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Improvement of cable defect identification for power distribution networks

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ABSTRACT

Power distribution networks are critical infrastructures that secure delivery of electricity in a power system. Since electricity is mainly distributed through underground 11 kV and 22 kV power cables on Hong Kong Island, the maintenance of underground power cables is one of the most challenging jobs that The Hongkong Electric Co., Ltd. (HK Electric) has to face. This is because excavation for repair and replacement is difficult and time-consuming due to busy traffic and congested underground conditions. In order to improve maintenance efficacy, this study puts forward a new method to screen and locate potential defective component(s) of underground power cables by collectively using online and offline partial discharge (PD) diagnosing methods. The study also introduces new evaluation metrics (standard deviation of mean tan delta, and delta of mean tan delta) to identify cables at risk of developing water trees inside the cross-linked polyethylene (XLPE) insulation. The effectiveness of these two proposed methods has been validated on its distribution network. These improved identification methods for detecting cable defects could further enhance the reliability and security of HK Electric's power distribution system.

KEYWORDS Power system; power distribution network; partial discharge; water tree; smart grid
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1. Introduction

The Hongkong Electric Co., Ltd. (HK Electric) supplies electricity to Hong Kong Island and Lamma Island. Electricity is generated at the Lamma Power Station, then transmitted through transmission (275 kV and 132 kV) and distribution networks (22 kV and 11 kV) to various customers (HK Electric, 2021). Underground power cables are primarily used in both networks in view of their immunity to weather influences, such as typhoons, and because of the highly developed urban areas of Hong Kong Island. Although the design life of the distribution cables can exceed 50 years, their actual performance will be considerably affected if defective components such as cable sections/joints with discharge are not removed promptly and proactively (Zhu et al., 2018; Zhu and Pong, 2019). Hence, continuous inspection and condition assessment are both vital and conducted regularly on the distribution cable network in order to ensure network reliability and safety.

The performance of underground distribution cables can be impaired by several ageing factors, including thermal, electrical, mechanical, and environmental stresses (Aras et al., 2007; Zhu et al., 2017; Zhu et al., 2017). These defects can act separately or synergistically on the cable insulation, and could subsequently cause partial discharges (i.e., a local dielectric breakdown of a small portion of electrical insulation when subjected to high voltage stress) to occur in the cable insulation. Partial discharge (PD) often precedes insulation breakdown in power cables, which can result in costly repairs and possible prolonged outages depending on the extent and seriousness of the damage done by the discharge.

There are different diagnosing techniques available for PD detection, which can either be performed offline or online prior to insulation breakdown (Ahmed et al., 1998; Gulski et al., 2000; Tai and Leung, 2012). In an offline PD test which uses a very low frequency (VLF) test voltage, the underground power cable is disconnected from the load, then energised by the test voltage. The PD signals are detected at the test point and the location of the PD is calculated based on the time difference between the triggered and reflected PD signals. To avoid disconnecting in-service power cables, a number of online PD diagnosing tools have been developed. For example, a PD measurement instrument based on an antenna sensor is presented in the work done by Romano (2019). The sensor is able to recognise different types of PD source by referring to the frequency response of the antenna sensor. However, as the PD signals travel along the cable and decay, the exact defective component/location that generates the PDs needs to be located by shifting the sensor along the cable several times. This is difficult to do, as not every section of the target cable is exposed. In summary, neither the offline nor online PD diagnosing tools fully meet the operational requirements.

Water treeing is one of the main causes behind the shortened lifespan of steam-cured polymeric insulated cable (Steennis and Kreuger, 1990; Liu et al., 2019). Residual water in the insulation system of the power cables leads to long-term effects when the cables are exposed to high voltage. The growth of a water tree causes a reduction in the effective insulation thickness below the point required to withstand the electric stress, after which electrical trees will form and cause the cable to fail. Water trees in a power distribution cable are difficult to detect by PD diagnosing techniques, unless the water tree has already evolved into an electrical tree. To solve this problem, researchers have proposed the time-domain reflectometry (TDR) method (Burkes et al., 2015). This method implements an optimal pulse generator placement algorithm on a cable for performing TDR, and can determine the exact location of a water tree in a cable, regardless of cable length and type. However, as there are thousands of cables in a power distribution network, the inspection workload would be huge if each cable is tested with this additional instrument. Based on current VLF test practice, research in recent years, such as IEEE Std 400.2™-2013 (IEEE Std. 400.2, 2013) and the Cable Diagnostic Focused Initiative (CDFI) – Phase II (Hartlein et al., 2016), has introduced two new metrics, i.e., the difference of Tan Delta readings between two different test voltages and the time stability of Tan Delta measurements at a voltage, to determine and evaluate the defects in a cable. These new metrics may have great relevance to the presence of water trees. Unfortunately, as the judgement criteria in the aforementioned research are mainly derived from data sets in North America, where cables are made from different materials, as well as constructed and installed differently, the results cannot simply be applied to judge the performance of HK Electric's cable network.

