

Use of insulation resistance imbalance degree for the condition assessment of power distribution cables

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ABSTRACT

Medium-voltage (MV) underground power distribution cables are critical assets of The Hong Kong Electric Co., Ltd. (HK Electric) for ensuring reliable customer power delivery. The inspection and condition assessment of these power distribution cables are conducted regularly to determine their health. During diagnostic tests, all MV cables have to pass a threshold of insulation resistance (IR) before they can be energised. Low IR readings may indicate a deterioration in insulation related to a high leakage current. However, defining a threshold value to assess the intrinsic condition of the power distribution cables for every test is challenging. This is because the reference value is determined by several factors such as cable length, the composition of the cable circuit, e.g., cable type, number and types of cable joints, service years and surface leakage from cable splices and terminations. In order to tackle this problem, a concept of imbalance degree in IR testing is developed to supplement the existing tests on dielectric losses for the purpose of enhancing the condition assessment of three-phase power MV distribution cables when performing IR measurement. The effectiveness of this method has been validated with historical testing records of 11kV distribution power cables at HK Electric. Based on our experience and study results, this improved method could further enhance the diagnosis and maintenance efficacy of HK Electric's power distribution cables.

KEYWORDS Power system; power distribution network; insulation resistance; smart grid

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1. Introduction

Since its establishment in 1890, The Hong Kong Electric Co., Ltd. (HK Electric) has been instrumental in sustaining the city's economic and quality development (HK Electric Investments, 2021). Electricity is generated at Lamma Power Station, then delivered to various customers through transmission (275 kV and 132 kV) and distribution networks (22 kV and 11 kV). HK Electric has a long record of maintaining a world-class supply reliability rating of over 99.9999% since 1997, even reaching an excellent record of over 99.99999% for three years in a row since 2020 (viz., an average unplanned Customer Minutes Lost of less than half a minute). Recently, HK Electric has been increasing the use of natural gas to generate electricity, reaching over 50% of its total power output in 2022 as part of its ongoing efforts to combat climate change (HK Electric, 2020).

The high reliability and quality of power supply cannot be realised without adopting a systematic life cycle and risk-based approach to asset management of our transmission and distribution system (Zhou et al., 2017; Zhu et al., 2022). In transmission and distribution networks, underground power cables are mainly used at HK Electric, making them less prone to the impacts brought about by adverse weather conditions such as typhoons (Zhu et al., 2017). However, there still exists a significant challenge as to how to manage the vast network of these cables effectively, especially for those which are approaching or have passed their design lives (Bumby et al., 2010; Zhu et al., 2017). Specifically, if defective components such as

cable sections/joints with discharge/water tree(s) are not removed promptly, and proactively, the cable will have a high risk of failure when serving in the network (Werelius et al., 2001). Hence, inspection and condition assessment of power distribution cables are necessary and conducted regularly.

The current major technologies for monitoring the health of power cables are summarised in Table 1. Their principles and operating mode (i.e., online or offline) are illustrated as below:

- (1) Partial discharge (PD): the PD phenomena are local dielectric breakdowns of a small portion of electrical insulation that is subjected to high-voltage stress (Refaat, 2018; Zhu et al., 2019). It can result from weak spots, e.g., voids, cracks or particles in bodies, joints and terminations of power cables. PD measurement and analysis are widely adopted in order to check the insulation quality of power cables and cable accessories before on-site commissioning or for troubleshooting when cables are in service. Recently, there has been an increasing number of online, e.g., usage of high-frequency current transformers clamped in cable networks, and offline, e.g., PD measurement under very-low-frequency tests, PD monitoring applications in the market, thanks to the development of PD sensors, data communication, acquisition, and storage technologies (Sheng et al., 2014).
- (2) Dielectric loss: dielectric loss measurement is also named tan-delta testing to reflect the integrity level of cable insulation (Perkel et al., 2013). This offline

measurement technique treats the cable as a simplified equivalent circuit consisting of a resistor and capacitor. Tan-delta is defined as the ratio between the resistive and capacitive current. Different criteria have been developed for diagnosing a cable insulation system using tan-delta values based on IEEE400.2 (Hampton, 2007).

- (3) Insulation resistance (IR): cable insulation is an essential protective material for cable conductors (Soma et al., 1986). A DC test voltage is applied to determine how strong the insulation is for prevention of leakage of current flowing through the insulation of a complete cable. The IR level of a power cable will decrease when the cable ages over time or has intrinsic insulation defects. Hence, it is necessary to ensure a good pass in the IR test for reliable service of power cables (Tai et al., 2012; Zhu et al., 2018).
- (4) Space charge: space charge measurement is mainly developed for high-voltage DC power cables (Fu et al., 2007). The space charge that accumulates in the cable dielectric will lead to distortion of the electric field and accelerate cable aging and premature failures. A direct method for measuring space charge distribution in dielectric materials is the usage of Pulsed Electro Acoustic (PEA) based on the CIGRE TB 496 Standard (Buchner et al., 2019). Extensive studies have been conducted to understand better the evolution of electric fields and space charges over time.

Table 1. Major technologies used for the condition assessment of power cables.

