Study on Partial Discharges Features Evolution of Underground Cable Joints during Insulation Degradation

Chien-Kuo Chang, National Taiwan University of Science and Technology, Taiwan
Chang-Sing Lai, National Taiwan University of Science and Technology, Taiwan
Ruay-Nan Wu, National Taiwan University of Science and Technology, Taiwan

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Abstract
Underground cables are significant links in metropolitan power systems. Hence, any cable accident can cause high economic losses and disruption of service to customers. Recently, the condition-based maintenance (CBM) method proposed to improve the weakness of time-based maintenance becomes feasible in smart grid, which optimizes and improves the reliability of power systems. This paper focuses on analyzing the partial discharges evolution during insulation degradation and researching the proper features for the judgement in the status of condition monitoring. The experimental objects are 25 kV distribution underground cable straight joint containing one of two different type of artificial defects. The total experiment are 10 samples set including five defect X and five defect Y. The partial discharge measurement conducts according to the pulse current method of IEC 60270. Through the noise suppression, data simplification and feature extraction methods, each measured data becomes 104 features. By observing the evolution trend of each features, in the final stage the initial phase of the discharge area extends to the area, which is the voltage zero-crossing zone. This phenomenon might develop diagnostic rules for judging the transition of the insulation state, especially for final stage that is about to insulation breakdown. These diagnostic rules could provide the maintenance personnel simple instructions as an early warning for condition-based maintenance.

Keywords: partial discharge, PD, power cable, joint, feature extraction.

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Introduction

Underground cables are significant link in metropolitan power systems. Hence, any cable accident can cause high economic losses and disruption of service to customers. However, there are huge amount of cables and accessories such that it takes a lot of time and expense to maintain all of them by traditional method, time-based maintenance (TBM). It becomes more feasible to plan maintenance actions according to inspection and diagnosis conditions, which is called condition-based maintenance (CBM).Cable joint must be constructed on site and it may still have potentially fatal defects. Partial discharge (PD) has been regarded as a condition-based maintenance (CBM) which optimizes the reliability of power systems.

There are two main types of research literature on insulation degradation and partial discharge of underground cables. The first one is to conduct electric tree testing using a test platform composed of the insulation specimen and a needle-plate electrode, and to observe the electric tree image of the insulation specimen by using a charge-coupled device (CCD) camera. This research focuses on the relationship between the amount of partial discharge, the branch structure of the electric tree, and the length of the electric tree. In relevant research results, K. Wu et al. found that the conductivity of the electric tree channel can be regarded as an important factor in the discharge activity. When the electric tree channel changes from non-conductive to conductive due to carbonization, the discharge phenomenon may stop for a period of time until the new channel is generated, and it repeats in this way until insulation breakdown. The entire electric tree growth process can be divided into four stages: PD inception, tree growth, after tree growth stops, and after PD extinction. Ibrahim Iddrissu et al. proposed the fifth stage for the electric tree growth process, called reverse tree growth, to illustrate the phenomenon when the electric tree is very close to another electrode. Through further research, H. Zheng found that there were two different electric tree phenomena in the reverse tree generation process, namely, the filamentary tree and the reverse tree, and the pulse phase of the external partial discharge gradually shifted to the area with high test voltage change rate, that is, near the position where the voltage is 0 degrees or 180 degrees.

The second research is to simulate the defect with actual cable samples, which focuses on the practice of partial discharge measurement and insulation degradation. For example, E. Gulski used defective cable joints to obtain a large number of partial discharge test data, and used data exploration technology to design the threshold value of insulation diagnosis. M. B. Ashtiani et al. made a variety of cavity-sized defects in the cable insulation layer, and then, developed a set of decision tree rules for judging the state of insulation degradation by morphologically taking the features of the partial discharge waveform to reflect the deterioration degree of the insulation state.

In summary, the first type of research is easier to repeat a large number of tests, which can facilitate in-depth understanding of the phenomenon and mechanism of partial discharge and insulation degradation under simple conditions. While the second type of research is more difficult to make test objects, it can obtain data under the conditions of the actual power equipment, and plan the diagnostic rules for equipment maintenance. If the two types of research can be mutually referenced and verified, it may help to clarify the theory and application of partial discharge. The author of this paper has long worked in the second type of research, and through multiple cable tests, found that from the initial stage to final stage of the degradation test, the phase of partial discharge shifted to the highest voltage/time derivatives, i.e., at zero crossings, which echoes the discovery of the first type of research literature.

