Improving Cable System Reliability with Monitored Withstand Diagnostics - featuring high efficiency at reduced test time

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ABSTRACT

Medium voltage cable systems are degrading over time and subsequently more failures are recorded. Effective asset management strategies are required to manage the ageing underground cable infrastructure. Here, smart cable diagnostic methods are implemented to provide information on cable degradation at reduced test voltage levels avoiding unnecessary stress.
Effective maintenance programmes help to renew the weak cable accessories or cable sections in time.
Monitored Withstand Diagnostics offers the highest efficiency and significant time saving due to simultaneous PD and tan delta diagnostics. The simultaneous diagnostic trending provides unique information. Best practice examples of Monitored Withstand Diagnostics are illustrated.

KEYWORDS

Condition-based maintenance CBM, cable diagnostics, Monitored Withstand Diagnostics MWD, Monitored Withstand Testing, hybrid cable systems, diagnostic trend monitoring, partial discharge, dissipation factor tan delta, tan delta hysteresis, aged cable systems, very low frequency, improving cable system reliability

INTRODUCTION

Medium-voltage cable systems are common and important components for a reliable electric energy supply. The cable networks of power suppliers have mostly evolved over time. The older cable networks mainly comprise paper-insulated lead covered cables (PILC) laid decades ago as well as, in recent years, popular extruded cable types with PE, XLPE or EPR insulation. Many older cable systems have been built with PILC cables and through ancient network extensions and reconstructions have been converted to hybrid cable systems now consisting of various cable insulation types.
Medium-voltage cables are typically developed and designed for a service life of 30 to 40 years. Many medium-voltage cables of the older generation have reached the end of the statistical service life, including the cable accessories such as terminations and joints.
Replacing buried cables is very expensive and very complicated, especially in dense city areas, and is usually associated with administrative complications often caused by city authorities. Power utilities are required here to ensure reliable power supply to customers using efficient maintenance strategies.

Fig.1: old 3-phase termination of a 3-lead cable

Maintenance strategies:

To safeguard power supply, utilities usually prepare maintenance plans, whereby the cable systems are regularly tested for electric strength and reliability by a voltage withstand test and priority is given depending on the importance of the cable and the cable history. The VLF cable test in particular has been established in recent years and is used worldwide by most power utilities. As commonly known, during a cable test the cable is loaded with higher test voltage to detect prospective defects and weak points. The cable withstand test, guided by international and national standards, is described and known as a destructive test procedure: weak spots in the cable system are brought to breakdown and then the defective insulating material is replaced. [1]
Unlike the conventional cable test, cable diagnostics is a gentle and smart procedure for condition evaluation. Cable diagnostics is mostly applied with a slightly reduced test voltage and provides information on developing faults and the condition of the cable system without damaging the cable.
Many European utilities have built their maintenance strategy based on this technology and have been using it successfully for many years.

Strategic approach for condition-based maintenance CBM of aged cable networks:

A considerable part of the cable networks is not only outdated statistically, but even the frequency of faults has increased over the years. Effective maintenance strategies are now required, particularly for careful detection of weak insulation spots in aged cable networks. First of all, this means avoiding unnecessary investment caused by complete replacement of the cable. Many old cable systems are still intact despite an advanced age and can easily be classified as reliable after rectifying the weak spots. An efficient reconstruction programme, based on cable diagnostics and that was developed for these purposes, on the one hand ensures a reliable power supply and on the other hand, saves the expensive replacement of cable routes thanks to useful diagnostic findings. In this process, potential defects in the cable system are detected on time making refurbishment of insulation defects or of partial cable sections possible.

Fig 2: MWD Diagnostics on old cable systems

Based on experience some utilities now limit the application of the conventional voltage withstand test to new cables. A condition-based maintenance strategy takes place for aged cables. To avoid high voltage stress and unnecessary cable defects, the combined cable diagnostics is used as a smart solution for condition evaluation. VLF-based partial discharge measurement is used for the cable diagnostics, which can show faults in cables and in particular also in cable joints and cable terminations.
PD diagnostics helps to locate weak insulation spots such as hollows, delamination, electrical treeing as well as insulation components with local high electric field strength that is often caused by installation mistakes.

