DOI 10.15199/74.2020.9.

# Quality Management of Transmission Power Cables for Safe and Reliable Grid Operation

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**Keywords**: power cables, on-site testing, after-laying testing, diagnostic testing, continuous and damped AC voltages, VLF, partial discharges, defect localization, dissipation factor, tanδ, testing HV power cables with very long lengths

Taking under consideration, that reliable transmission of energy is fundamental to proper operation of national power grid, quality control is essential for newly installed and in-service cable connections. It is known that routine tests (insulation coordination) completely check the quality of a power cable and accessories at the manufacturer. Nevertheless, the risk of problems with the delivery and installation of accessories can affect the quality of a newly installed power cable circuit. Based on international experience gathered on various power grids over the past 20 years, this article focuses on the use of non-destructive testing for after-installation- and diagnostic tests of all types of transmission cables. This document discusses in particular various actual aspects of testing new connections as well as the condition assessment of service aged HV power cables.

**Considering, that reliable energy transmission and distribution are fundamental for a country, the various aspects of maintaining the quality control for newly installed cables and cables in service operation is important matter.**

## WHAT IS A SAFE AND RELIABLE GRID OPERATION?

With increasing transmission level voltages, more power capacity to be transmitted, longer cable links for both on- an offshore networks, request a more dedicated approaches for safe and reliable grid operation for power cables, see fig. 1.

As a result, important questions for power companies about maintaining /updating internal procedures for a reliable cable network operation are:

- How do you perform in a sensitive and non-destructive way the detection of poor workmanship defects of newly installed HV cable circuits?
- How do you perform non-destructive diagnostics of HV cable circuits in service to determine the actual condition?

## WHY IT IS NECESSARY TO PERFORM NON-DESTRUCTIVE PD MONITORED TESTING?

It is known that IEC standards like [16, 18, 19] are dedicated mostly for cable manufacturers and therefore the majority of their content is discussing the factory testing aspects. In most of the standards no up-to-date guidelines are provided regarding recent field experiences by after-laying and maintenance testing of cable circuits. Traditionally recommended over-voltage testing with the binary test result outcome "break-down" or "no break-down" can exclude only major defects, but does not provide much added value to assure a safe and reliable grid operation as it has to be expected from today's new transmission cable networks. Therefore some of the TSOs are in the process or have developed their own more dedicated procedures to test

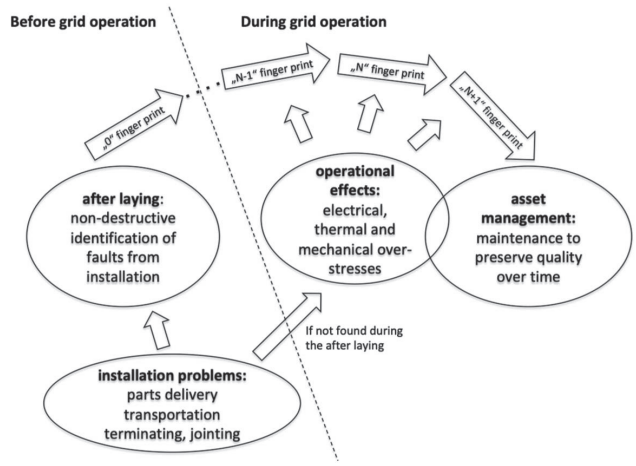


Fig. 1. Basic factors determining a safe and reliable grid operation for power cables. The "finger-print" approach means a cable system quality determination over the life-time by evaluation of diagnostic parameters e.g. partial discharges, dissipation factor, etc.

