INCREASING CONFIDENCE IN MEDIUM VOLTAGE CABLE DIAGNOSTICS – EVALUATION LOGICS AND STRATEGIC APPROACH

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Abstract

Cable diagnostics based on VLF TanDelta and VLF Partial Discharge measurement is most beneficial, when clear application procedures for new installations, for maintenance test after repair and for regular inspection [Figure 1] are defined and evaluated in network tailored evaluation logics using clear action plans. The remaining lifetime estimation is the latest software invention and allows investment planning for asset managers. Huge saving potentials are realistic when the underground medium voltage cables can be operated to the optimum lifetime, while the reliability of the network is increased at the same time.

Introduction

Cable diagnostics has been proven to be the only way to understand the condition of the underground medium voltage cable network. The application of VLF (Very Low Frequency) ramp-up diagnostics can be used for cable condition assessment. Voltage levels starting from 0.5 x U_0 to maximum 1.7 x U_0 (U_0 is defined as the phase to ground voltage) are fully sufficient for comprehensive condition assessment and avoiding any insulation overstress during testing. Cable diagnostics with VLF TanDelta (VLF TD) and VLF Partial Discharge (VLF PD) can be conducted at the same time in one single sequence (VLF TD//PD parallel) [Figure 2]. For maintenance tests, which are often conducted after repairs and sectional cable replacements, the ramp up application is followed by a 2.0 x U_0 Monitored Withstand Test [1] [Figure 3]. For new installations, a commissioning or also called acceptance test is conducted. To verify the quality of newly laid cables including the newly installed accessories such as joints and terminations, a ramp up diagnostic sequence is followed by a 3.0 x U_0 Monitored Withstand Test (MWT) [Figure 3]. It is recommended that the MWT is covering the TD loss factor measurement as well as the PD Partial Discharge measurement during the testing period (FULL MWT). Depending on the cable condition, the test duration can be optimized.

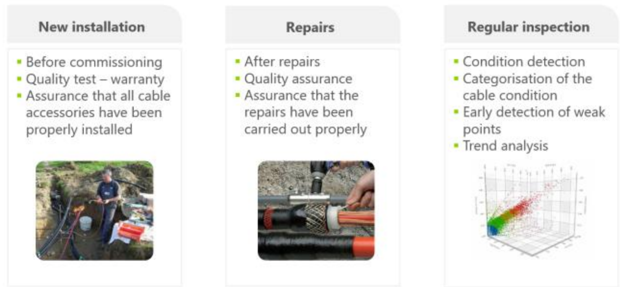

Figure 1 Application of VLF TD//PD and VLF FULL MWT

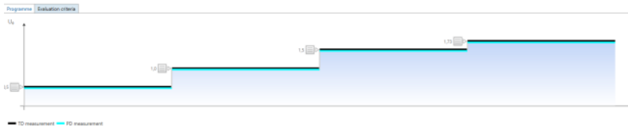

Figure 2 Sequence of parallel VLF TD and VLF PD diagnostics

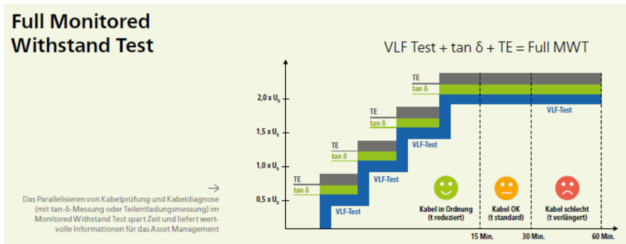

Figure 3 VLF Full Monitored Withstand Test FULL MWT

Background and motivation

VLF testing and diagnostics for MV cable application is defined and recommended by IEC 60502-2 - 2014 and IEEE 400.2-2013 [2]. Test voltages and the applicable diagnostic methods of VLF TanDelta Loss factor measurement and PD Partial Discharge measurement are mentioned. IEEE 400.2-2013 is the only existing field guide that describes evaluation criteria for VLF TanDelta diagnostics for different cable types [Figure 4].