No	Technology	Principle	Mode
1	Partial discharge	Local dielectric breakdowns of a small portion of electrical insulation that is subjected to high-voltage stress.	Online/Offline
2	Dielectric loss	Dielectric loss increases its magnitude during the service life of power cables, or with insulation degradation.	Offline
3	Insulation resistance	Poor or damaged insulation may result in short circuits, electric shocks, or fire.	Offline
4	Space charge	Space charge that accumulates in cable dielectric leads to distortion of local electric field and accelerates cable ageing.	Offline

As per the current practice of HK Electric, the partial-discharge, dielectric-loss, and IR methods are mainly used for evaluating the health of MV power distribution cables (Tai et al., 2012). Among them, IR measurement is still the most convenient application, thanks to its easier measurement, straightforward data interpretation, and lower instrument cost than other techniques (Yuan et al., 2017). Nevertheless, there are difficulties in its practical usage, viz., how to quantify a specific IR threshold in condition evaluation for each power cable test (Choudhary et al., 2022; Zhu et al., 2015). This is because the reference value is determined by several factors such as cable length and the composition of the cable circuit, e.g., cable

type, number and types of cable joints, service years and surface leakage from cable splices and terminations. Many researchers have endeavoured to solve this problem in past years. The authors (Um and Lee, 2014) utilised the time rate of IR change following a decay-accelerating factor in the Arrhenius equation to determine the cable lifetime. However, it will be based on two different measurements, and thus not feasible to inspect newly constructed cables or overlaid ones in commissioning tests. Researchers (Yi et al., 2022) developed Weibull analysis to link the failure rate of a cable with its age and type. However, it will increase the workload for onsite engineers regarding inputting the cable details for each section. A new onsite and non-destructive technique, Polarisation Current Analysis (PCA), was developed to evaluate the reliability of the three-phase XLPE cables (Watson et al., 2004), but the frequency spectrum of dissipation factor and capacitance must also be measured in addition to IR. Thus, it is not easy to apply. Korea Western Power Co., Ltd. utilises a newly developed device to predict the lifetime of power cables by measuring IR, yet this product is still not commercially available for other power utilities to purchase (Um, 2017). In order to tackle the problem, a concept of imbalance degree in IR testing has been developed to enhance the condition assessment of three-phase power distribution cables by IR measurement at HK Electric. This developed method has overcome the limitation mentioned above, and is also efficient and convenient to operate for onsite engineers. In addition, there is no further cost involved due to having to purchase or develop new measurement devices for evaluating the remaining life of power cables. The feasibility of this method has been validated by reference to the testing records of the 11kV distribution power cables of HK Electric.

The structure of the rest of the paper is as follows. Section 2 introduces the principle and methodology of IR measurement for an MV three-phase power cable, followed by an illustration of how to define the IR imbalance degree and how to use the IR imbalance degree to evaluate a power cable's condition. Section 3 presents several cases to demonstrate the feasibility of the developed methodology. The conclusion and further work to be carried out are presented in Section 4.

2. Cable insulation resistance test

This part introduces the IR measurement method of an MV three-phase power distribution cable. The principle of IR imbalance degree for insulation resistance is presented.

2.1. Insulation resistance measurement

Measurement of the insulation resistance between the cable conductor and armour of a power distribution cable is a non-destructive test, and it is a way to determine the condition of cable insulation for the purpose of

inspecting any contamination due to moisture, dirt, and so on (Andjelkovic et al., 2001). The insulation resistance is measured using a Megohmmeter, and different voltages are used for cables with different voltage ratings. When using a Megohmmeter to measure IR, the following steps are taken (Figure 1):

- (1) Isolate the power distribution cable from the circuit and ensure that it is de-energised;
- (2) Discharge all potentially stored capacitance in the cable by grounding it before testing;
- (3) Connect the line terminal of the Megohmmeter to the phase conductor to be tested;
- (4) Connect the earth terminal of the Megohmmeter to the cable sheath; and
- (5) Similarly measure the IR values of the conductor of other phases, one at a time with other phases connected to earth.

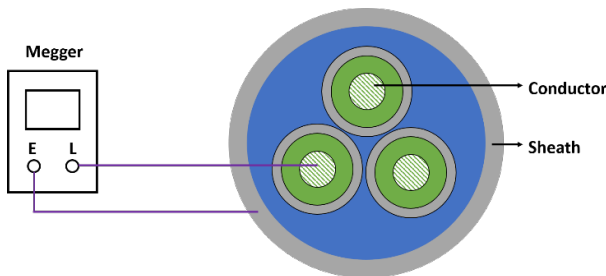


Figure 1. IR measurement of a three-phase power distribution cable.

After the measurement, the insulation resistance should be above a minimally acceptable threshold (Kim et al., 2019). The Insulated Cable Engineers Association (ICEA) stipulates a minimum value of insulation resistance in its specifications for various types of new single-conductor cable, and it is mathematically calculated as

$$IR = K \log_{10}(D/d), \quad (1)$$

where IR is insulation resistance per 1,000 ft of the cable (meg-Ohms), K is a constant depending on the cable insulation material, D is the outside diameter of conductor insulation, and d is the inside diameter of the conductor. Regarding the K value, the minimum values of some common insulation materials used in power distribution cables are listed in Table 2. The K value changes with cable insulation material and temperature.

Based on Equation (1), the demerits of using a constant IR value for assessing the cable condition are summarised below:

- (1) This calculation only works for a single-phase cable, but in reality, the value is more difficult to calculate for a three-phase power distribution cable;
- (2) In actual circumstances, a power distribution circuit may comprise different cable sections of different cable brands, types (PILC or XLPE), lengths, and so on;

- (3) This calculation model does not count the composition of cable joints in the circuit; and
- (4) The K value is subjected to some other influences, such as servicing year of the cable and cable temperature, according to IEEE Std 43 (Electric Machinery Committee, 2013).

Thus, proposing a new index to enhance the condition evaluation of power distribution cables by IR testing is more appropriate.

Table 2. Minimum values of K at 60°F/1,000 ft.

Insulation Type	MΩ
Paper-insulated lead-covered (PILC)	2,640
Ethylene propylene insulation	20,000
Composite polyethylene	30,000
Crossed-lined polyethylene (XLPE)	20,000

2.2. Definition of IR imbalance degree

In principle, the IR measurement of three phases should be homogeneous if the cable body and joints are manufactured and laid without any defects. However, when they are eroded due to insulation defects (e.g., voids, cracks, or particles in the cable body and joints), the IR value will vary. A tiny defect generally originates from one phase, and then evolves to the others before insulation breakdown. Therefore, the three-phase IR measurement will become imbalanced. This observation provides a hint to assess a cable's condition, and thus it is studied and developed in this paper.

