M: Number of X(i) vectors constructed from the time series, $H(x)$: Heaviside function.

Given matrix in Eq. (2), value one is plotted with the black dot in RP, while value zero is plotted with white spaces in RP. The selection of threshold value (ε) is critical for RP. If the threshold value is too big, irrelevant points are produced in RP. However, if it is too small, useful data in times series

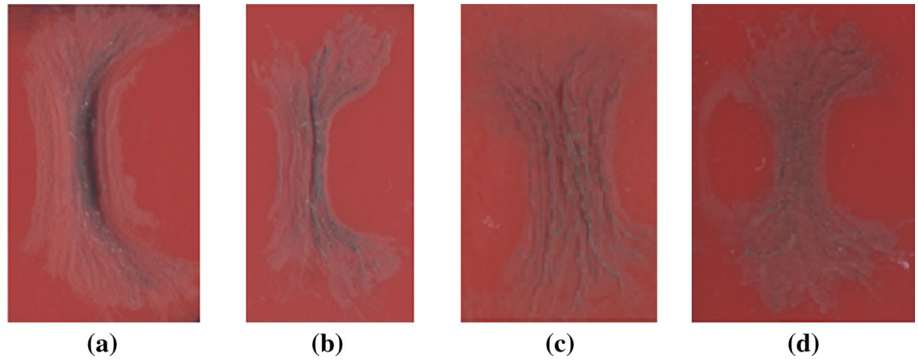

Fig. 5 Tracking on the samples **a** 600 V, **b** 500 V, **c** 400 V, **d** 300 V

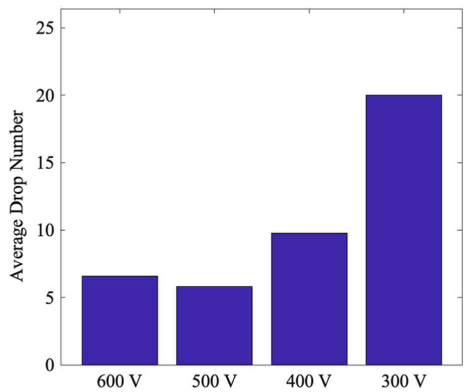

Fig. 6 Average drops number of the beginning of carbonization for different voltage levels

may cause loss [7]. There are some studies for the selection of threshold values in the literature [23]. For the purposes of classification and the detection of differences between signals, the standard deviation of the signal can be used. In the selection of threshold values, it is noted that it is appropriate to select between 20 and 40% of the standard deviation (σ) of the signal [23].

2.4 Recurrence Quantification Analysis

In some systems, points of recurrence plot are clearly determined the dynamics of the system, while in some systems, this may not be so obvious. In the analysis of such systems, researchers may find it difficult to interpret structures and patterns within the recurrence plot. Moreover, different researchers can make different evaluations and interpretations for the same recurrence plot [23, 24]. In order to ensure the objectivity of the methodology, recurrence quantification analysis was introduced by Zbilut and Webber [26, 27]. This method is used to define the dynamics of the recurrence plot [23, 25]. In this study, Webber et al. defined some parameters based on the diagonal lines within the recurrence plot. In this study, Recurrence Rate and (RR) and Determinism (DET) are used. RR defines point density in the recurrence plot. RR of the RP map is mathematically expressed as follows [23]:

$$RR(\varepsilon, N) = \frac{1}{N^2 - N} \sum_{i \neq j=1}^{N} R_{i,j}^{m,\varepsilon} \tag{3}$$

In this equation; ε: Predefined threshold value, N: Number of X(i) vectors constructed from the time series.

In the RP, systems with determinist dynamics are expressed by diagonal lines. The diagonal lines are long for a system with periodic features, while the diagonal lines are short for a system showing chaotic features systems with stochastic properties do not have diagonal lines. The predictability ratio of a dynamic system with DET can be determined. If the DET ratio of a system is high, it can be interpreted that this system contains periodic processes rather than chaotic processes. The DET ratio of the RP map is mathematically expressed as follows [23]:

$$DET = \frac{\sum_{l=l_{min}}^{N} l \cdot P(l)}{\sum_{i \neq j=1}^{N} R_{i,j}} \tag{4}$$

In this equation; $P(l)$: histogram of the lengths of the diagonal lines, l: lengths of the diagonal lines.

3 Results

3.1 CTI Experimental Results

PU samples were tested under 600 V, 500 V, 400 V, and 300 V in the experimental setup according to ASTM D5288. To kept the short-circuit current below 1 A for each voltage, an adjustable pre-resistor packet was designed. Tracking on the sample surfaces with applied 50 drops is shown in Fig. 5. In all of them, the high potential electrode is left on the side, whereas the ground electrode is on the right side. In experiments, the 0.5A current for at least 2 s from the sample surface flowed only under 600 V voltage.