Adapted evaluation criteria for XLPE for TD measurements from 0.5 U_0 to 1.5 U_0 – aged cables:

Table 4: Historical figures of merit for condition assessment of service-aged PE-based insulations (i.e. PE, XLPE and TRXLPE) using 0.1 Hz – TD measurement up to 1.5 U_0

Condition assessment	VLF-TD time stability (VLF-TDTS measured by standard deviation at U_0 [10^{-3}]		Differential VLF-TD (VLF-DTD) (difference in mean VLF-TD) between 0.5 U_0 and 1.5 U_0 [10^{-3}]		Mean VLF-TD at U_0 [10^{-3}]
No action required	< 0.1	and	< 5	and	< 4

Figure 4 TD evaluation criteria acc. to IEEE400.2-2013 for aged XLPE cables

However, the meaning of the categorization published, has been questioned as soon as aged cables and mixed cable circuits have been diagnosed. For PD measurement, there is no official field guide available, that would describe limits of PD activities in cables and its accessories. PD evaluation till today has been done based on experienced values only.
Many power utilities who initially understood the importance of cable diagnostics for condition assessment, often lost the fate of doing so, as clear action plans related to the analysed parameters have not been given or defined by standards. Cable diagnostics can be compared to medical check-ups, where professional devices measure and read parameters of a human body. Only the final interpretation of the specialist allows the definition of detailed treatment plans and the patient to know what further treatment is required. Converted to cable diagnostics, it is equally important to be able to read the details of the many parameters that are diagnosed during the cable diagnostics sequence. A holistic approach, that combines numerous parameters and behavioural characteristics and trending sings visible in cable diagnostics reports, are required to identify and localize the source of degradation. BAUR GmbH has understood, that a premium-quality diagnostics tool is the basic requirement to be able to measure the relevant aging parameters with sufficient precision and sensitivity. A logic combination of the measuring parameters is required to achieve an appropriate categorization and an action plan for each kind of aging effect. VLF diagnostics combines the TDR, TD as well as PD diagnostics with all its relevant details and pattern [Figure 5].

category	1	2	3	4	5
operational state	operable	operable	operable	operable	critical
action plan as a result of: cable sheath condition STD, Skirt, DTD, MTD PD concentration, PDIV, PD - level in the cable / joints / cable terminations	repeat measurement	repeat measurement	repeat measurement	**repair / replacement** needs to be planned and implemented	**repair / replacement urgently** needs to be planned and implemented
cable condition	no significant aging	low aging	Aged, few weaknesses	intense aging, potential weaknesses	high probability of failure
action period	**repeat measurement diagnostic according to Statex® recommendation or in 10 years**	**repeat measurement diagnostic according to Statex® recommendation or in 5 years**	**repeat measurement diagnostic according to Statex® recommendation or in 2 years**	**repair / replacement** within 12 months	**repair / replacement urgent** or within 2 months

Figure 5 Categorization logic with clear action plan for TDR, TD and PD diagnostics

Experience

Since 1991, BAUR GmbH has been the leading manufacturer and inventor of VLF testing and diagnostic equipment. For the last 20 years, BAUR has been involved in cooperations with numerous power utilities worldwide, with the target to gain evaluation experience and support to develop evaluation logics where the relevant diagnostic details are combined with our customers. The close contact and field work allowed gaining insight and draw conclusions on the diagnostic trend behaviour of the many different elements in a cable network. Today's modern test and diagnostic equipment includes pre-programmed sequences with automatic evaluation criteria for VLF TD and VLF TD MWT (Monitored Withstand Test) according to IEEE 400.2-2013. The provided categorization in "No action required", "Further study advised" and "Action required" has raised many questions [Figure 4] [3].