In order to tackle the above limitations, this study revisits the problem and proposes new methods to improve the accuracy of identifying cable defects. The study puts forward a new method to screen and locate the PD source using online and offline PD diagnosing methods collectively. This method first uses online PD diagnosing tools to conduct an initial screening for a number of power cables, then deploys offline PD diagnosing tools to countercheck the suspected defective cable components. Furthermore, in order to apply the two new metrics to the cable network, this study reviewed over 3,000 sets of Tan Delta measurement results from the past 10 years to form specific evaluation criteria. The effectiveness of these two methods has been validated in HK Electric's power distribution network.

The structure of the rest of the paper is as follows. In Section 2, the method of using online and offline PD diagnosing techniques collectively for underground power cables is introduced and validated. The details for introducing two evaluation metrics, (i.e., standard deviation of mean tan delta, and delta of mean tan delta) in VLF Tan Delta testing are outlined in Section 3. The conclusion and further work are presented in Section 4.

2. PD detection and location

First the method of deploying online and offline PD diagnosing tools to inspect underground distribution cables is introduced, then a case study using this method is presented.

2.1. Detection strategy

The PD phenomenon in cables is associated with a change in electromagnetic energy, and can be identified by detecting this change without interrupting the operating condition. For example, a series of antenna sensors can be used to measure electromagnetic pulses radiated by PD activity to identify cables with potential PD defects (Romano et al., 2018; Prysmian Group, 2021; Zheng et al., 2019). By putting antenna sensors on the cable surface, electromagnetic signals can be captured if the PD signals travel along the cable and pass through the sensing point. As there is a large number of underground power cables, the online PD diagnosing tool is ideal for initial screening/inspection of cables in batches.

However, the effective measurement distance of the online PD diagnosing tool is constrained up to a few hundred metres because the amplitude of an electromagnetic wave propagating through a conductor decays exponentially (Ishimaru et al., 2017).Thus, for long underground power cables (e.g., more than 1 km in length), PD signals cannot be measured by using a high-frequency current transformer (HFCT) that picks up remote PD signals at the cable termination (IPEC, 2021). Although some portable instruments can be deployed to conduct measurements at several points along the cable surface without service interruption (e.g., to move the online PD diagnosing tool along the cable from point #1 to #2 in order to detect signal strength and polarity to locate the PD source, as shown in Figure 1(a)), it is not easy to access the sections of cable that are installed underground.

In order to overcome this limitation, the offline PD diagnosing method will be used, since it can detect and locate the PD source from either end of the cable. For example, Figure 1(b) shows the use of an offline VLF test at the near end of the cable to receive and analyse the pulse signals from the PD source. Locating the PD source by using an offline VLF test (Romano et al., 2018) is calculated as

$$L_F = \frac{v \times \Delta t_1}{2}, \tag{1}$$

$$\Delta t_2 = \frac{2(L_N + L_F)}{v}, \tag{2}$$

$$L_N + L_F = L, \tag{3}$$

where L_N is the distance between the test location and PD source, L_F is the distance between the cable end and PD source, v is the pulse velocity transmitted in the cable, and is the time difference measured for the triggered and reflected pulse arriving at the testing source.

Therefore, both the online and offline PD diagnosing tools can supplement each other for detection of PD in distribution cables (Figure 2). First, for a number of distribution cables, the online PD diagnosing tool is applied for initial screening at the termination of each cable. For example, Figure 2 shows how a portable online PD detection tool is used to screen at the termination of a series of underground power cables. The suspected abnormal cable will be revealed when the PD signals are detected (e.g., Position B for underground power cable #3 in Figure 2). Second, the offline VLF test is deployed to detect and locate possible PD sources for those suspicious power cables with PD signals picked up in the initial screening.