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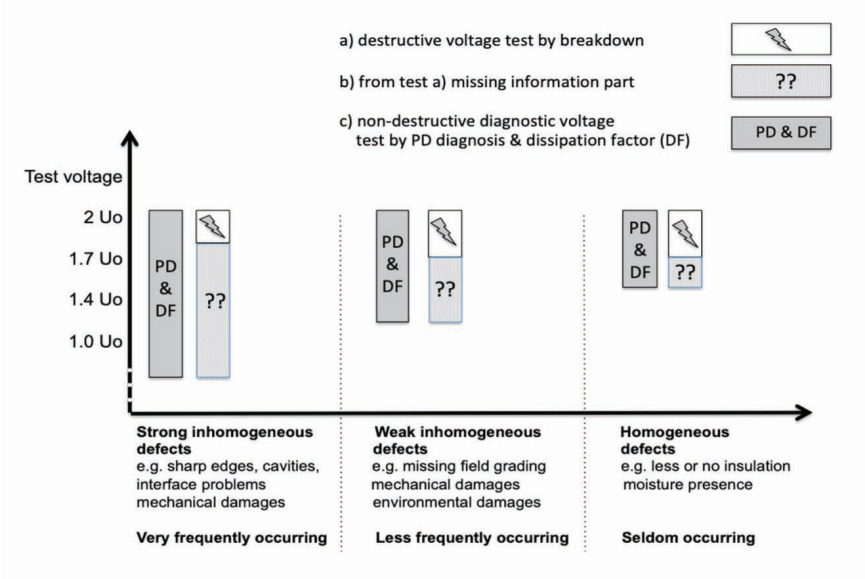


Fig. 2. Schematic effectiveness to detect insulation defects in a HV cable system using PD diagnosis versus voltage breakdown testing

newly installed cables that are based on own experiences, the international standards [13, 20, 21, 22, 27], which are prepared in cooperation between power companies, manufacturers and testing companies and in combination with selected other IEC documents [14, 15, 17]. These regulations are representing a more actual state-of-the-art of non-destructive methods for both after-installation and maintenance testing and diagnosis [26, 27].

According to [23] using on-site simple non-monitored voltage tests with voltages up to 1,7×Uo as maximum level, the number of breakdowns normalized per 100 km as observed by newly installed cable circuit might be even up to 8 per 100 km. The reasons of those failures are related to e.g. wrong cable jointing, due to time pressure to finish the project and due to poor workmanship of the installers [23]. It is known, that during an over-voltage test, an insulation breakdown occurrence depends mostly on the homogeneity degree of a defect, see fig. 2. As a result, it could be concluded that the number of installation defects per 100 km cable length, as reported in [23], might be much higher considering that only serious defects can be detected using voltage breakdown testing. This has been confirmed in ~~[5]~~ by reporting that only 42% of defects produces breakdown during testing whereas 72% of defects produces PDs that might be considered as pre-breakdown phenomena. As a result, a responsible operation and asset management of transmission power cables has to consider a number of aspects [13, 14], see Table 1.

It follows from Table 1 that a safe and reliable grid operation starts already at the moment of commissioning a newly installed HV cable circuit. Considering the fact that the number of installation defect might be more than 10 per 100 km cable length and that the on- and off-shore HV cable links are getting longer and longer it can be concluded that:

- Destructive over-voltage testing only is not technically optimal and sufficient for detection of all possible installation defects.
- PD diagnosis is more sensitive to detect all defects.

As a result, sensitive PD-monitored voltage withstand test can be more effective in the identification of faults originating from poor installation and to providing the so-called "0"- finger print for further condition evaluation of a cable circuit, e.g. to be compared just before the end of the warranty period, see fig. 1, [2, 11, 12, 25, 28, 31].

## WHAT ARE THE TESTING METHODS AND ACCEPTANCE CRITERIA?

In the last 30 years of testing of the distribution and transmission power cables, different testing methods have been introduced and are currently in use: continues AC resonant (ACR), damped AC (DAC) and very low frequency (VLF) ~~[1-11, 16-18, 20, 27, 28, 30],~~ Consequently, from the beginning of the offshore wind farm installations, these methods have also been used for

**TABLE 1.** Basic aspects of a responsible operation and asset management of transmission power cables

| Goals of after installation testing of newly installed transmission cable systems | | Goals of maintenance and diagnostic testing of transmission cable systems in operation | |
|---|---|---|---|
| Source of problems | Probability to find | Source of problems | Importance |
| Manufacturing related defects | Low due to high level of manufacturing quality control | Operational damages and electrical, thermal and mechanical over-stresses | High cannot be neglected e.g. transients, over-voltages, over-loading, etc. |
| Accessories parts delivery problems | Medium due to diversification in the supply chains | Assess aging processes | Medium depends on many operational and local factors e.g. presence of installation defects, constructions works, etc. |
| Installation related defects | High due to diversification in the installation supply chains, poor workmanship, etc. | Lack of knowledge about the remaining life | High goal of most asset managers are to keep CAPEX and OPEX on an optimal level |