The proposed IR imbalance degree for a three-phase power distribution cable can be determined from a simple calculation as follows. Firstly, the IR of each phase is subtracted from their mean value to find out the maximum difference. Then, the total IR imbalance degree is estimated by a ratio of the maximum deviation to their mean value. Numerically, it is illustrated as

$$ID = \frac{|\max(IR_i - IR_{average})|}{IR_{average}} \times 100\% \quad (i = A, B, C), \quad (2)$$

$$IR_{average} = \frac{IR_A + IR_B + IR_C}{3}, \quad (3)$$

where ID is the imbalance degree of a three-phase power cable in the IR test, $IR_{average}$ is the mean value of a three-phase IR measurement, and IR_i is the IR measurement of phase A, B, and C, respectively. Based on Equations (2) and (3), the IR imbalance degree of a three-phase power distribution cable can be obtained in a cable test.

2.3. Range of IR imbalance degree

The range of IR imbalance degree is demonstrated as follows. First of all, the minimal value of imbalance degree of a three-phase power distribution cable is equal to zero if

the IR measurement is symmetrical. This is similar to the concept of a three-phase voltage/current balance in a power system. When one phase begins to deviate, the imbalance degree in Equation (2) is calculated as below:

$$\begin{aligned}
 ID &= \frac{|\max(IR_i - IR_{average})|}{IR_{average}} \times 100\% \quad (i = A, B, C) \\
 &= \frac{|\max(IR_i - \frac{IR_A + IR_B + IR_C}{3})|}{\frac{IR_A + IR_B + IR_C}{3}} \times 100\% \\
 &= \frac{|\max(IR_i - \frac{k_a p + k_b p + k_c R_C}{3})|}{\frac{k_a p + k_b p + k_c R_C}{3}} \times 100\% \\
 &= \frac{|\max(IR_i - \frac{k_a p + 0 + k_a p}{3})|}{\frac{k_a p + 0 + k_a p}{3}} \times 100\% \\
 &= \frac{|\max(IR_i - \frac{2k_a p}{3})|}{\frac{2k_a p}{3}} \times 100\% \\
 &= \frac{\frac{2k_a p}{3}}{\frac{2k_a p}{3}} \times 100\% = 100\% ,
 \end{aligned} \tag{4}$$

where $IR_A = k_a p$, $IR_B = k_b p$, and $IR_C = k_c p$, supposing that $k_A = k_C$, $k_B \ll k_A$ (k_C) when the IR measurement of phase B significantly deviates from the one of phase A (or phase C). This derivation demonstrates that the IR imbalance degree equals 100% when one phase IR measurement largely deviates from the other two.

Similarly, the IR imbalance degree of a three-phase power cable is calculated as follows when two-phase IR measurement markedly deviates from the left one:

$$\begin{aligned}
 ID &= \frac{|\max(IR_i - IR_{average})|}{IR_{average}} \times 100\% \quad (i = A, B, C) \\
 &= \frac{|\max(IR_i - \frac{IR_A + IR_B + IR_C}{3})|}{\frac{IR_A + IR_B + IR_C}{3}} \times 100\% \\
 &= \frac{|\max(IR_i - \frac{k_a p + 0 + 0}{3})|}{\frac{k_a p + 0 + 0}{3}} \times 100\% \\
 &= \frac{|\max(IR_i - \frac{k_a p}{3})|}{\frac{k_a p}{3}} \times 100\% \\
 &= \frac{\frac{2k_a p}{3}}{\frac{k_a p}{3}} \times 100\% = 200\% ,
 \end{aligned} \tag{5}$$

where $IR_A = k_a p$, $IR_B = k_b p$, and $IR_C = k_c p$, supposing that $k_B \ll k_A$, $k_C \ll k_A$ when the IR measurement of phase B and C significantly deviate from phase A. This derivation demonstrates that the IR imbalance degree equals 200% when two-phase IR measurement largely deviates from the left one.

A real-life demonstration of the above derivation is presented in Figure 2. When the values of the IR measurement of all three phases are identical (e.g., one base unit for L1), the IR imbalance degree is calculated as zero. If the situation worsens from a one-phase imbalance to a two-phase imbalance, the IR imbalance degree jumps from 100% to 200%. Meanwhile, about 5,700 sets of IR measurement data in the HK Electric database, which were obtained either after cable work or from proactive

testing in the past ten years, have been reviewed, and the distribution of IR imbalance degrees is presented in Figure 3. The majority of the test data are more or less balanced, with the IR imbalance degree at around 20%. For data with an IR imbalance degree more significant or equal to 100%, the percentage is about 7%, among the 5,700 sets of testing records.

2.4. Criteria of using IR imbalance degree in HV cable tests

In order to define a critical threshold of IR imbalance degree for identification of a weak 11 kV three-phase power distribution cable, about 5,700 sets of IR measurement values in the HK Electric database in the last decade were extracted. In this method, data obtained in 10 kV IR measurement are chosen for 11 kV distribution cables as naturally, more severe defects will arise when a more substantial voltage stress is imposed (10 kV is about 1.5 times the rated phase voltage of an 11 kV three-phase power distribution cable) though the 1, 5, and 10 kV (phase-to-ground voltage) voltage are applied for each phase IR test at HK Electric as a reference.

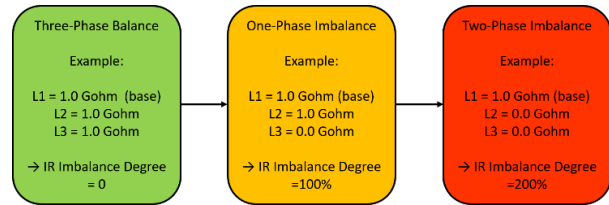


Figure 2. Demonstration of IR imbalance range from three-phase balance, to one-phase imbalance, and to two-phase imbalance.