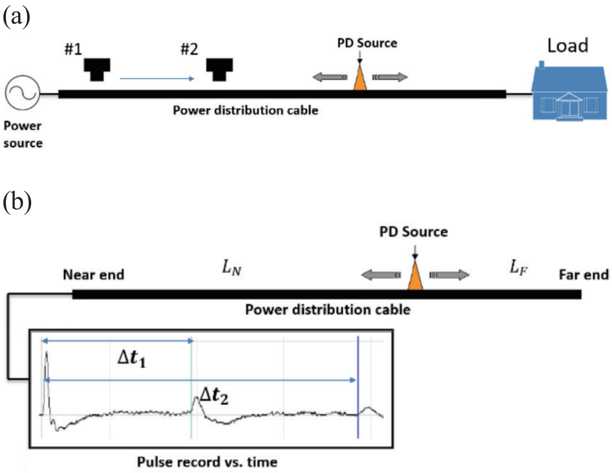


Figure 1. Online and offline PD diagnosing methods for a power distribution cable. (a) Online and portable PD detection method along the cable surface; and (b) offline PD detection and location at the cable termination.

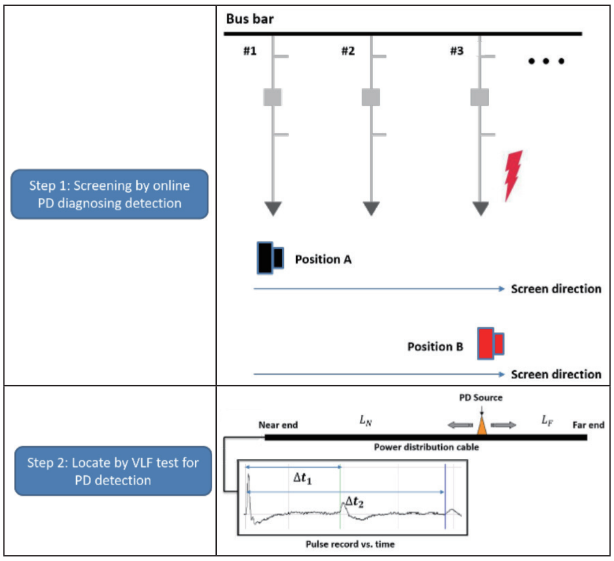


Figure 2. Strategy for collectively using online and offline PD diagnosing methods on underground power distribution cables.

2.2. Case study

The effectiveness of the proposed strategy for the power distribution network was verified through an onsite test in a zone substation (Z/S). The substation consists of four busbars with a total of 56 switchgear panels and 38 outgoing power distribution cables (Figure 3).

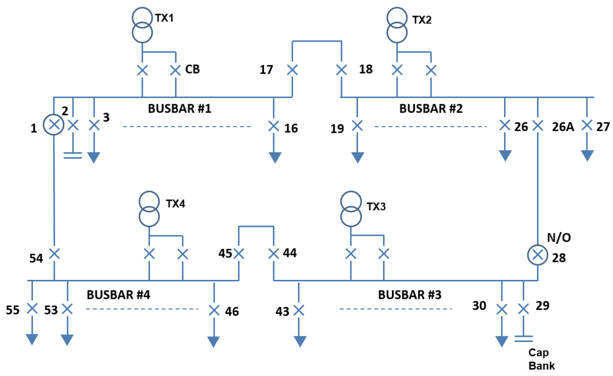


Figure 3. Electrical circuits for the substation, consisting of transformers (TX), busbars, circuit breakers (CB), and capacitor banks.

The initial inspection using the online PD diagnosing tool is as follows.

First, the online PD diagnosing tool with antenna sensors was placed at the termination ends of the outgoing cable from switchgear Nos. 1–16, 19–27, 29–43, and 46–55. An abnormal and strong PD was found at the outgoing cable connecting to Panel No. 46. A magnitude of 623.8 mV (Figure 4) was recorded. This was considered high when compared to the measurement results obtained from other switchgear panels.

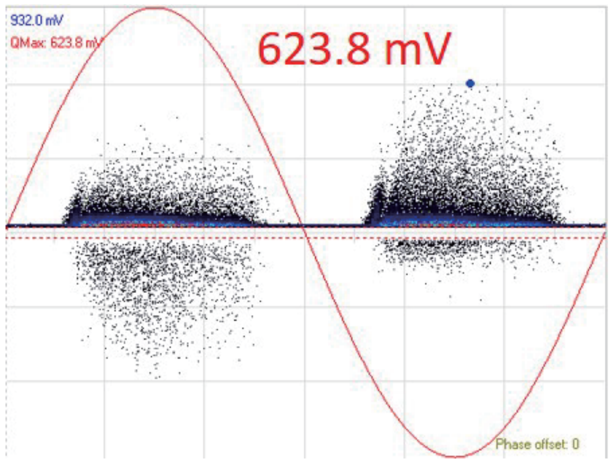


Figure 4. Online PD measurement for the outgoing distribution cable connecting to Panel No. 46.