The experiments were repeated five times for each voltage level. The average drops number of formed carbonized, the

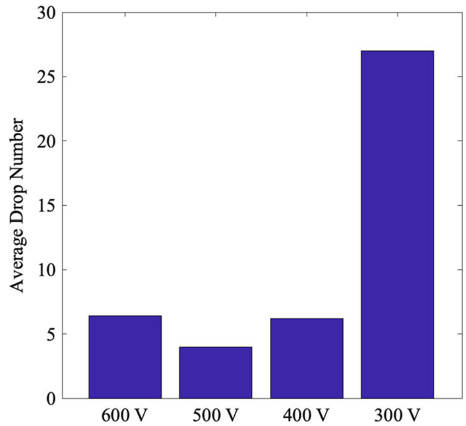

Fig. 7 Average drops number of the beginning of permanent discharge for different voltage levels

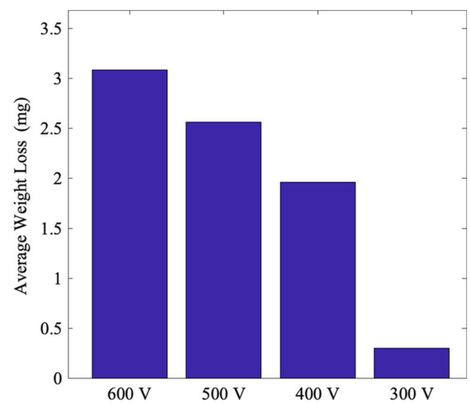

Fig. 8 Average weight loss for different voltage levels

average drops number of permanent discharge and the average of weight loss were calculated after applied 50 drops for each voltage level. The average drops number for carbonization on the sample surfaces for different voltage levels is shown in Fig. 6. The carbonization process on the surface was started at 6.4, 5.8, 9.8, and 20 for 600 V, 500 V, 400 V, and 300 V, respectively. When the applied voltage level reduced from 600 to 500 V, the average number of drops of formed carbonized decreased by 9.38%. When the applied voltage level was 400 V, the average of number of drops of formed carbonized increased by 53.13% and 68.97% compared to 600 V and 500 V, respectively. When applied voltage level reduced to 300 V, the average of the number of drops of formed carbonized has been approximately bigger 3, 3.5, and 2 times compared to 600 V, 500 V, and 400 V, respectively.

The drops number at permanent discharge started on the sample surface was obtained from the leakage current data recorded. The average of them was taken for each voltage level. These are shown in Fig. 7 for different voltage levels. The average drops number of permanent discharges were 6.4, 4.0, 6.2, and 27 for 600 V, 500 V, 400 V, and 300 V, respectively. When these data are compared except for 300 V, the average number drops of carbonization and surface discharges formation are almost simultaneous. In contrast, at 300 V, carbonization occurred first, then followed by permanent discharges.

After the applied experiments with the 50th electrolyte drops, the average weight loss is shown in Fig. 8 for different voltage levels. The average weight loss of samples was 3.08 mg, 2.56 mg, 1.96 mg, and 0.3 mg for 600 V, 500 V, 400 V, and 300 V. The average weight loss of samples under 600 V was higher by 20% than the average weight loss of samples under 500 V. Compared to the average weight loss of samples under 600 V, 500 V, and 400 V, average weight loss of samples under 400 V was less by 36.36% and 23.44% than samples under 600 V and 500 V. Compared to the average weight loss of samples under 600 V, 500 V, 400 V, and 300 V, average weight loss of samples under 600 V, 500 V, 400 V has been approximately 10, 8.5, and 6.5 times of weight loss under 300 V, respectively.

Table 1 Calculated delay time and embedding dimension for different voltages

Voltage level (V)	Delay time (τ)	Embedding dimension (m)
600	6	14
500	2	12
400	2	7
300	3	7

3.2 Results of Recurrence Plot and Recurrence Quantification Analysis

Recurrence Plot (RP) analysis is a method used to define the degree of aperiodicity of time series. With this method, recurrence situations in a time series can be presented graphically. Recurrences in dynamics in the structures of dynamic systems can be visualized in a simple and convenient way using the RP [7]. The collected leakage currents are evaluated by the recurrence plot method. When analyzed by this method for each voltage level, the period of 2 s was taken after the evaporation of drops observed carbonization on the sample surface. The leakage current contains a fundamental power frequency (50 Hz). The periodicity of the AC waveform prevents to unveil nonlinear behavior in time series [7, 10, 17]. Therefore, fundamental power frequency should be decomposed from the analyzed signal before the recurrence plot analysis.