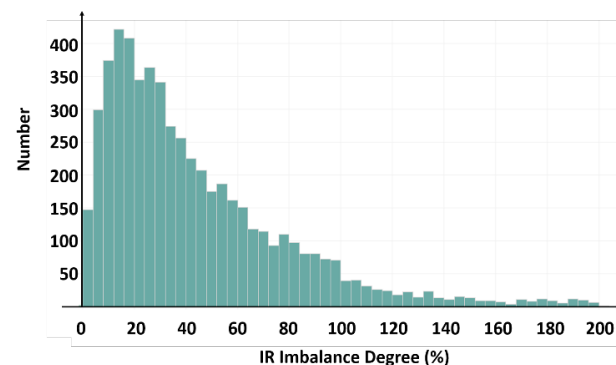


Figure 3. IR imbalance degree distribution of about 5,700 sets of testing records of HK Electric.

The 10 kV IR imbalance degrees for these 5,700 sets of IR measurement records in the HK Electric database are calculated and depicted in Figure 4, ranking from the lowest to the highest. The demarcation lines for one- and two-phase imbalance conditions are also marked in

Figure 4. For the sake of determining the criticality of the proposed evaluation metric, the Pareto principle (Sanders et al., 1987) is adopted. The Pareto principle, also known as the 80/20 rule, states that 80% of the output from a given situation or system is determined by 20% of the input. In this application, the criticality is classified into 0-90% (Acceptable) and 90-100% (Need serious attention) (Figure 5). Using this criterion, a 10% deviation from the demarcation point of one-phase imbalance is drawn in Figure 4, leading to a critical threshold of IR imbalance degree of 75%. Therefore, it is considered that a three-phase 11 kV power cable will be regarded as being in a highly critical condition when its 10 kV IR imbalance degree is over or equal to a level of 75%.

Though each power distribution cable has a specific IR threshold as a reference which is subjected to several factors such as cable length, the composition of the cable circuit, service years, and so on, a low IR value is invariably an indicator that adequate attention must be paid. Accordingly, based on the Pareto principle with a 10% criticality level, the alarming IR value is also extracted from these 5,700 IR measurement records in the HK Electric database (Figure 6). The critical point is derived from the lowest 10% deviation from the total measurement, and the critical IR value is found to be 0.150 G-Ohm.

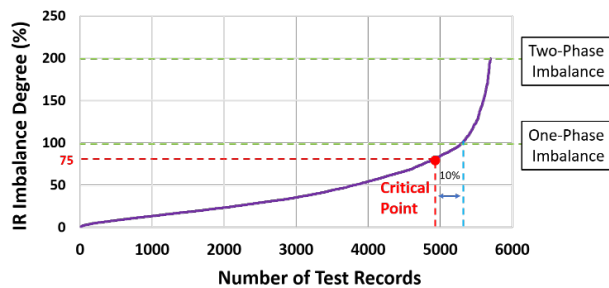


Figure 4. IR imbalance degree distribution from about 5,700 sets of testing records of HK Electric.

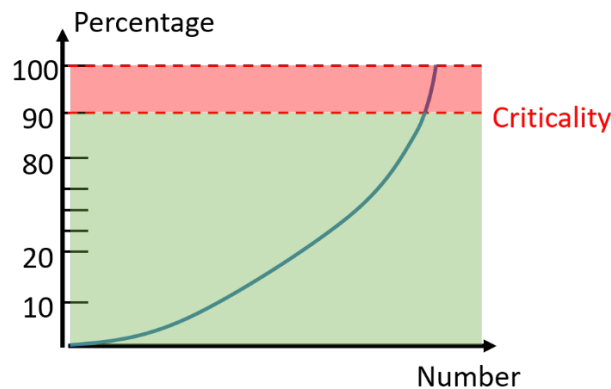


Figure 5. Threshold of defining criticality based on the Pareto principle.

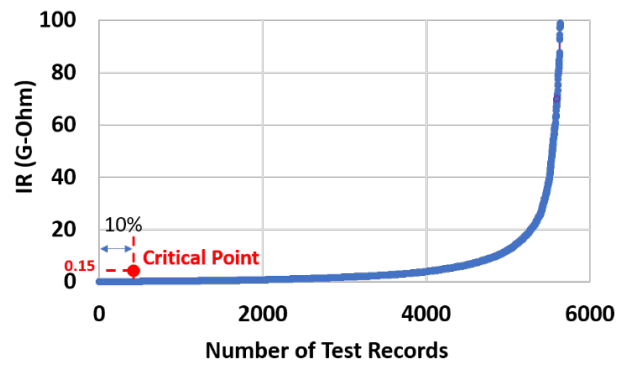


Figure 6. Threshold of defining criticality based on the Pareto principle for IR measurement.

Therefore, the strategy of using IR imbalance degree for an 11 kV three-phase power distribution cable is summarised in Table 3:

- (1) When the IR imbalance degree and IR absolute value of any phase are both alarming (i.e., IR imbalance degree > 75% and IR of any phase < 0.150 G-Ohm), the three-phase power cable needs serious attention;
- (2) When the IR imbalance degree is alarming but the IR absolute value of individual phases is absolutely safe (i.e., IR imbalance degree > 75% but IR of any phase > 0.150 G-Ohm), it is suggested to conduct a further study of the cable using more information to find out the reason for the three-phase IR imbalance;
- (3) Similarly, it is worthwhile conducting a further study of the cable if the IR absolute value of individual phases is alarming (viz., IR of any phase < 0.150 G-Ohm) but the three-phase IR imbalance degree is safe (i.e., IR Imbalance Degree < 75%). It has to be verified whether the nature of the cable circuit is causing the low insulation; and
- (4) No action is needed if both the IR imbalance degree and IR measurement of all three phases are safe (i.e., IR Imbalance Degree < 75% and IR of any phase > 0.150 G-Ohm).

The actual application of this method will be demonstrated in the next section.

Table 3. Strategy of cable maintenance strategy based on IR imbalance degree.