The questions of "How to study further?", "What action is required?" triggered BAUR's motivation to act. Performing only one type of diagnostics method such as VLF PD does not allow understanding if a cable is in high operating risk and what action to take. Only when combining VLF TD with VLF PD diagnostics as well as a sensitive TDR measurement, a clear judgement, addressing all aspects of cable aging, is possible [Figure 2]. In many cases cable details are required to judge the cable more precisely, especially on mixed cable circuits. For these particular judgements, the TD resolution of 1 x 10^{-6} is crucial. Certain aging characteristics can only be recognized with highest resolution. When judging the PD activities, it is important to know, that VLF PD activities, which are also measured based on the VLF 0.1 Hz frequency, offers similar results to the 50 / 60 Hz power frequencies. It is understood that PD activities in joints and terminations are influenced by the presence of moisture and water ingress. Only when the VLF TD diagnostics shows dry conditions, the real PD activities can be seen. The evaluation logic needs to combine the indicator for moisture together with the PD activity judgement. Further, it is essential to differentiate the severity of a PD activity based on its PD inception voltage (PDIV) and PD extinction voltage (PDEV), the PD quantity per time unit [Figure 7] as well as the PRPD (Phase resolved PD) pattern [Figure 8]. Today's diagnostic equipment combines VLF TD and PD in one system and the parameters can be measured at the same time [Figure 2].

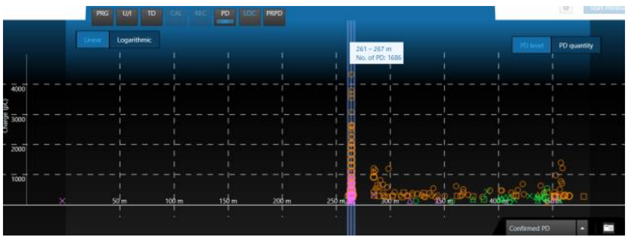

Figure 6 PD localization graph with PD in a transition joint, PD in PILC cable

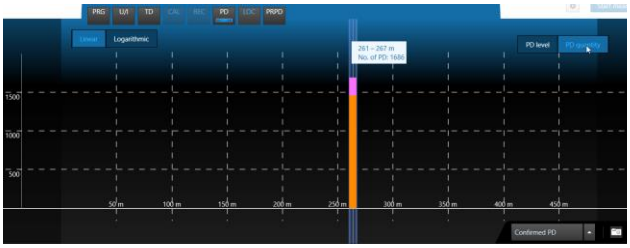

Figure 7 PD activity (quantity per time unit) at transition joint

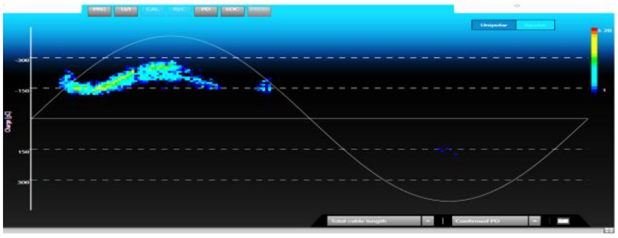

Figure 8 PRPD pattern of PD at transition joint, internal PD

Figure 9 portable VLF TD and PD diagnostic system

Critical PD levels in Pico Coulombs (pC) are different for various types of accessories as well as cables. For XLPE cables, no PD activities are acceptable in the cable body, as critical electrical trees and severe sheath damages can cause PD along the cable itself. For PILC cables, PD activities are acceptable, especially in belted cable type where they often originate from dried out cable sections. Transition joints between old PILC cables and XLPE sections are very often critical and due to the design of such joints higher PD levels also critical because it is not possible to know the exact spot where the PD is originating. This needs to be treated differently compared to straight joints between PILC and PILC or XLPE and XLPE. PD in premolded XLPE joints are often considered more critical compared to PD in heat shrink joints.
The experience showed, that when the diagnostic parameters are combined in a logic, it is very well possible to identify the problem spots even in very complex cable arrangements such as mixed cables.
BAUR has been involved as a contracting party for several utilities performing diagnostics in different cable networks over several years. One example in a metropolitan city in Asia involved BAUR to support the utility to establish an evaluation logic that would fit the very complex and old network where reliability improvement was the main goal. The cooperation required to judge the action requirements on more than 3.000 lines of 11kV cables. The large number of field results combined with proactive post-mortem work according to the recommendation allowed BAUR and the utilities to learn quickly and efficiently [Figure 10].

Figure 10 Post-mortem of joints with PD activities

The accuracy of identifying the weak spot or area in this very hybrid cable network was extra ordinarily high with a confidence level of above 98.5 %. That means, that only in 1.5% of the cases, an unexpected failure happened or that the recommended action did not improve the overall cable condition.