**TABLE 2.** Overall evaluation of test technologies for PD monitored withstand test of HV long lengths cables

| Test Technology | Technical Acceptance (Meets Recognized International Standards, e.g., IEC, IEEE) | Capability of Testing High Capacitive Load (Long and Multiple Cables) | Off-shore Application (Size, Weight) | Sensitive PD Detection (System PD level, PD Characteristics) | Price-Performance Factor |
|---|---|---|---|---|---|
| ACR + PD | ++ | +/- 1) | -- | - 3) | -- |
| VLF + PD | +/- 4) | +/- 2) | +/- | - 3) | +/- |
| DAC + PD | + | ++ | ++ | ++ | ++ |

[1)] when connecting multiple resonance reactors,
[2)] when lowering the VLF test frequency to e.g., 0.01 Hz,
[3)] voltage source produces high electromagnetic interferences during the PD measurement,
[4)] only accepted up to 69 kV for onshore, up to 33 kV for offshore

**TABLE 3. GENERAL TESTING AND EVALUATION GENERAL CRITERIA FOR TRANSMISSION POWER CABLES**

| General criteria | Cable voltage class up to 220 kV |
|---|---|
| Maximum test voltage | IEC 60840, IEC 62067, IEEE 400.4, IEEE 400 |
| After-laying test: 1.4 – 2.0 × Uo (depending on voltage class) | |
| Background noise level PD measurement (IEC 60270) | ≤ 25 pC with tolerance of ± 20% |
| Withstand test criterion | No breakdown during the withstand test (50 DAC excitations) respectively (1 hour using ACRT) at the maximum test voltage level |
| PD criterion | No concentrated PD activity (> 6 PD events per cycle) above the background noise level on a voltage level equal and below 1.4 ×Uo |
| Dissipation factor criterion | Tan δ ≤ 0.1% / Δ Tan δ ≤ 0.1% with tolerance of ± 20% up to the maximum test voltage level |

testing of the offshore power cables. Unfortunately considering higher demand on quality control as compared to on-shore [11, 12], versus off-shore HV cables or for very long onshore HV cables, not all of these methods are giving good results, as illustrated in the Table 2. Several studies performed by different parties during the last 20 years, have revealed that regarding to voltage stresses, partial discharge (PD) occurrence and the dissipation factor measurement (tan δ), there are no significant differences between traditional ACR method and modern DAC method [~~1, 2, 9, 24, 29~~]. It has been documented in recent publications [11, 21, 22] that for testing transmission power cables, the DAC after-laying and diagnostic testing [26, 27] is providing a sensitive PD detection. According to [15, 17, 20] using DAC a calibrated PD detection is possible on-site with a background noise below few tens of pC.

Compared to other methods, the DAC technology allows for more sensitive PD detection [4, 6, 10, 25] and localization of the problematic areas in a complete cable system (terminations, all types of joints, cable sections) due to its design concept, for both the on-shore and since a few years also in use for offshore power cables [11, 29, 25, 31].

Considering the use of PD as a criterion for accepting/rejecting a newly installed cable circuit, discussions are on-going regarding establishing acceptance criteria. Of course, due to liability reasons, no international organisations like CIGRÉ, IEEE or IEC will be able to define exact acceptance criteria for on-site testing. The above situation is fully understandable as PD detection is case-per-case related to factors like calibration uncertainty, detection sensitivity and to the local electromagnetic interferences occurring on-site. The ACR and VLF testing technologies applied for on-site HV cable testing are somtimes used in combination with PD detection in some form. However, even despite the use of noise suppression filtering, these technologies have disadvantages, and do not provide the required PD sensitivity, due to the following characteristics:

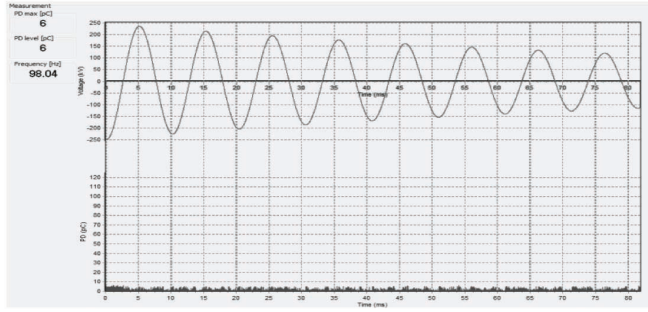

Fig. 3. Example of DAC PD background noise (< 6 pC) as measured on-site on a PD free 220kV power cable

- Very large footprint of the HV systems and up to tens of meters long HV connections being more exposed to substations electromagnetic interferences.
- The presence of internal noise up to few thousand of pCs that are coming from the power electronics in the HV sources.
- Due to distributed PD sensing a lack of an integrated solution for HV voltage source and PD detection.
- As a result using those systems an on-site background noise of few tens of pC (conform IEC 60270) is in this way actually not realistic.