The fundamental power frequency (48–52 Hz) is decomposed from leakage currents by Fast Fourier Transform (FFT). Thus, the predefined threshold is calculated by obtained signals for RP. It was mathematically expressed as

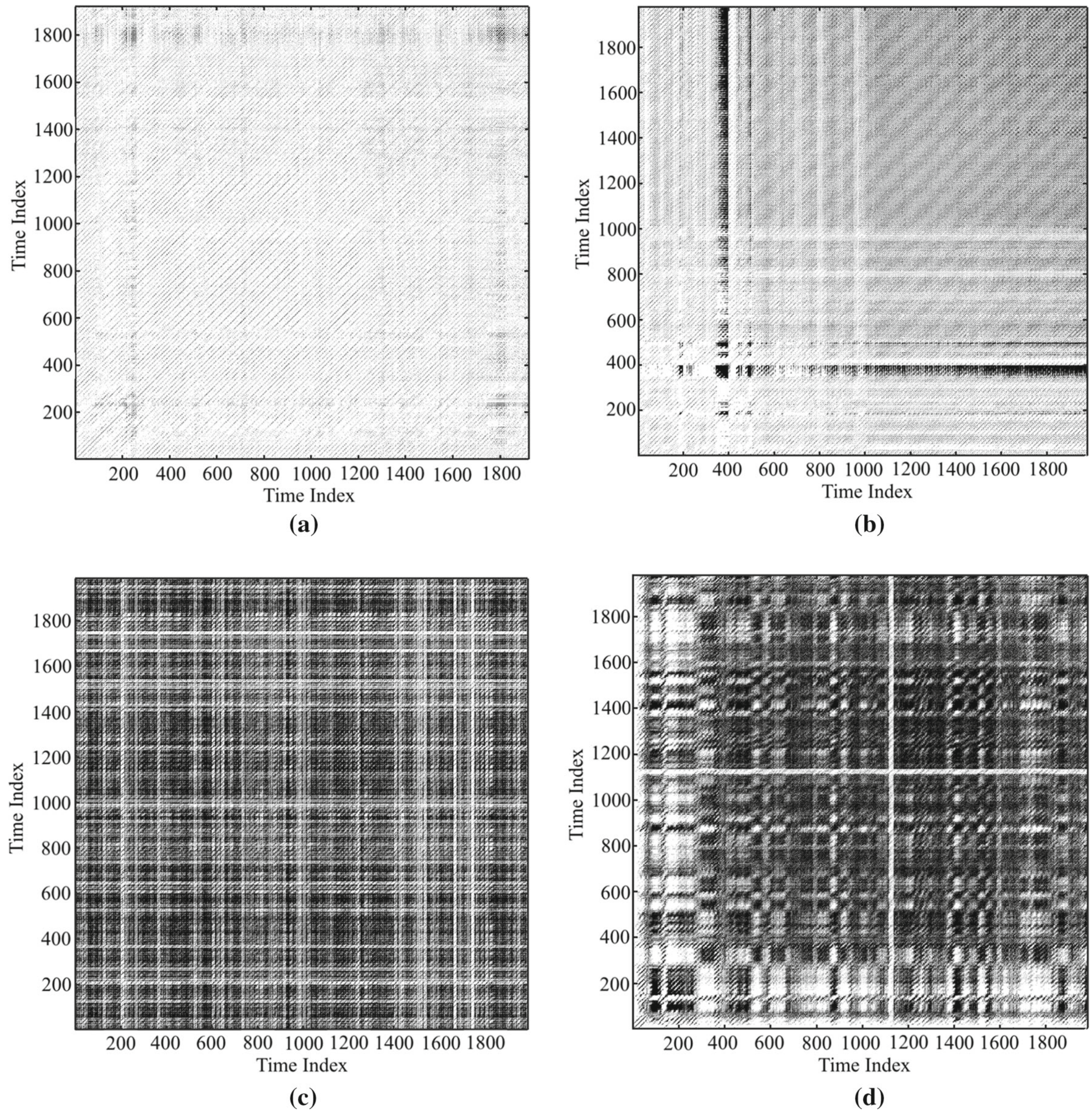

Fig. 9 RPs of leakage current at the beginning of carbonization for different voltage levels **a** 600 V, **b** 500 V, **c** 400 V, **d** 300 V

follows:

$$\varepsilon = 0.4\frac{S_1 + \cdots + S_n}{N} \tag{5}$$

In this equation; ε: Predefined threshold, S_1: Standard deviation of first time series, S_n: Standard deviation of nth time series, N: Number of time series.

The standard deviations of time series were averaged for calculating the threshold, and 40% of the calculated value was considered as the threshold value.