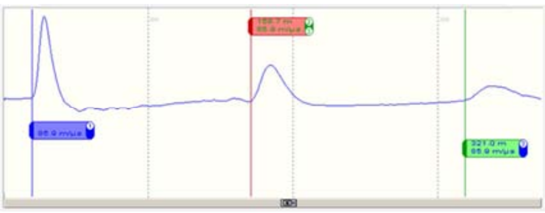


Fig.3: PD distance location graphic

The TDR-based PD distance location makes it possible to determine the precise distance to the PD spot (Fig.3). This process not only makes it possible to detect weak spots in joints or terminations, but also weak spots in the cable insulation, especially in PILC cables. The partial discharge measurement is a complex diagnostics procedure that requires trained and experienced test engineers for measurement and evaluation.

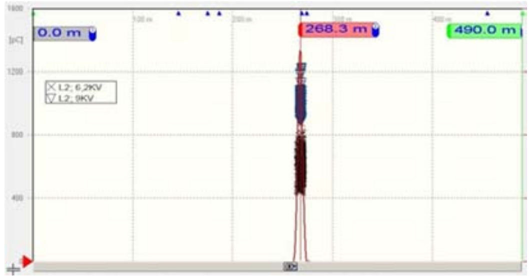


Fig.4: PD location mapping

The partial discharge test procedure is often used as a sole diagnostic procedure after laying new cables. However, the experience gained through various field tests shows that the partial discharge measurement is limited to determining electrical phenomena based on partial discharges and electrical treeing.
Statistics prove that the most frequent cause of faults is moisture ingress in joints. This kind of fault usually remains undetected during partial discharge measurement. The partial discharge measurement is also unsuitable for determining the ageing condition of cable insulating material.

Combined use of diagnostics procedures and holistic considerations:

The use of partial discharge measurement in aged cable networks as sole diagnostic procedure has only been proven to a limited extent, whilst, the use of a combination of partial discharge measurement and dissipation factor measurement has been proven successful.
The dissipation factor measurement at standard test frequency of 0.1 Hz (VLF) is used worldwide to determine the age of medium-voltage cables.
In particular, the ageing condition is determined here according to the insulating material type. The tan delta measurement at 0.1 Hz was originally developed for detection of harmful water trees in the PE and XLPE insulating material. However, it has also proven to be especially suitable for detecting moisture ingress in cable joints. Statistically, moisture ingress in joints is one of the most frequent causes of cable faults and certainly the most frequent cause in hybrid cable systems.
The tan delta measurement is achieved over 3 or more voltage levels. There, the tan delta mean value, the standard deviation as well as the tan delta tip-up is measured and evaluated automatically during a tan delta ramp-up.

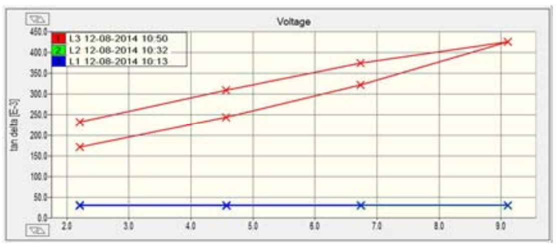


Fig.5: VLF tan delta hysteresies measurement on PILC cable

For critical cables, some experts apply the tan delta hysteresis measurement. This offers extended information on the tan delta progress, indicates the fault type and the fault progress. The tan delta hysteresis measurement is a helpful tool for evaluating the cable condition and for making decisions regarding the need for cable refurbishment (fig.5)

Particularly for aged cable systems, the holistic consideration by applying the partial discharge measurement and the dissipation factor measurement offers detailed information on the ageing condition, allows an estimation of the expected remaining service life of the cable system and offers the appropriate base for making decisions regarding partial refurbishment of the cable or replacement of critical joints and terminations.

Penetration of moisture in cables leads to early failure in most insulating materials and can be detected by the highly precise tan delta measurement combined with cable capacity determination.

Non-destructive cable diagnostics of old cable systems:

Old cable systems are valuable assets. Therefore, cautious handling of old cable insulation is the first priority during diagnostic measurements on old cable systems. Accordingly, experienced utilities limit the applied diagnostic voltage to 1.5Uo. Some of them limit the applied diagnostic voltage further down to Uo and consequently avoid unnecessary electric stress in old cable systems.

The utilities thereby deliberately ignore the extended diagnostic results that could be gained by applying higher test voltages in order to avoid possible risk of damages to the old insulation material.