Since PD signals travel along the cable, the PD source could be generated from any cable component connecting to Panel No. 46 (including the cable section of the outgoing power cable). As it is impossible to access every section of the power cable, the offline PD diagnosing tool was applied. In this case, it was connected to the termination end of the cable (i.e., X-end in Figure 5(a), and Y-end connected to busbar #4, as indicated in Figure 3). The roughly 200-metre-long cable consists of paper-insulated and lead-covered (PILC) sections, as well as cross-linked polyethylene (XLPE) sections. The PD measurement results are depicted in Figure 5(b). In Figure 5(b), the X-axis describes the distance from the X-end, and the Y-axis indicates the detected PD intensity (pC). The Y-end is near Panel No. 46, and the X-end is at the far end of the cable. In Figure 5(b), it can be seen that a concentrated PD signal as large as 3,000 pC was recorded (the scattered points in the middle of Figure 5(b) were caused by discharge inside the PILC cable section, which is normally not harmful due to the self-healing effect of PILC cable). Based on the PD mapping, it was suspected that the discharge occurred at the Y-end of the cable (as shown in Figure 5(b)), close to Panel No. 46. Thus, it was suspected that the PD source was actually initiated from the switchgear instead of the cable.

(a)

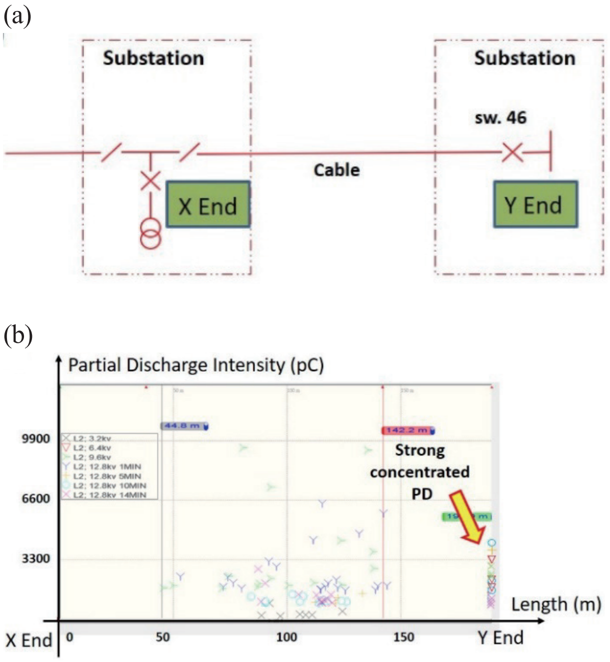


Figure 5. Offline PD diagnosing measurement. (a) Cable circuit diagram connected to Panel No. 46; and (b) offline PD mapping measurement results.

To further identify the PD source at Panel No. 46, the actions in Table 1 were taken to determine whether the PD source existed in the circuit breaker (CB) or the current transformer (CT) of the switchgear, as shown in Figure 6. Figure 6 shows the electrical structure of the switchgear panel, which consists of a connected busbar, CB, CT, and cable, as well as the PD measurement results of the outgoing cable from switchgear No. 46. The subsequent actions indicated that the PD signals still existed even after removing the CB from the circuit. However, the PD signal disappeared after replacing the CT in phase B (see Figure 8). As shown in Figure 8(a), no PD signals were detected in the outgoing cable from the switchgear after the CT was replaced using the online PD diagnosing tool. The offline PD diagnosing test was conducted again from the X-end of the cable, and no concentrated PD could be found, as shown in Figure 8(b). The case demonstrates successful PD screening and identification by deploying both online and offline PD diagnosing tools collectively.

Table 1. Actions taken to identify, locate, and clear the PD source in the circuit of switchgear No. 46.

No.	Action	Result	Interpretation
1	PD was measured at the outgoing cable connecting to the switchgear, with the circuit energised (Figure 6).	Large PD signals (max ~625 mV, as shown in Figure 6).	PD was detected.
2	PD was measured at the outgoing cable connecting to the switchgear, with the CB open but the cable still in service.	Large PD signals were still observed, as in sequence No. 1.	CB defect was excluded.
3	PD was measured at the outgoing cable connecting to the switchgear, with the CB fully racked down for isolation.		
4	PD was measured on the top of the CT during the HVAC test, with the CB racked down and cable termination disconnected.	Max. PD with a magnitude of 953 mV was detected in phase B (Figure 7).	CT in phase B was highly suspected as the PD source.
5	PD was measured at the outgoing cable connecting to the switchgear, after replacing the suspected defective CT using the online PD diagnosing tool.	No PD was detected (Figure 8(a)).	PD was cleared and the CT was confirmed as the PD source.
6	Offline PD diagnosing test was conducted again from the X-end of the cable (Figure 5).	No PD was detected (Figure 8(b)).	