On the contrary the DAC technology has been developed for on-site execution of PD monitored voltage testing of power cables up to 500 kV. As a result due to:

- The physical design, embedded system configuration, a small footprint.
- Very unique laser light controlled semi conductive switches.
- A linear grounding philosophy, optical control and dedicated shielding.

a reproducible on-site background noise of few tens of pC (conform IEC 60270) is possible, see fig. 3.

The introduction of DAC technology for the on-site testing of power cables 20 years ago [2, 21, 22, 30] opened the possibility of reproducible conditions for PD detection [15, 21]. As a result of scientific research projects [2, 29] and about 20 years of worldwide testing experience of MV and HV power cables at more than hundred different 3rd parties [16] for after-laying testing of transmission power cable the following parameters could be recommended as general criteria to determine if a transmission cable has passed the test and if it is sound for operation, see table 3.

## WHAT IS DAMPED AC TESTING?

The DAC technology has been first introduced in 1999 [27] and is now already in use since 20 years worldwide to test and diagnose MV and HV power cables [11, 21, 22]. Nowadays the DAC technology makes it possible to energize with a low input power demand long lengths of power cables and to provide sensitive PD detection and localization [7, 25, 31].

The application of damped AC voltages including standardized conventional PD detection and analysis is worldwide accepted for on-site testing and diagnosis of (E) HV power cables [13, 21, 22, 27]. In addition to the equivalence of sinusoidal DAC voltages (in the frequency range of 20-300 Hz), compared to the 50/60 Hz network stresses, the characteristics of the applied technology meet the specification of modern on-site testing system:

- Lightweight modular system with a low effort for system assembling.
- Compactness in relation to the output voltage and low power demand, even for long cable lengths.
- Low-level noises and possibility of sensitive cable termination based PD detection and localization as well as dissipation factor measurements.

The use of DAC voltages for testing HV power cables is in compliance with relevant test parameters derived from IEC, IEEE, and CIGRÉ international standards and guidelines [13-15, 17-22, 27]. DAC testing is used mostly in combination with partial discharge (PD) and dissipation factor (tan δ) measurements for newly installed and cables in service, see fig. 4.

In contrast to cross-bonding based distributed HF PD sensing (non-conventional) [4, 6] as used with other test systems e.g. ACR, the concept of PD detection at DAC systems is based on an IEC 60270 standardized end-to end PD detection over the complete HV cable length. From a practical- and effectiveness point of view, the DAC method is much more favourable [26].

According to [13, 21, 22, 27] to execute the voltage withstand test, this procedure should be repeated at least for 50 DAC excitations followed after each other, to perform a voltage withstand test on the maximum test voltage [16, 18, 19, 21].

Considering the time from the PD initiation till breakdown, due to the shorter duration of a DAC excitation and decaying characteristics of the maximum voltage, the DAC test results regarding "time till breakdown" might be for some defects different from those obtained by ACR withstand voltage testing [21]. Assuming that testing should not be unnecessarily destructive till breakdown and that the PD inception indicates already presence of defects, this difference in the time till breakdown has to be considered as an advantage of DAC testing.

After conventional PD calibration conform [15, 17], of the complete test circuit the DAC test procedure is in the line with [21] and provides the following parameters, see table 4.

Moreover, in [26] has been reported that using DAC testing with PD mapping helps in faster pinpointing the fault locations after breakdown of a HV cable with accuracy of several meters. Whereas the use of continuous test voltages like ACR and VLF may create extra damage at the fault location for every deliberate breakdown executed with consequences of more difficult fault investigation, more difficult and costly repair.