The efficiency of cable diagnostics is essentially increased through extended diagnostic options applying dissipation factor measurement and partial discharge measurement. The conventional ramp-up of the diagnostic voltage is applied during tan delta and partial discharge measurement and extended by tan delta hysteresis measurement for critical cables.

Adaptive trend analysis MWD:

Most recently, for critical cable systems an adaptive trend analysis by means of tan delta and partial discharge measurement has been used to gain more information on the extent of ongoing cable deterioration and the indicated fault phenomena. The high significance of the acquired information helps to understand the fault phenomena and to subsequently make the right decisions with regard to cable refurbishment.

The newly developed diagnostic procedure is called **Monitored Withstand Diagnostics** MWD, and offers adaptive trend analysis (see Fig.6).

MWD shows similarities to the diagnostics procedure Monitored Withstand Testing (MWT). The Monitored Withstand Testing [2] was developed by the American Institute NEETRAC and has already been integrated in the American Cable Testing Standard IEEE 400.2 -2013 [1].

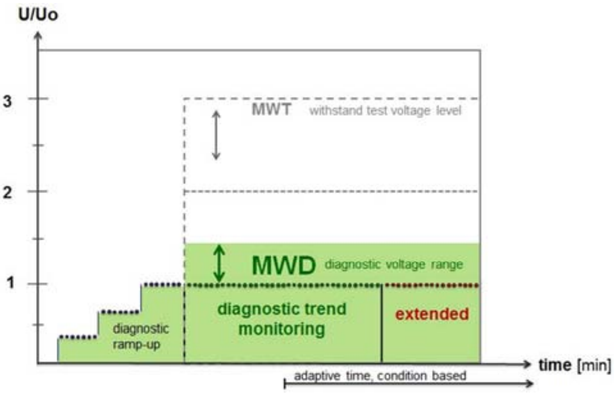


Fig.6: Monitored Withstand Diagnostics

The adaptive trend analysis Monitored Withstand Diagnostics differs fundamentally as it is carried out with reduced diagnostic voltage and avoids excessive stress on the insulating material. The VLF test voltage is ramped up in stages up to max. 1.5Uo then the trend monitoring of the diagnostic values is carried out. For significantly aged cable installations the applied diagnostic voltage can be reduced or even limited to Uo.

The measurements of tan delta and partial discharge are performed simultaneously, thereby the measuring results are continuously available during all the MWD process. Simultaneous measurements reduce the handling risk in the cabin and the time spent for diagnostic measurement by 50%. This provides a significant improvement in terms of time efficiency for the measuring crew.

The diagnostic measuring time can be further reduced depending on the condition, e.g. when good diagnostic results are gained or in the event of poor insulation, it is accordingly extended. For poor insulation a longer diagnostic monitoring time is proposed. Diagnostic data gained during the extended trending, provides additional information on fault phenomena and cable operation risk.

MWD combines the well–proven dissipation factor measurement and partial discharge measurement with final trend monitoring and can also be extended by a location-selective phase resolved partial discharge PRPD (Fig.7)

The latter enables the separate evaluation of partial discharge phenomena on various cable joints, terminations or partial cable routes and can also be applied selectively on simultaneously appearing PD activity of multiple weak points.

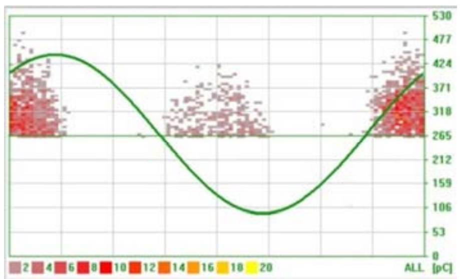


Fig.7: Phase resolved PD measurement (PRPD)

BEST PRACTICE CASE STUDIES:

Effect of PD trending on PILC cables:

PD activities in aged PILC cables are often tolerated due to the generic insulation design and PD activity caused by geometric expansion on temperature change. The PD inception voltage of PILC cables is often below Uo. It can be concluded that PD spots that are widely spread over the cable length and that do not form concentration clusters are non-harmful and accepted for condition assessment. Whilst on the other hand concentrated PD clusters will lead to a degradation of the insulation material and are considered hazardous. PD concentrations detected at nominal operation voltage Uo or below should not be accepted because in the long term, they may lead to insulation damage.