IR imbalance degree	IR (G-Ohm)	Action
> 75%	< 0.150	Need serious attention
	> 0.150	Further study advised
< 75%	< 0.150	Further study advised
	> 0.150	No action required

3. Case demonstration

11 kV power distribution cables are mainly used to deliver power between two substations (Figure 7). At HK Electric, paper-insulated lead-covered (PILC) and cross-linked polyethylene (XLPE) cables are installed (Figure 8). The PILC cables were mainly installed before the 1980s, and now they are gradually being replaced by XLPE cables. Regarding the cable joints connecting two cable sections, there are also three main categories: Joint Type 1 (non-screened with mastic filling between cores and beneath the over-sheath, no breakout to block longitudinal water movement), Joint Type 2 (non-screened joint with additional insulation tubing was added at connector areas to reinforce insulation at the centre position, and breakout are installed at both ends to stop longitudinal water movement except PILC-PILC joint), and Joint Type 3 (screened water blocked mastic filled joint).

In order to demonstrate the effectiveness of the proposed evaluation criteria, the following three cases are presented. These cases demonstrate the situations where the cables need serious attention, further study, or no action is required. These cases are either under regular proactive testing for checking the health of 11 kV three-phase power distribution cables or in a commissioning process after cable work at HK Electric.

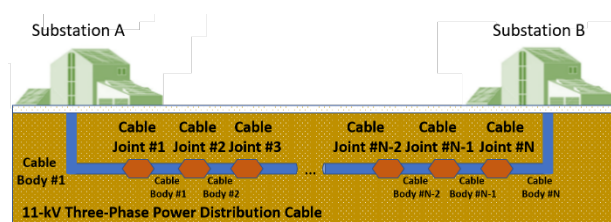


Figure 7. General construction and composition of an 11 kV three-phase power distribution cable for electricity delivery between substations.

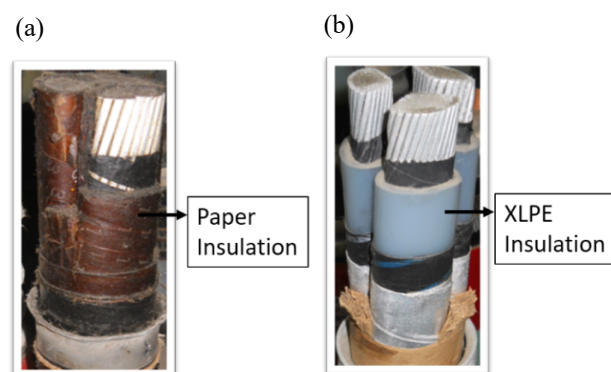


Figure 8. Cable categories which are deployed in the network of HK Electric: (a) paper-insulated lead-covered (left); and (b) cross-linked polyethylene cable (right).

3.1. Case 1: a test record under “Need Serious Attention”

This 11 kV three-phase power distribution cable was screened out for a proactive test under the cable category with transition joint(s) (viz., XLPE-PILC cable joint) without previous testing records. The purpose of this test was to sort out the weak cables in the distribution network of HK Electric and to overstress it in order to locate the faulty component for repair if possible. This proactive test and maintenance strategy aim to prevent the failure of in-service power distribution cables which would otherwise lead to unplanned power interruption for customers.

In this case, the details of the cable section and joint are summarised in Table 4. Based on the schedule, this 11 kV three-phase power distribution was de-energised for an IR test, and the results are presented in Table 5. The 1, 5, and 10 kV IR tests were conducted. The 10 kV IR measurement results indicated that this three-phase power cable was in a critical condition since the IR imbalance degree was as high as 177%, much higher than the demarcation level of 75%. Also, the absolute IR values of phases L1 and L2 were smaller than the threshold of 0.150 G-Ohm.

Table 4. Composition of an 11 kV three-phase power distribution cable under proactive testing.

Information on cable-body sections			
No.	Length (m)	Type	Laid year
#1	12	XLPE	1989
#2	37	PILC	1970
#3	13	XLPE	2002
Information on cable joints			
No.	Joint Type	Laid year	
#1	Type 1	1989	
#2	Type 2	2002	

Table 5. IR measurement results for case 1.

Phase	IR insulation resistance (G-ohm)		
	1 kV	5 kV	10 kV
L1	0.07	0.08	0.08
L2	0.09	0.09	0.09
L3	1.96	2.25	2.05
IR Imbalance Degree	N/A		177.02%

Subsequently, a monitored withstand test (i.e., to apply the voltage above the normal operating voltage to stress the cable's insulation in a prescribed manner for a set period) was followed (Figure 9). The results of the monitored withstand test of this cable under a 12.80 kV (i.e., 2U₀) and 30 minutes test duration are plotted in Figure 10. The measurement results indicated that L2 was faulty at 14 minutes, and the fault was at No. #1 joint by

onsite excavation (Figure 11(a)). Around 150 mm of the cable joint was cut away and returned to the workshop for dissection (Figure 11(b)). The outer jacket of the joint was found to be damaged on one side, likely caused by a prior excavation. The outer sleeve of the joint was sufficiently shrunk, and the armour wrap-case was slightly rusty (Figure 11(c)). After removing the connector insulation sleeve, yellow mastic applied over phase L1 and L3 connectors was found to have changed to pale yellow, indicating water ingress (Figure 11(d)). Based on a series of findings, this joint failure should be attributed to prior prolonged water ingress from the cable onto the XLPE insulation surface beyond the core's screen cutback. This defect was perfectly reflected in IR measurement, and there was no wonder that the cable failed under an application of the 2Uo and 30 minutes monitored withstand test.

This case has successfully demonstrated the appropriate choice of the criteria for the IR imbalance degree in Table 3 under the "Need Serious Attention" category.

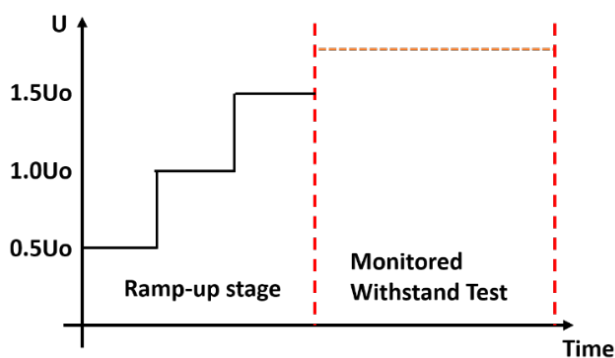


Figure 9. The monitored withstand test to evaluate the dielectric property during the voltage holding period.