The single sided terminal measurement in combination with a DAC power source showed good results in the recent years with on-site measurements [7, 25, 31, 32]. To improve the setup a second PD measurement unit has been introduced and connected to the other cable end. The dual-sided measurement is applied for improving the PD - sensitivity and localization, especially in relation to longer cable lengths [25, 31]. The worst case for localization is a PD fault location at the cable end. In that situation, the PD pulse attenuation is the highest, due to a travelling distance of the whole cable length. The dual-sided measurement brings advantages due to the use of two PD measurement units. However, the hardware is more complex, than compared to the single side measurement. In particular the synchronization and data transmission over long

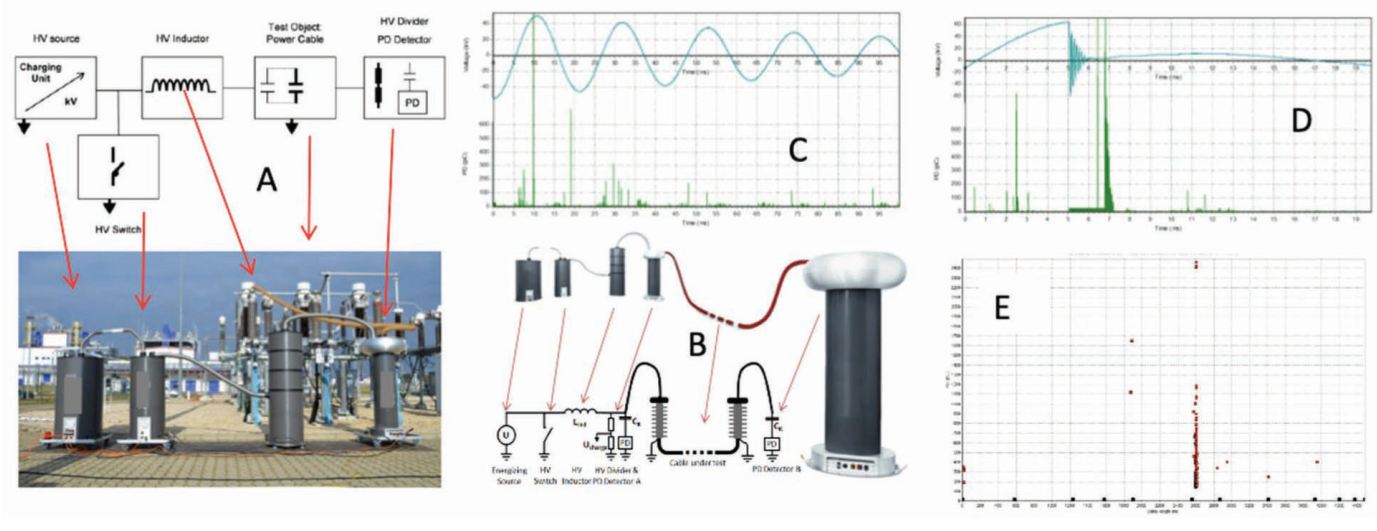


Fig. 4. Damped AC (DAC) system for on-site testing and PD detection of transmission power cables: a) schematic overview, b) configuration for 2-side PD detection for long cables, c) PD monitored DAC voltage, d) PD monitored DAC voltage breakdown, e) PD mapping to localize the discharging site in a cable

**TABLE 4.** Damped AC (DAC) testing and diagnostic parameters

| Voltage withstand test | Partial Discharges | Dielectric losses |
|---|---|---|
| YES / NO breakdown during min. 50 DAC excitations voltage withstand test at max. selected test voltage conform [16, 18, 19, 21] | PD inception / extinction voltage (PDIV / PDEV) | Dissipation factor tan δ |
| | PD magnitude in pC conform [15, 17, 21] | |
| | qV- characteristics | |
| | Phase-resolved PD pattern | The ration of tip-up tan δ |
| | PD localization in a complete cable circuit | |