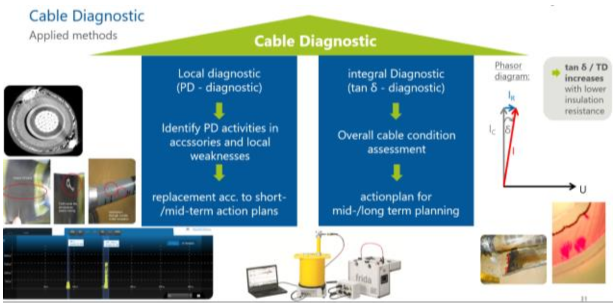

Figure 11 Combined VLF diagnostics TD and PD addresses all weaknesses in a cable

Concept of home of diagnostics

Understanding the challenges of power utilities as well as having gained plenty of practical experience in the field, we at BAUR confirmed that VLF TD and VLF PD diagnostics based on truesinus VLF voltage is appropriate and correct, based on a practical approach. This experience and satisfaction of so many power utilities worldwide confirmed what several studies interpreted more than 20 years ago already. We understood that the combination of several aspects need to be considered to be successful to implement a preventive maintenance approach. The basis for all the success are a very precise and reliable equipment, very well-trained field engineers who need to conduct the measurements, a clear definition of the testing and diagnostic sequence for the basically three applications (Commissioning Test, Maintenance Test and Condition Assessment), guidance for interpretation of the test results and finally, a clear evaluation and result judgement logic with interpretation plan.

home of diagnostics is the BAUR trademark for the combination of all these above-mentioned points from one supplier. The success can only be achieved if the support and guidance after the purchase of test equipment is given. Long-term relationships and cooperations over several years are the key for success. Consultation service in addition to test equipment is a key factor that needs to be considered.

One of the biggest achievements in cooperation and support by BAUR combined with the utilities own motivation and success shall be mentioned. KEPCO Korea has been implementing VLF diagnostics application as a standardized procedure. An automatic evaluation algorithm has been established to evaluate the diagnostic parameters of VLF TD [Figure 12] in a sophisticated and patented way. Since the implementation, already 120.000 cables (as of 05-2022) have been diagnosed and a huge database could be established. Out of this huge statistical data, KEPCO has established the logic to estimate the remaining lifetime of underground cables with highest reliability [4] . BAUR has become the worldwide partner for this new technology and in cooperation with KEPCO. The software statex®, which combines statistics with experience, has been developed for XLPE. The latest version includes an upgrade for PILC cables as well as Mixed Cables. Several technical papers have been published already. [5]

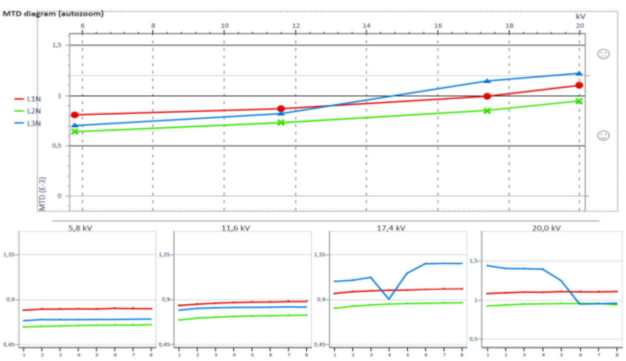

Figure 12 VLF TD diagnostics, the basis for estimation of the remaining lifetime of a cable

When understanding the above-mentioned complexity of the cable diagnostic parameters, it can be understood, that prior to the estimation of the remaining lifetime of a cable, "unpredictable" accessories (e.g. joints with PD activities and joints with water ingress) need to be replaced according to the action plan of the evaluation logic beforehand. Once they are cleaned from "high risk" accessories, the estimation of the remaining lifetime and the recommendation of the next date for retesting can be trusted reliably.