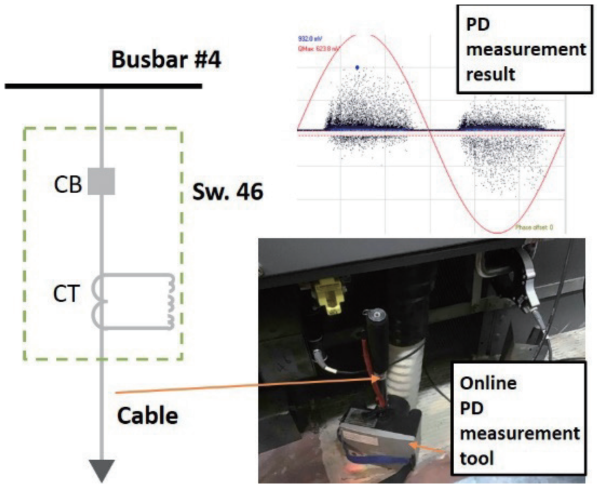


Figure 6. Measurement results from the online PD measurement tool at the outgoing cable from the switchgear.

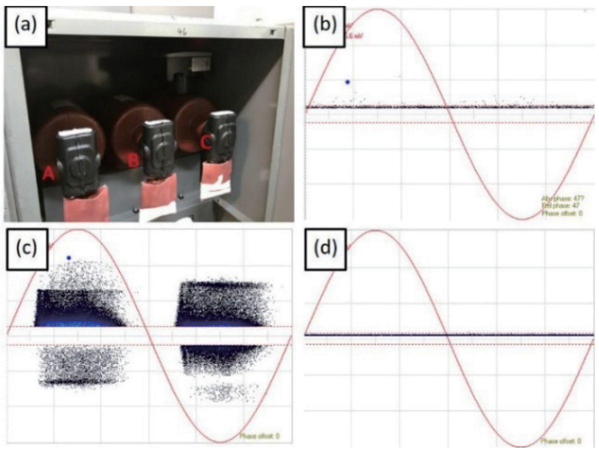
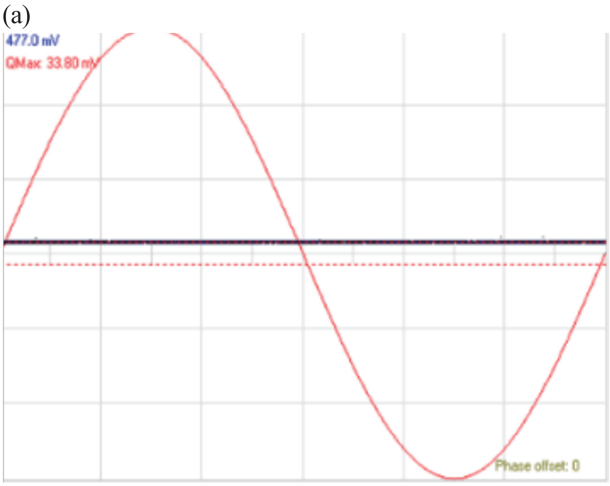


Figure 7. PD measurement on the top of the CT during the HVAC test. (a) Three-phase outgoing cable disconnected from the switchgear; (b) PD measurement in phase A; (c) PD measurement in phase B; and (d) PD measurement in phase C.

(a)



(b)

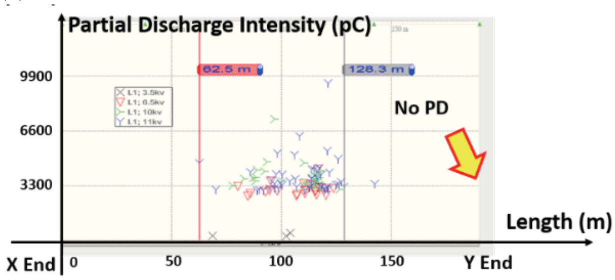


Figure 8. PD measurement after replacing the CT in phase B. (a) Online PD measurement results; and (b) offline PD measurement results.

3. Cable water tree inspection

The process of introducing new evaluation criteria to identify power distribution cables with a high probability of having water tree(s) is introduced as follows.