This paper focuses on analyzing the partial discharges evolution during insulation degradation and researching the proper features for the judgement in the status of condition monitoring. The total experiment are 10 samples set including five defect X and five defect Y. The partial discharge measurement conducts according to the pulse current method of IEC 60270.

Partial Discharge Experiment:
The experimental objects are 25 kV XLPE cable straight joint. The total experiment are 10 samples. Each joint contains one artificial defects. Two types of defects: Defect X is the shortage of insulation of cable; Defect Y is a hole inside the cable insulation (φ 3 mm, d 4 mm). The partial discharge measurement conducts according to the pulse current method of IEC 60270. The experiments of partial discharges were implement using the high-voltage laboratory of the National Taiwan University of Science and Technology. The partial discharges measurement is constructed according to the pulse current method of IEC 60270, which consists of the capacitive voltage divider, the subject, and the partial discharge measuring device (MD), as shown in Figure 1.

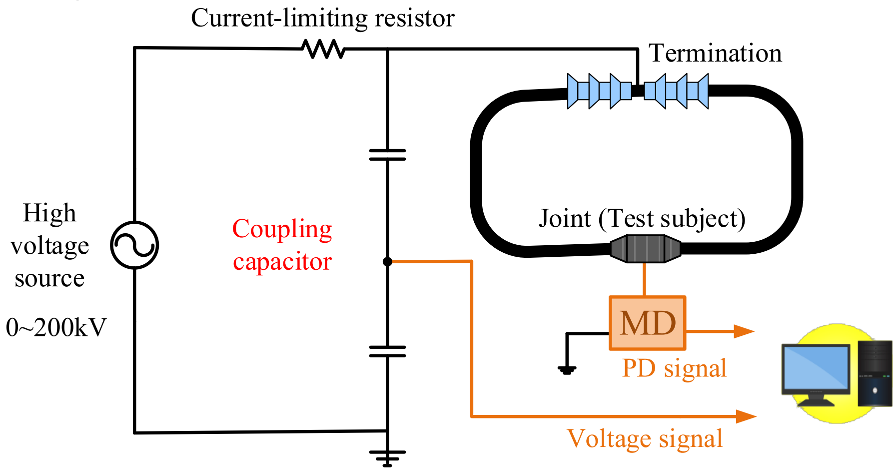


Figure 1: Cable joint experiment and partial discharges measurement.

In the test voltage control, as shown in Figure 2, the method of voltage ascending with resting interval was adopted. The experiment subject was applied from the partial discharge initial voltage (V_{PDIV}) to the breakdown voltage (V_{BR}). The voltage keeps for 2 days and turns off for 1 day (24 hours) and then, raised up in 5kV increments, and so on until the insulation broke down. The reasons for using the ascending voltage is to control the experiment to finish within a feasible amount of time, to avoid the test being too short or too long. To make the sample out of power for one day is to reset the test circumstance intentionally including subsiding space charge if existed. Table 1 shows that the experiment voltages of defect X is from 20 kV to 65 kV and the test voltages of defect Y is from 25 kV to 60 kV.

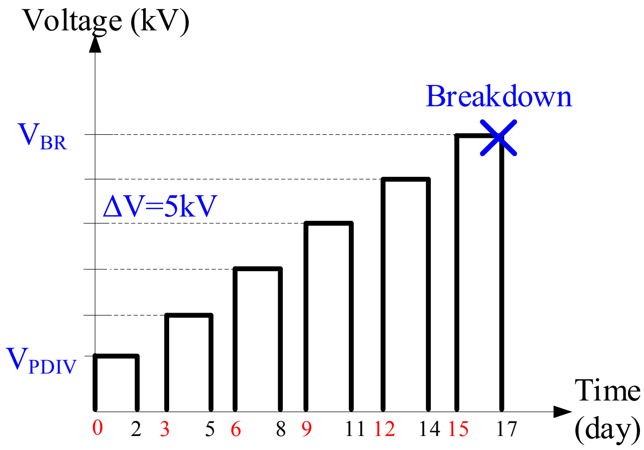


Figure 2: Test voltage control procedure.

Table 1: Test voltage and partial discharge features

Test Sample	Inception voltage (kV)	Breakdown voltage (kV)	Positive phase weight (degree)	Negative phase weight (degree)
X1	20	65	58→2	238→184
X2	20	50	60→18	222→196
X3	20	60	65→12	240→190
X4	20	20	41→28	232→224
X5	20	30	40→27	220→210
Y1	25	30	23→22	220→200
Y2	25	30	33→20	250→198
Y3	25	60	27→20	247→196
Y4	25	30	56→38	250→214
Y5	25	25	33→22	212→197

Figure 3 shows the anatomical schematic diagram and photos of the electric racking experiment objects with broken insulation. It proved that the deliberately-produced defect did induce partial discharges, which was also the inception of discharge position that caused insulation breakdown. Although all discharges began at the defects, the subsequent evolution of the discharge pattern might be different. Hence, they could be classified into two types, namely, the surface type and the electric tree type.