Embedding dimensions and delay times of time series were, respectively, calculated using the false nearest neighbors (FNN) method and common information method for each voltage level. Calculated delay time (τ) and embedding dimension (m) for different voltages are given in Table 1. This table shows that the embedding dimension of the time series increased with increasing voltage levels.

The topological structures of RPs of time series are given in Fig. 9 for different voltage levels. It is clearly seen, white spaces in the RP map of 600 V are more intense than RP maps of 500 V, 400 V, and 300 V. This indicates that the discharge at the voltage level has a greater amplitude value than others. According to RP maps, the leakage currents measured at 600 V and 500 V were shown similar behavior at 0–0.4 s time intervals. After this time interval, it can be deduced from the RP maps that the amplitude of the leakage current measured at 500 V voltage level decreases compared to the amplitude of leakage current measured at 600 V voltage level. So, point

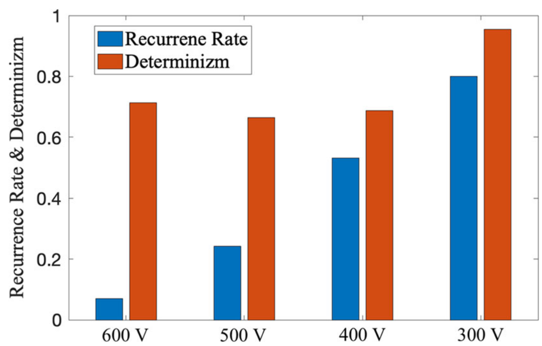

Fig. 10 Recurrence rate and determinism for different voltage levels

density in the RP map at 500 V is more intense at 0.4–2 s time interval. The point density in RPs maps at 400 V and 300 V are almost the same. Point density in RP maps of these two voltage levels is more intense than point density of RPs at 500 V and 600 V. On the other hand, white spaces of RP at 500 V is more intense than white spaces of RPs at 400 V and 300 V. This shows that surface discharges in applied experiments under 500 V are more intensity than applied experiments under 300 V and 400 V. The RP points at the 600 V, and 400 V showed homogeneous distribution. According to RP maps at these voltage levels, surface discharges showed similar behavior throughout the entire time series.

The relationship between the quantitative indicators of Fig. 9 is given in Fig. 10 for different voltage levels. The RR of RP maps are 0.0657, 0.2166, 0.5631, and 0.5636 for 600 V, 500 V, 400 V and 300 V, respectively. The DET of RP maps are 0.5264, 0.5484, 0.7413, and 0.8628 for 600 V, 500 V, 400 V and 300 V, respectively. The RR and DET were increased by decreasing the voltage level. Although the difference in RR between 600 V, 500 V, and 400 V voltage levels is clearly seen, the difference in RR between 400 and 300 V voltage levels is very small. Likewise, although the difference in the DET between 500 V, 400 V, and 300 V is clearly seen, the difference in the DET between 600 and 500 V is very small.

4 Conclusions

CTI is a test method generally applied to cable insulators and polymer isolator materials in the literature. With this study, the CTI test method was applied to the PU, which is used in cable joints as filling material. Later, recorded leakage currents from the sample surface during experiments were analyzed by RP and RQA methods. As a result of these:

- The number of drops of formed carbonized on samples surface at 600 V is greater than the 500 V. But, the number of drops of formed carbonized increased with decreasing voltage level at 500 V, 400 V, and 300 V.
- By decreasing the applied voltage level from 600 to 500 V, the number of drops of formed permanent discharge on the sample surface decreased. The number of drops of formed permanent discharge on the sample surface decreased with the increasing voltage level at 500 V, 400 V, and 300.
- Weight loss of the samples increased with increasing applied voltage levels.
- 0.5 A and above leakage current flowed from the sample surface for 2 s with the application of an average of 20 drops on the sample surface. So, samples have failed at this voltage level. The leakage current flowed from the sample surface did not exceed 0.5 A throughout the time series.
- By decreasing the voltage level, it was seen that the recurrence point density of RPs increased, and the white spaces of RPs decreased. Since the density of white spaces is greater, it is meant from RP maps that high amplitude discharges are more intense with increasing voltage levels.
- According to RP maps of leakage currents at 600 V and 500 V, recorded leakage currents showed similar behavior in the first 0.4 s time interval.
- The RR and DET of RPs increased with decreasing the voltage level.

The chaotic behavior of the leakage current data recorded from the sample surface with the RP method has been successfully visualized and analyzed. By using the RR and DET parameters obtained by RQA, it was ensured that the tracking resistance of the samples could be evaluated quantitatively. In addition, in the visual examinations, it was observed that the size and depth of tracking on the sample surface increased with the increased applied voltage. In order to better understand the tracking behavior, the environmental parameters can be included in a controlled manner for future studies.

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