3.1. Introduction of new evaluation metric

The VLF Tan Delta test is currently used to determine the overall insulation condition of HK Electric's underground power cables (Wong et al., 2016). When a power distribution cable is in a good condition, it more or less acts like a perfect capacitor (Figure 9). The voltage and current are phase shifted by 90 degrees and the current through the insulation is capacitive. However, if there are impurities in the insulation, e.g., moisture, air pockets, and water trees etc., the resistance of the insulation decreases. The current and voltage will no longer be shifted by 90 degrees, and the extent can indicate the contamination level of the insulation. The extent of contamination is evaluated by using Tan Delta ($\tan\delta$) and calculated as

$$\tan\delta = \frac{true\ power}{reactive\ power} = \frac{U^2/R}{U^2\omega C} = \frac{1}{\omega CR}, \quad (4)$$

where U and ω are the source voltage and angular frequency for the test, and C and R are the equivalent capacitance and resistance of the cable, respectively. The larger the $\tan\delta$, the worse the insulation condition of the cable.

To determine the maintenance priority of HK Electric's distribution cables, a five level Health Index based on the δ results is being used as HK Electric's current practice. For example, the criteria of the five levels for XLPE distribution cables with lengths less than 1,000 metres are depicted in Table 2. In the table, the healthiest distribution cables have scores of "1" (lowest $\tan\delta$), while the worst have scores of "5" (highest $\tan\delta$).

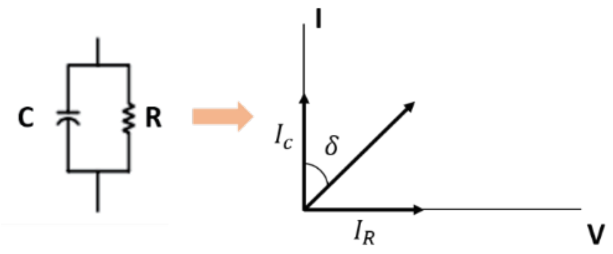


Figure 9. The Tan Delta ($\tan\delta$) measurement for power distribution cables, obtained by measuring the capacitive (I_C) and resistive (I_R) current.

Table 2. Health index for power distribution cables.

Health index	Test result
5	Tan Delta at $1U_0$ or $1.5U_0 > 100$
4	Tan Delta at $1U_0$ or $1.5U_0 > 80$ AND ≤ 100
3	Tan Delta at $1U_0$ or $1.5U_0 > 40$ AND ≤ 80
2	Tan Delta at $1U_0$ or $1.5U_0 > 10$ AND ≤ 40
1	Tan Delta at $1U_0$ or $1.5U_0 \leq 10$

Tan Delta ($\tan\delta$) is an indication of the overall insulation condition of the power distribution cable; however, the causes for non-ideal insulation measurement results can vary, such as aging effects, impurities, and water trees, etc. As such, it is necessary to study and propose new evaluation metrics for the current cable inspection system in order to single-out deteriorations related to water trees and plan for mid- and long-term cable replacement, as water-tree defects are irrecoverable.

Research such as IEEE Std 400.2™-2013 (IEEE Std. 400.2, 2013) and the Cable Diagnostic Focused Initiative (CDFI) – Phase II (Hartlein et al., 2016) have proposed the following two metrics, which are most likely associated with water-tree deterioration in a power cable under a Tan Delta test:

(a) Standard deviation of Tan-Delta (STD). This is the standard deviation of the Tan Delta ($\tan\delta$) measurement at a certain voltage, which is mathematically described as:

$$STD = \sqrt{\frac{\Sigma(TD_i - \overline{TD})^2}{N-1}}, \quad (5)$$

where TD is the measured value of $\tan\delta$ at a certain voltage (Figure 10), N is the number of measurements, and $\overline{TD}$ is the mean value of several measurements.

In general, the measured Tan Delta should be stable over time for a cable with good insulation. However, the leakage current, i.e., the measured value of TD, might change over time if there is a water tree(s) in the cable under an electric field, as the vibration of water molecules under an electric field can alter the conduction degree of the water branches, see the work done by Bolliger et al. (2018) and Yang et al. (2014). Some recent publications have also discovered the relationship between STD and water tree(s) in power cables. For example, Bolliger et al. (2018) observed that an improvement in the Tan Delta value over time during the voltage hold phase; i.e., a downward slope of Tan Delta over time may indicate a drying effect from the application of voltage for an extended period of time. Yang et al. (2014) concluded that the stability of dielectric loss over time has a high linear correlation with long water branches, and a certain linear relationship with short water branches. Thus, the high STD, representing an unstable leakage condition, could be regarded as an indication of insulation deterioration, such as water tree(s), in the cable circuit if a high TD value is also recorded. In light of the harsh underground environment and directly buried underground cable system in Hong Kong, it would be highly likely for a cable section/joint to have been subjected to prolonged water ingress if a high STD is detected.