The breakdown trajectory of the surface type started from the defect position on the high pressure side to the outer semi-conductive layer on the low-voltage side via the contact surface of the cable insulation and the joint insulation. The breakdown trajectory of the electric tree type started from defect position on the high-voltage side directly to the insulation of the joint and formed the electric tree; or it formed the electric tree in the joint insulation after a distance through the contact surface of the cable and the joint insulating, and the electric tree finally extended to the outer semi-conductive layer of the low voltage side.

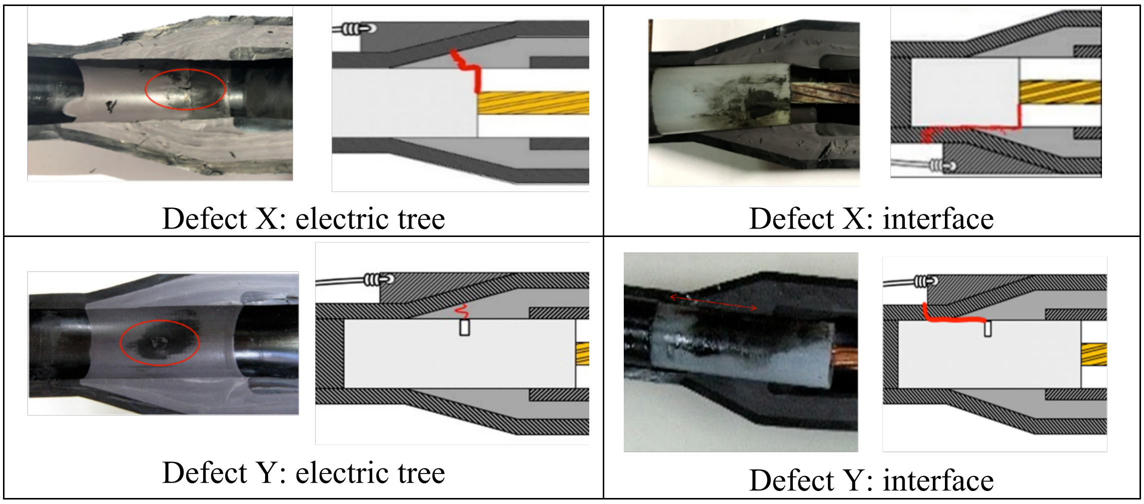


Figure 3: Anatomical photos and the schematic diagram of electric track

In table 1, the phase weight of discharge range (φ_w) of tests has a decline trend. The positive and negative *φ_w* are approximately 50 and 230° in the initial stage; In the final stage, they decrease gradually and approach the quadrant boundaries of 0 and 180°. The equations of phase weight of DPR (φ_w) is described as Equation (1)

$$\varphi_w = \frac{\sum_{t=1}^{T}\sum_{\varphi=1}^{\Phi}(\varphi \times q(t,\varphi))}{\sum_{t=1}^{T}\sum_{\varphi=1}^{\Phi} q(t,\varphi)} + \varphi_{ini} \qquad (1)$$