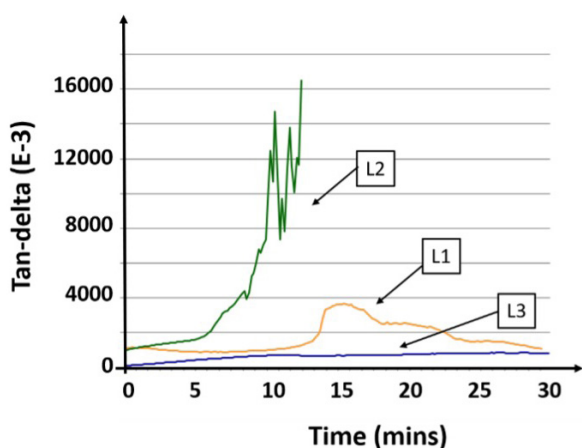


Figure 10. Tan-delta values for the three-phase power distribution cable under the 2Uo and 30 minutes monitored withstand test (MWT).

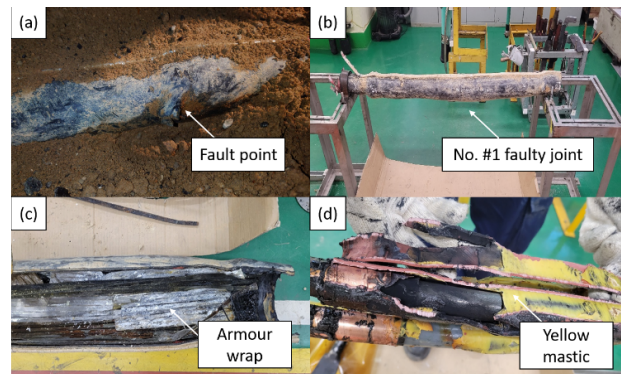


Figure 11. Dissection results of the faulty component in case 1: (a) Fault point of No. #1 joint by onsite inspection; (b) faulty joint returned for dissection; (c) armour wrap of the faulty joint; and (d) yellow mastic wrapped over the semi-conductive tape.

3.2. Case 2: a test record under "Further Study Advised"

This 11 kV three-phase power distribution cable was tested for commissioning purposes after cable work. The 272 m cable composition is summarised in Table 6. After a cable repair, this 11 kV three-phase power distribution cable was tested for condition evaluation before energisation. The IR test results are presented in Table 7, in which a high IR imbalance degree can be found (i.e., IR imbalance degree at 10 kV = 91.77% > 75%). According to the criteria proposed in Table 3, this cable needs additional tests to determine its condition.

Subsequently, the results from tan-delta, monitored-withstand and PD-mapping testes for this cable were supplemented and analysed. Firstly, based on the results of the tan-delta and monitored withstand test (MWT) (Figure 12), the abnormality of L2 was also seen as its characteristics were obviously different from that of L1 and L3. This measurement result was consistent with the IR measurement result in Table 7, in which the deviation of the L2 data from those of L1 and L3 resulted in the IR imbalance degree. Furthermore, it was found that there were concentrated partial discharges of L2 at the cable termination from the PD mapping as shown in Figure 13. Regarding these findings, it was suggested to check and clean the cable termination and then re-test the cable for follow-up evaluation of the IR again.

This cable has successfully demonstrated the appropriate criteria for the IR imbalance degree of Table 3 under the "Further Study Advised" category.

Table 6. Composition of an 11 kV three-phase power distribution cable under testing in case 2.

Information on cable-body sections			
No.	Length (m)	Type	Laid year
#1	18	XLPE	2020
#2	26	XLPE	2009
#3	27	XLPE	1990
#4	45	XLPE	1990
#5	85	XLPE	1990
#6	71	XLPE	1990
Information on cable joints			Laid year
No.	Joint Type		
#1	Type 3	2020	
#2	Type 2	2009	
#3	Type 2	1990	
#4	Type 2	1990	
#5	Type 2	1990	

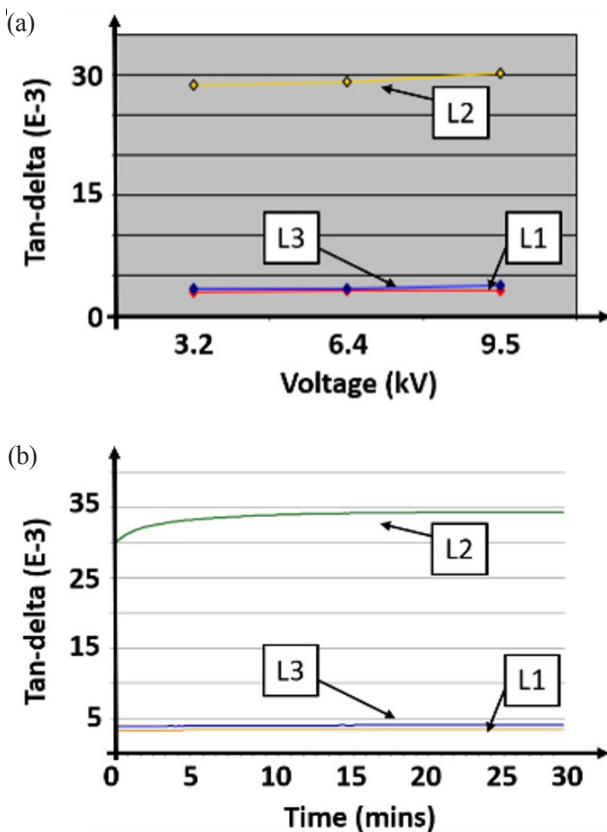


Figure 12. Tan-delta and MWT results for case 2: (a) Three-phase tan-delta test results; and (b) MWT results in a 30-minute test for three phases.