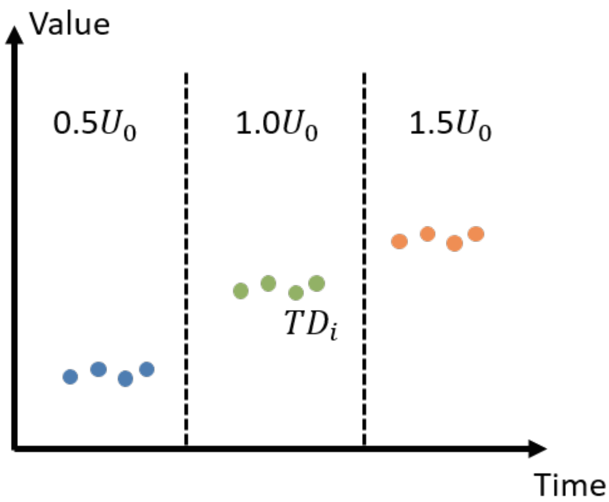


Figure 10. Tan Delta measured at different voltages for several times (U_0 is the rated cable voltage).

(b) Delta of Tan-Delta (DTD). This is calculated as the difference between two mean values of the $\tan\delta$ measured at two respective voltages, which is mathematically calculated as:

$$DTD = \overline{TD}_{1.5U_0} - \overline{TD}_{0.5U_0}, \quad (6)$$

where $\overline{TD}_{1.5}$ is the mean value of several $\tan\delta$ measured at 1.5 times the rated cable voltage, and $\overline{TD}_{0.5}$ is the mean value of several measured at 0.5 times the rated cable voltage.

Based on publications such as IEEE Std 400.2™-2013 (IEEE Std. 400.2, 2013) and Cable Diagnostic Focused Initiative (CDFI) – Phase II (Hartlein et al., 2016), a cable is considered to be defective if a larger value of DTD is obtained. Water tree(s) can be one of the main potential causes for high DTD, as the dielectric performance of insulation with water tree(s) is found to be voltage dependent (Dou et al., 2005). When the outer sheath of a cable is damaged and external moisture enters the XLPE cable insulation, moisture will gather around the impurities of the XLPE, which quickly leads to the formation of a large number of bowtie water trees under the action of the electric field. Because the electric field is uneven and very high in the local area of the impurities, even though the size and quantity of impurities in the XLPE cable medium are very small, the initiation and development speed of water tree(s) can be fast under high electric field intensity. When the voltage reaches a certain value, e.g., 1.5 times the rated voltage applied, the conductivity of water-tree channels might increase suddenly, thus showing nonlinear volt-ampere characteristics (Zhao et al., 2014; Ozaki et al., 2001). As such, by measuring the change of dielectric loss with different voltages, and judging whether the dielectric loss increases significantly with an increase in voltage, the severity of water tree(s) in cables can be evaluated.

In order to apply STD and DTD to evaluate HK Electric's distribution cables, 3,000 sets of Tan Delta measurements from the past 10 years were reviewed. Unfortunately, the criteria stated in IEEE Std 400.2™-2013 cannot be directly used, as its judgement criteria are mainly derived from a data set in North America, where cables are made from different materials, as well as constructed and installed differently. In order to determine the maintenance priority using the new evaluation metrics, i.e., STD and DTD, the Pareto principle, whereby roughly 80% of consequences come from 20% of the causes, was chosen to define the limits. The data set was classified into 0–80% (no action required), 80–95% (further study required), and 95–100% (action required) based on the STD obtained (Figure 11).

Accordingly, the maintenance priority based on the STD and DTD values were summarised to set the criteria (see Table 3). When the STD and DTD are both small, indicating no action is required, the cables are considered safe and without suspected water tree(s). If the STD and DTD are both very high, indicating that action is required, the cables are highly susceptible to potential insulation defects such as water tree(s).

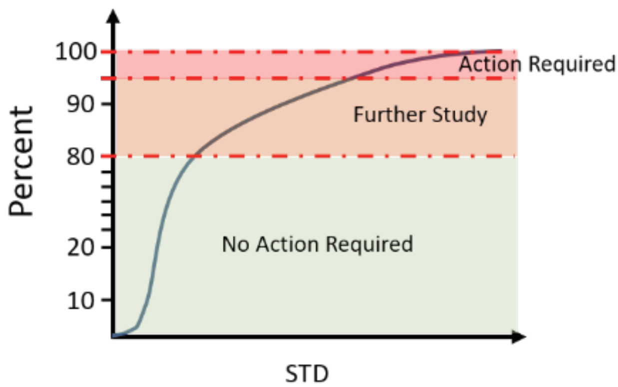


Figure 11. Extraction STD (or DTD) threshold using the Pareto principle.

Table 3. Threshold values for STD and DTD to determine maintenance priority.