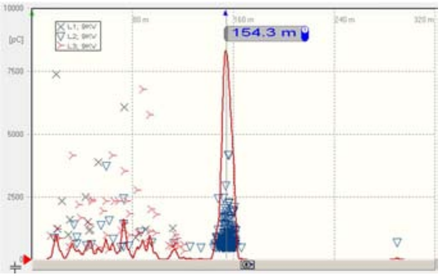
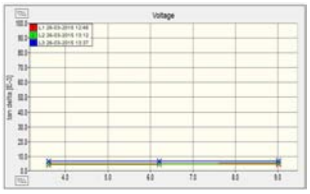


Fig.8: PD on PILC cable, widely spread and PD cluster

Attention should be paid to the PD trending during the diagnostic procedure especially on PILC cables with a non-migrating compound (MIND). Often PILC cables are diagnosed as aged due to presence of PD.
PD and tan delta trending offers additional information on the ageing condition which may lead to initial decisions made based on the conventional short-time PD analyses being revised. The case study on cable 10-1964 provides detailed information on PD activity that is widely spread on the cable length and also pointed to a PD cluster at 154m. A common short period PD measurement would rank the cable as critical. (Fig.8)
In contrast the applied diagnostic trending provides even more useful information. During PD trending over 10 min, a significant change of PD activity took place. The tan delta trending remains convenient and stable over time. During a 10 minute PD trending, the PD activity disappeared on the large cable section as well as on the PD cluster at 154 metres (Fig.9).

Fig.9: PD on PILC cable after 10 min trending

By combining the good tan delta results and the important information on PD trending, the cable can be ranked as non-critical (Fig.9,10,11). Further periodic diagnostics is recommended to monitor the long- term trend.



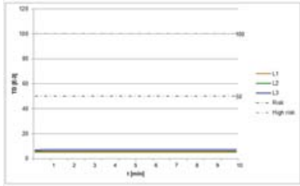
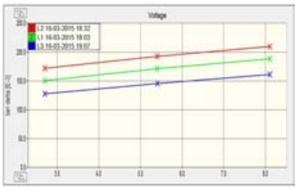


Fig.10: tan delta ramp-up **Fig.11: tan delta trending**

However, for case study 10-1144, the monitored withstand diagnostics presented critical results. The dissipation factor measurement indicates high ageing of the hybrid cable consisting of XLPE cable, 3-lead PILC dated 1966, XLPE dated 2005, 3-lead PILC dated 1975.



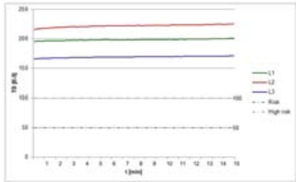


Fig.12: tan delta ramp up **Fig. 13: tan delta trending**

During the PD trending at L3, a PD clusters appeared at a distance of 12m. Investigation on L2 initially showed no PD during PD trending. Suddenly, after 11 minutes of monitored withstand diagnosis carried out at nominal operation voltage Uo, a critical PD spot appeared at L2 indicating high PD density at a distance of 4.6m, close to a transition joint, as shown in figure 14 and 15.

Fig.14: PD trending L2 **Fig.15: PD cluster L2**

The PD spot has to be classified as a high operational risk due to low inception voltage at Uo and the high PD density of up to 160 pulses per cycle (Fig.14). The PD trend monitoring could detect a weak insulation spot. It can be considered that a commonly short duration PD test would not be adequate to detect this harmful insulation defect. It is advised to replace the front 10 m cable section of the 3-lead PILC dated 1966 and to re-test the circuit after refurbishment process.

Sucessful cable refurbishment:

Figure 16 provides information on the successful refurbishment of cable 10-0892, an old hybrid cable consisting of XLPE and EPR cable sections dated 1979 and 1974. After replacing a short section of the EPR cable, a new diagnostic measurement confirms that the risky PD cluster at 318m cable distance has been removed. The tan delta measurement confirms the successful cable refurbishment.