Table 7. IR measurement results for case 2.

IR insulation resistance (G-ohm)			
Phase	1 kV	5 kV	10 kV
L1	10.10	9.94	9.50
L2	0.50	0.50	0.49
L3	9.32	8.67	7.88
IR imbalance degree	N/A		91.77%

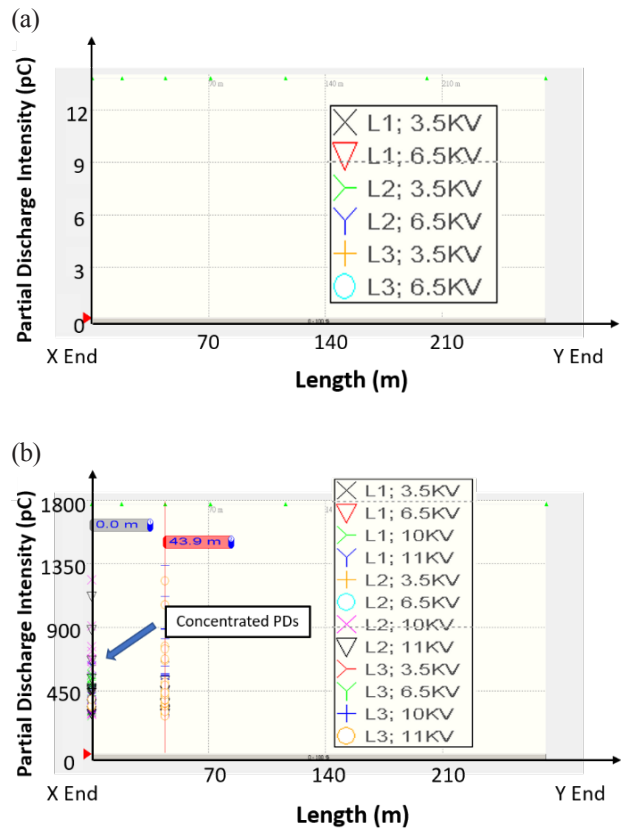


Figure 13. Offline PD measurement: (a) three-phase PD mapping at 3.5 and 6.5 kV; and (b) three-phase PD mapping at 3.5, 6.5, 10 and 11 kV.

3.3. Case 3: a test record under “No Action Required”

This 11 kV three-phase power distribution cable was screened out under a proactive test for condition evaluation. The 555 m cable composition is summarised in Table 8. Based on the schedule, this 11 kV three-phase power distribution cable was de-energised for a condition evaluation. The measurement results of insulation resistance at 1, 5, and 10 kV are presented in Table 9. The IR imbalance degree was 20.83%, which was far below the demarcation level of 75%. Also, the absolute values of all three phases were larger than the threshold of 0.150 G-Ohm. Regarding these findings, the cable was treated as healthy, and no action was required. The result was consistent with other inspection methods from tan-delta, monitored-withstand,

and PD-mapping. Therefore, the cable was put back into service.

This case has successfully demonstrated the choice of the criteria using IR imbalance degree for cable condition assessment in Table 3 under the “No Action Required” category.

Table 8. Composition of an 11 kV three-phase power distribution cable under proactive testing in case 3.

Information on cable-body sections			
No.	Length (m)	Type	Laid year
#1	145	XLPE	1988
#2	17	XLPE	1988
#3	134	PILC	1974
#4	8	XLPE	2007
#5	72	PILC	1974
#6	6	XLPE	2005
#7	88	PILC	1978
#8	85	XLPE	1999
Information on cable joints			
No.	Joint type	Laid year	
#1	Type 2	1988	
#2	Type 2	1988	
#3	Type 3	2007	
#4	Type 3	2007	
#5	Type 3	2008	
#6	Type 3	2008	
#7	Type 3	1999	

Table 9. IR measurement results for case 3.

Phase	Insulation resistance (G-ohm)		
	1 kV	5 kV	10 kV
L1	0.58	0.57	0.53
L2	0.59	0.55	0.53
L3	0.53	0.42	0.38
IR imbalance degree	N/A		20.83%

4. Conclusion

There is no doubt that power cables are crucial parts of modern power transmission and distribution systems. Facing the vast network of power cables, it is a challenge for the operation and maintenance personnel to evaluate the health of power cables accurately as much as possible for optimisation of the maintenance schedule and to timely prevent failures that would otherwise lead to unplanned interruption of power supply to customers. This paper introduces a new method for condition assessment of MV power distribution cables based on conventional IR tests but with a new data analysis approach to single out cables with a high risk of failure. The IR imbalance degree and IR

threshold value are simple to use but proved influential in categorising cables in different health conditions in order to prioritise the maintenance effort. Some preliminary cases have been demonstrated in this paper to validate the application of the method. The method's effectiveness will be continuously monitored, evaluated, and reviewed.

The IR measurement is a mandatory practice for commissioning before cable energisation. Namely, IR measurement is executed for three-phase 275/132 kV transmission cables and 22/11 kV distribution cables after cable work (HK Electric, 2020). Thus, this proposed method also has the potential to be deployed for other power cables, and the rule will be formulated accordingly.

In conclusion, the applicability of IR measurement to the condition assessment of MV voltage power distribution cables has been extended in this study. The improved inspection methodology could further enhance the reliability and security of HK Electric's power supply.

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References

- [1] Andjelkovic D and Rajakovic N (2001). Influence of accelerated aging on mechanical and structural properties of cross-linked polyethylene (XLPE) insulation. *Electrical Engineering*, 83, pp. 83-87.
- [2] Bumby S, Druzhinina E, Feraldi R, Werthmann D, Geyer R and Sahl J (2010). Life cycle assessment of overhead and underground primary power distribution. *Environmental science & technology*, 44(14), pp. 5587-5593.