Metric	No action required [E-3]	Further study advised [E-3]	Action required [E-3]
STD at U0	STD<0.04	0.04<STD<0.5	STD>0.5
	AND	OR	OR
DTD	0<DTD<2	2<DTD<9	DTD>9

3.2. Case study

To validate the effectiveness of the proposed evaluation criteria, the test results of a faulty three-phase cable (phase A, phase B, and phase C) with a water tree were used. The cable failed during service and the fault was located. After the cable section adjacent to the fault point was dissected, the insulation layer of the cable was sliced; the microscopic scan result is depicted in Figure 12. The length of the water trees were longer than 2.8 mm (the red area indicates the insulation layer between the cable core and sheath). The Tan Delta measurement result is shown in Table 4, and the evaluation are as follows:

(1) For the Tan Delta measured at U_0, the value for three phases were classified as level "1", as per HK Electric's current practice according to Table 2. This result indicated that the whole insulation condition was acceptable.

(2) However, the STD and DTD values were high and exceeded 80% according to the historical records, i.e., 0.058 for STD and 3.349 for DTD, which indicated that the cable had a potential insulation problem, with a high probability of water tree(s).

These STD and DTD metrics indicate that the reading can be used to identify cables with potential water-tree problems.

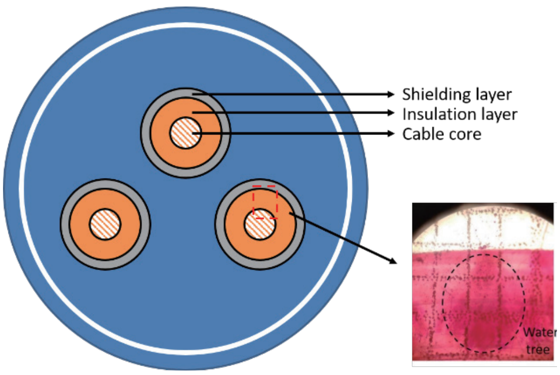


Figure 12. Water tree remark identified in cable sample.

Table 4. STD and DTD measurement results for the tested three-phase cable suspected of having a water tree.

	Tan-Delta (phase A) (E-3)			STD (E-3)	DTD (E-3)
Cable	$0.5U_0$	U_0	$1.5U_0$		
	1.756	1.913	2.113	0.003	0.357
	Tan-Delta (phase B) (E-3)			STD (E-3)	DTD (E-3)
	$0.5U_0$	U_0	$1.5U_0$		
	1.844	2.087	2.333	0.005	0.489
	Tan-Delta (phase C) (E-3)			STD (E-3)	DTD (E-3)
	$0.5U_0$	U_0	$1.5U_0$		
	1.635	2.337	4.984	0.058	3.349

4. Conclusion

The reliability of power distribution cables in a power network plays a pivotal role in providing a secure and reliable supply to customers. As there are tens of thousands of underground distribution cables in HK Electric's network, the maintenance schedule must be arranged such that resources can be focused on those cables with potential problems. This paper proposes a new method to screen and locate potential defective components of underground power cables by collectively using both online and offline PD diagnosing methods. In addition, new evaluation metrices are explored by using the existing VLF Tan Delta test for identifying cables with potential water-tree problems. Some initial studies had confirmed the effectiveness of these method and metrics; however, their effectiveness should be further monitored in HK Electric's distribution networks before full implementation.

In conclusion, the applicability of offline PD diagnosing and VLF Tan Delta methods has been extended in this study. Their practical usage will further enhance operational and maintenance efficiency in HK Electric's power distribution network.

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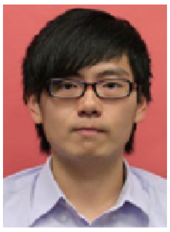
Dr Ke Zhu was born in Yichang, China in 1990. He received his B.Eng. in Electrical Engineering in 2013 from China Three Gorges University (CTGU), China, and obtained his Ph.D. in Electrical and Electronic Engineering in 2018 from The University of Hong Kong (HKU), where he worked as a postdoctoral fellow from 2018 to 2019. He then joined The Hongkong Electric Co., Ltd in 2019, where his main duties are to study and develop the Smart Grid in the power transmission and distribution section of the power grid.



Mr Ting Fat Ng received his B.Eng. (first-class honours) and M.Sc. (credit) in Electrical Engineering from The University of Hong Kong in 2014 and 2018, respectively. He joined The Hongkong Electric Co., Ltd in 2014 as a graduate trainee. Since then, he has been engaged in the operation and maintenance of the transmission and distribution system, and is currently an engineer in the Transmission and Distribution Division.

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