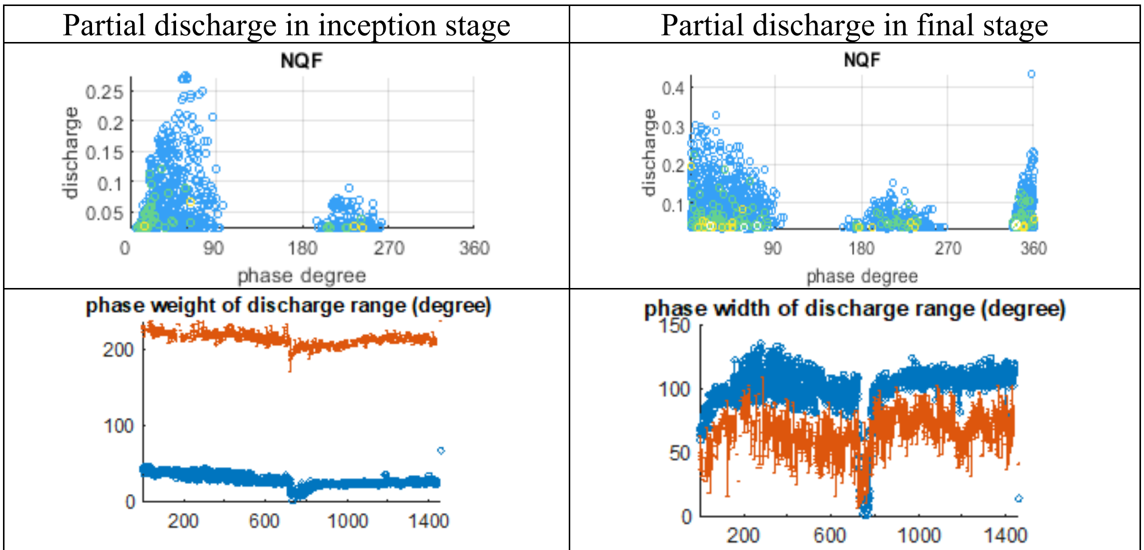
where,

$q(t,\varphi)$: *discharge magnitude in phase window* φ *in the electric cycle t.*

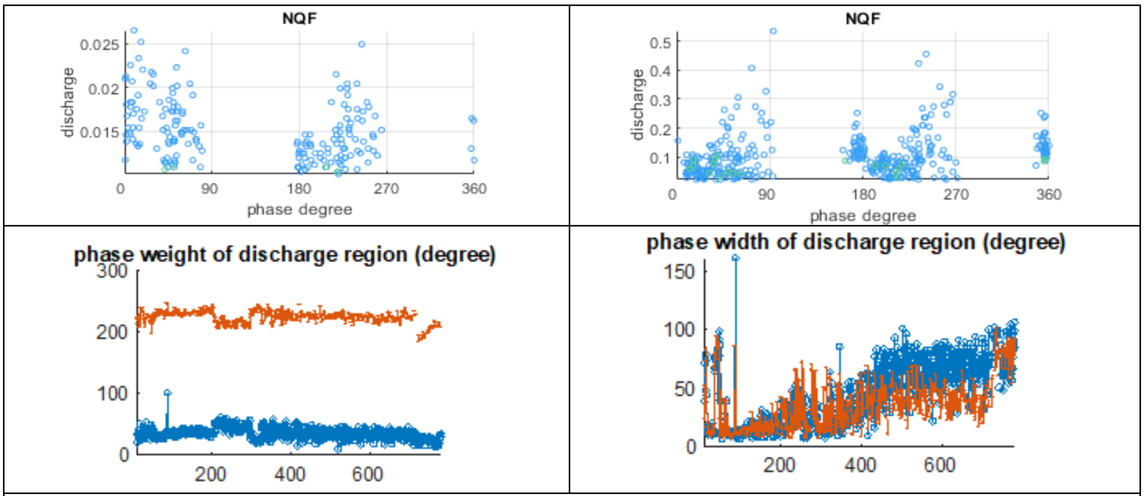
T: total number of electric cycles, 40.

Φ : *total number of phase windows in one electric cycle, 600.*

φ_{ini} : *initial phase of discharge range.*



(a) Defect X5



(b) Defect Y2

Figure 4: Trend of the phase weight of positive DPR and negative DPR

Discussion

According figure 4, it could be found that partial discharges quantities are not always increasing or decreasing, even disappeared for a long time before breakdown. It could be derived that it is too careless to evaluate the overall insulation condition only through the few measurements of the partial discharge data. Hence, long-term measurement data is necessary to develop a comprehensive diagnostic method.

From observing the evolution trend of the feature values, it can be found that, the final stage of the initial phase of the discharge area extends to the area where the voltage variation rate is high, that is, the voltage zero-crossing point, and the discharge area gradually becomes larger. This phenomenon is consistent with the features proposed in literature, and can be used as the basis for judging the transition of the insulation state. Then, after cluster analysis, each test data may be given the definition of the initial stage or final stage of the insulation state.

Conclusion

Since the underground power cable joint must be constructed on site, even if there is a commissioning test after completion test, it may still have potentially fatal defects. For instance, the cavity in the cable insulation may evolve into the electric tree via partial discharges, thereby causing insulation failure. Hence, it is absolutely need to combine online analysis with condition monitoring of the partial discharges and prediction of the breakdown event before occurrence. This paper found that the phase weight of discharge region can be used to recognize the stage of deterioration and these features are independent of discharge magnitude and measurement method.

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Contact emails: chienkuo@ntust.edu.tw