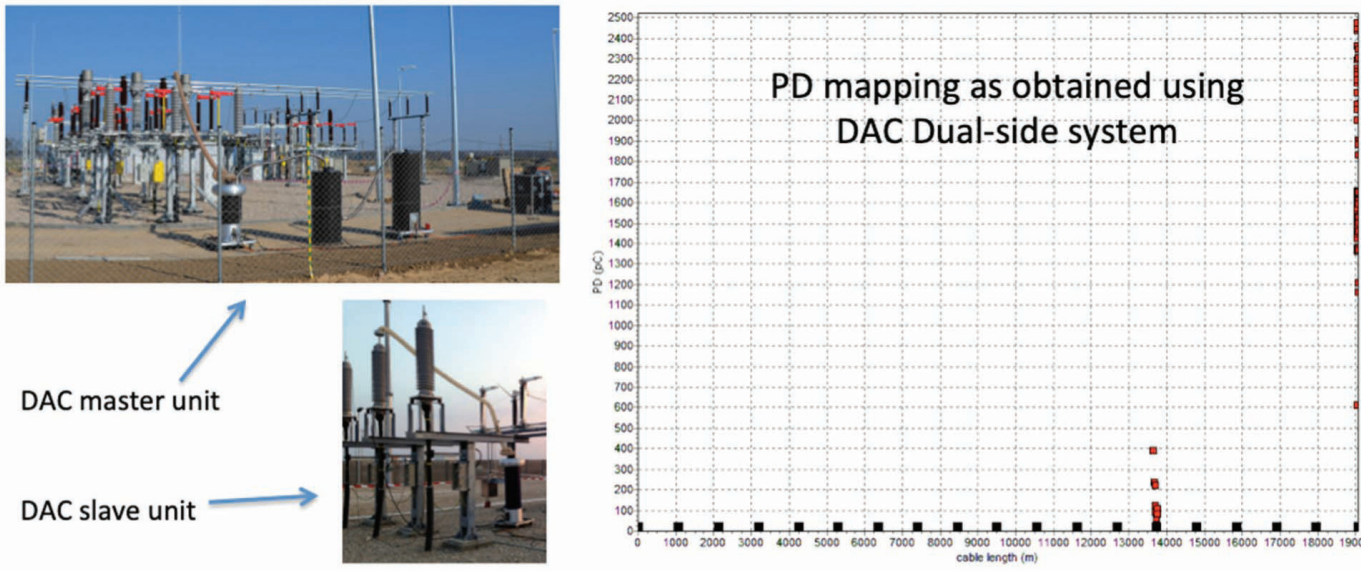


Fig. 5. PD mapping resulting from a dual sided measurement (energizing the 110 kV XLPE cable with a DAC master unit at the cable near-end and a slave unit at the cable far-end) on a 19.1 km long cable indicating in Phase L1 PD activity in a joint at 13.7 km position

distances is a challenge. The attenuation decreases the amplitude of measurable PD pulses. This attenuation can be described with an exponential function. A decreasing PD amplitude can have about 70 percent of the original amplitude, depending on the location. In a single side measurement setup the reflected pulse over the far end decreases to 5 percent. A dual-sided measurement increases the remaining PD amplitude to about 26 percent [15, 17, 20, 25, 31].

The dual-sided measurement brings advantages in detecting sensitivity and localization possibilities of PD pulses on long cable lengths [7, 25, 31].

Nowadays as an after installation test at wind-farms a number of newly installed HV power cables with lengths up to the 60 km lengths have been on-site commissioned using DAC in Europe [7, 11, 25, 31], fig. 5.

## WHAT ARE THE CONCLUSIONS?

Based on the discussion in this contribution supported by extensive references the following conclusions may be drawn:

- To assure safe and reliable grid operation, modern TSOs have to maintain own policies for quality control of newly installed power cable circuits and to develop approaches to preserve power cable quality over the operation time.
- In contrast to traditional voltage withstand test by ACR, applying non-destructive DAC testing will improve the quality threshold to capture faults from installation and to accept or reject the installation on new HV cable circuits.
- To avoid enhanced failure risks per 100 km during operation the newly constructed HV cable systems with lengths of tens of kilometers cannot be tested in a traditional way by a voltage withstand test only.
- In contrast to distributed HF PD sensing at earth links (e.g. at cross-bonding joints), as used e.g. with ACR systems, the concept of DAC systems is based on an IEC 60270 standardized end-to end PD detection all over the cable length. From practical and effectiveness point of view the DAC method is much more favorable.
- It has been reported that in case of high-ohmic cable breakdowns the DAC testing with PD can be used for less-destructive fault localization. What in its turn might minimalize the repair overall efforts.
- The PD based condition fingerprinting during cable service life is important for condition evaluation of lifetime strategies of aged cable systems.

*Artykuł recenzowany, wpłynęło 19.08.2020*

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