- [3] Buchner A and Schichler U (2019). Review of CIGRE TB 496 regarding prequalification Test on Extruded MVDC cables. In: *Proceedings of the Nordic Insulation Symposium* (No. 26).
- [4] Choudhary M, Shafiq M, Kiitam I, Hussain A, Palu I and Taklaja P (2022). A Review of Aging Models for Electrical Insulation in Power Cables. *Energies*, 15(9), pp. 3408.
- [5] Electric Machinery Committee (2013). *IEEE Recommended Practice for Testing Insulation Resistance of Electric Machinery*.
- [6] Fu M, Chen G, Dissado LA and Fothergill JC (2007). Influence of thermal treatment and residues on space charge accumulation in XLPE for DC power cable application. *IEEE Transactions on Dielectrics and Electrical Insulation*, 14(1), pp. 53-64.
- [7] Hampton N, Altamirano J, Perkel J and Hernandez JC (2007). VLF Tests Conducted by NEETRAC as Part of the CDFI.
- [8] HK Electric (2020). *Transmission & Distribution*. [online]. Available at: <<https://www.hkelectric.com/en/our-operations/transmission-distribution>>. [Accessed on 13 February 2023].
- [9] HK Electric Investments (2021). Crafting a Greener Future. [online]. Available at: <https://www.hkelectric.com/en/InvestorRelations/Documents/Financial%20Reports/2021/AR/2021_HKEI_AR_E_FULL.pdf>. [Accessed on 13 February 2023].
- [10] Kim C, Jiang P, Liu F, Hyon S, Ri MG, Yu Y and Ho M (2019). Investigation on dielectric breakdown behavior of thermally aged cross-linked polyethylene cable insulation. *Polymer Testing*, 80, 106045.
- [11] Perkel J, Del Valle Y, Hampton RN, Hernandez-Mejia JC and Densley J (2013). Interpretation of dielectric loss data on service aged polyethylene based power cable systems using VLF test methods. *IEEE Transactions on Dielectrics and Electrical Insulation*, 20(5), pp. 1699-1711.
- [12] Refaat SS and Shams MA (2018). A review of partial discharge detection, diagnosis techniques in high voltage power cables. In: *2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2018)*, pp. 1-5. IEEE.
- [13] Sanders R (1987). The Pareto principle: its use and abuse. *Journal of Services Marketing*, 1(2), pp. 37-40.
- [14] Sheng B, Zhou C, Hepburn DM, Dong X, Peers G, Zhou W and Tang Z (2014). Partial discharge pulse propagation in power cable and partial discharge monitoring system. *IEEE Transactions on Dielectrics and Electrical Insulation*, 21(3), pp. 948-956.
- [15] Soma K, Aihara M and Kataoka Y (1986). Diagnostic method for power cable insulation. *IEEE transactions on electrical insulation*, (6), pp. 1027-1032.
- [16] Tai S and Leung C (2012). HK electric's experience of VLF diagnostic testing on distribution cables. In: *2012 China International Conference on Electricity Distribution*, pp. 1-6.
- [17] Um K (2017). Developing a Device for Predicting the Lifetime of Cables at Power Stations by Measuring Insulation Resistances. *Journal of Nanoscience and Nanotechnology*, 17(11), pp. 7939-7942.
- [18] Um KH and Lee KW (2014). A study on cable lifetime evaluation based on characteristic analysis of insulation resistance by acceleration factor of the Arrhenius equation. *The Journal of The Institute of Internet, Broadcasting and Communication*, 14(5), pp.231-236.
- [19] Watson R, Lowe S and Bhumiwat SA (2004). The New Technique for Reliability Assurance of in-service XLPE Power Cables. In: *Electricity Engineers' Association of New Zealand-Conference*, Christchurch, pp. 18-19.
- [20] Werelius P, Tharning P, Eriksson R, Holmgren B and Gafvert U (2001). Dielectric spectroscopy for diagnosis of water tree deterioration in XLPE cables. *IEEE Transactions on Dielectrics and Electrical Insulation*, 8(1), pp. 27-42.
- [21] Yi H, Wang X, Suo C, Zhang Y, Ghias AMYM, Tan KW, Gooi HB, Wee CT, Chern WK and Yucel (2022). Enhanced Cable Insulation Resistance Guidelines Based on Weibull Analysis and Diminishing Method. In: *2022 IEEE International Conference on High Voltage Engineering and Applications (ICHVE)*, pp. 1-4.
- [22] Yuan Y, Dong J, Gan J, Li S, Zhao W, Huang S and Chen L (2017). A three-core power cable online monitoring system based on phase current sensing. In: *2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pp. 1-6.
- [23] Zhou C, Yi H and Dong X (2017). Review of recent research towards power cable life cycle management. *High Voltage*, 2(3), pp. 179-187.
- [24] Zhu B, Jia ZD, Yuan Y, Lu GJ, Fan WN and Guan ZC (2015). Research on the insulation properties of 10kV XLPE damp cable. In: *2015 IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*, pp. 592-595.
- [25] Zhu K, Han W, Lee WK and Pong PW (2017). On-site non-invasive current monitoring of multi-core underground power cables with a magnetic-field sensing platform at a substation. *IEEE Sensors Journal*, 17(6), pp.1837-1848.
- [26] Zhu K, Lee WK and Pong PW (2017). Energization-status identification of three-phase three-core shielded distribution power cables based on non-destructive magnetic field sensing. *IEEE Sensors Journal*, 17(22), pp. 7405-7417.

- [27] Zhu K, Lee WK and Pong PW (2018). Fault-line identification of HVDC transmission lines by frequency-spectrum correlation based on capacitive coupling and magnetic field sensing. *IEEE Transactions on Magnetics*, 54(11), pp.1-5.
- [28] Zhu K and Ng TF (2022). Improvement of cable defect identification for power distribution networks. *Transactions on Hong Kong Institution of Engineers*, 29(1), pp. 37-45.
- [29] Zhu K and Pong PW (2019). Fault classification of power distribution cables by detecting decaying DC components with magnetic sensing. *IEEE Transactions on Instrumentation and Measurement*, 69(5), pp. 2016-2027.