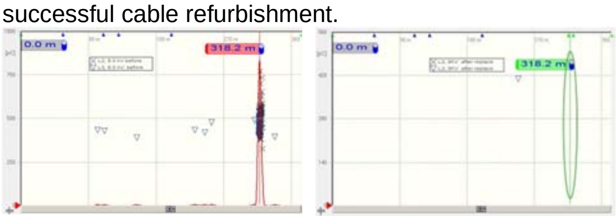


Fig.16: PD before / after refurbishment

Furthermore the refurbishment made on cable 10-2865, an aged hybrid cable system consisting of XLPE cables dated 1992 and 3-lead PILC cables dated 1975, provides successful conclusion. Here an XLPE cable section of 20m was replaced. The tan delta (Fig.17) and PD measurement (Fig.18) now confirms the successful cable refurbishment.

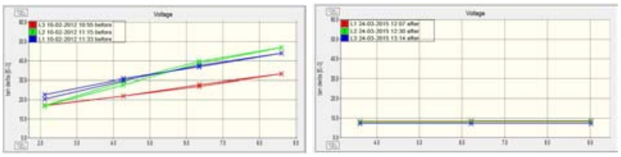


Fig.17: tan delta before / after refurbishment

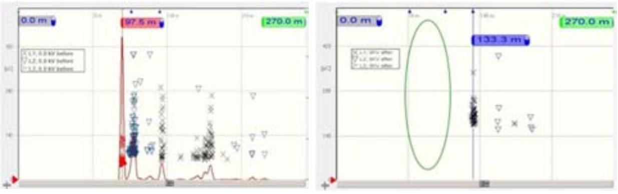


Fig.18: PD before / after refurbishment

Useful multi- method approach with MWD

MWD exposes significant diagnostic results for cable 10-1720, a cable composing of PILC sections dated 1990 and 1976. The important diagnostic results gained on this cable could not have been made available by conventional PD testing. The PD diagnostics at L1 does not indicate any PD activity, wheras the tan delta ramp up and the tan delta trending provide information on the high operational risk as shown in figure 19.

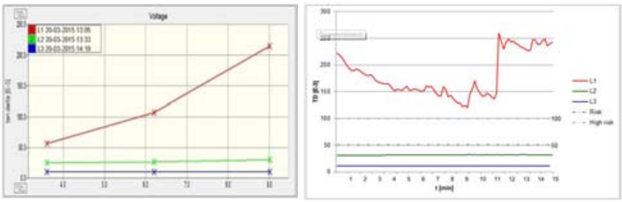


Fig.19: tan delta ramp up and tan delta trending

Similar results were obtained for cable 10-3773, an EPR insulated cable dated 1972. No PD could be detected, whereas the tan delta ramp up and the tan delta trending offer information on high operational risk due to moisture ingress on the single cable joint (Fig.20).

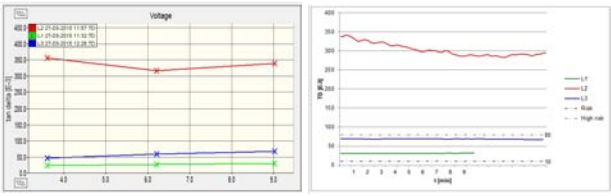


Fig.20: tan delta ramp up and tan delta trending

Many of the before mentioned diagnostic measurements confirm the need for a multi method approach to provide conclusive access to all diagnostic parameters. The simultaneous use of tan delta and partial discharge measurements combined with trend monitoring offers unique diagnostic information for a successful condition-based maintanance approch of aged cable systems.

Fig.21: MWD Diagnostics on aged cable systems

Conclusions:

This paper describes a novel asset management strategy for condition- based maintenance (CBM) of aged medium voltage cable systems.

The described maintenance programme is called Monitored Withstand Diagnostic (MWD). To avoid high voltage stress and unnecessary cable defects on old cable systems, the combined cable diagnostics is used as a smart solution for condition evaluation.

MWD offers extended diagnostic information with the highest efficiency and significant time saving due to simultaneous PD and tan delta diagnostics.

Useful information can be obtained to develop an effective refurbishing programme for aged cable systems that, on the one hand ensures the reliability of power supply and on the other hand saves the expensive replacement of old cables.

Acknowledgments

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GLOSSARY

CBM: Condition-based maintenance
EPR: Ethylene Propylene Rubber
MWD: Monitored Withstand Diagnostic
MWT: Monitored Withstand Testing
MIND: Mass Impregnated Non Draining
PD: Partial Discharge
PE: Polyethylene
PILC: Paper insulated lead covered cable
PRPD: Phase Resolved Partial Discharge
VLF: Very Low Frequency
XLPE: Cross-Linked Polyethylene