Challenges

The challenges for a power utility can be addressed in a very simple way. To decide implementing an evaluation logic, it is required to define a minimum quality standard for the cable network. That means, that a quality level in terms of reliability is desired. A utility needs to be ready to act when critical values are reached or exceeded. Only when the identified weaknesses of cable accessories and cable sections are replaced, an improvement of the cable network is possible. To do so, the Asset Management Department of the utility needs to define a plan on how the reliability of the network shall be improved and how this relatively small investment will be the way to save much more money in return. The investment into a diagnostic team with the right tools in hand (equipment, resources, manpower and a diagnostic department with clear guidelines) is relatively small in comparison to the huge potential savings considering the prevention of cable faults, replacement of cable sections instead of entire cables, extending the cable service lifetime and avoiding unnecessary cable replacements. Cable diagnostics are the key, when assessing the condition of underground cables.

Examples, case studies

Numerous examples for successful use cases have been collected. Comprehensive cable diagnostics allows to identify weak spots even in very complex cable constellations. Weak spots that show PD activities are relatively easy to identify and localize. Clear PD localization graphs show the weak spot in a length related localization graph [Figure 13].

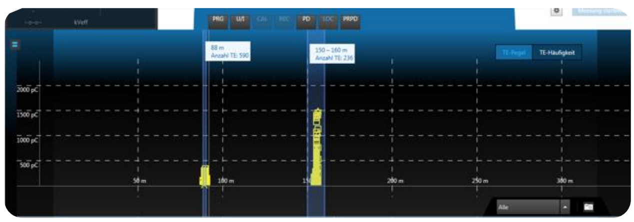

Figure 13 PD localization graph indicating PD activities in 2 locations

Weaknesses such as water tree aging and water ingress in joints as well as terminations are more difficult to localize. TD diagnostics are used to identify the presence of water ingress. Comprehensive TDR analysis are the basis to further localize water ingress in joints.

The main financial benefit is reached, when the cable diagnostics are applied to determine the remaining lifetime of cables. Many utilities are still following the old conventional approach, to replace cables after reaching a certain age. Commonly, 40 to 50 years are mentioned as the end of lifetime of XLPE cables. PILC cables that are still in good condition, can already be as old as 70 years or even older. But when is the end of the lifetime reached? Regular cable diagnostics as shown in Figure 14 allows to recognize weaknesses early, avoid cable failures and optimize the cable lifetime.

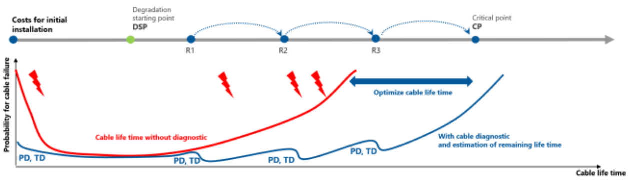

Figure 14 Optimizing the reliability and cable lifetime by regular cable diagnostics

Example 1:

A PILC cable has been installed in 1980's and has reached the 40 years of age. A replacement has been scheduled in the coming few years. For a cable length of 2,000 meters the replacement cost would reach approximately 300,000 EUR. The original plan of the utility was to apply a 3.0 x Uo VLF test for 15 minutes. If the test can be passed, the cable could stay in service for another 10 years. If the test would fail, the cable would need to be replaced. The new approach with cable diagnostics showed no PD activities and very low TD values. The cable condition is still very good, and a replacement would not be necessary. Statex® software evaluated a very low aging speed and it is possible to prognose a long remaining lifetime of another 20 years based on the statistic approach. To judge this more precisely, a retest is recommended in 10 years [Figure 15].

Summary

Phases	Index R	Stat. remaining life time	Next measurement
L1	0,276	> 30 Years	07.03.2032
L2	0,325	20 Years	07.03.2031
L3	0,274	> 30 Years	07.03.2032

Figure 15 statex(r) summary, remaining lifetime, example 1

From financial point of view, considering the dramatic price increase of cables and replacement costs, this approach would save approximately 100,000 EUR considering the cable can stay in service for another 10 years.

Example 2:

A PE (polyethylene) cable has been installed in the 1980's and has reached the estimated end of lifetime. It is known to be a first-generation PE cable and is expected to be water tree aged. The initial intention by the power utility was to apply a 3.0 x Uo VLF test for 15 minutes to verify its suitability for further use. If the test would fail, the entire 2,000 meters of length would need to be replaced. The estimated costs would be around 300,000 EUR. The new approach with cable diagnostics confirmed, that especially L1 was highly water tree aged [Figure 16]. No PD activities have been present.

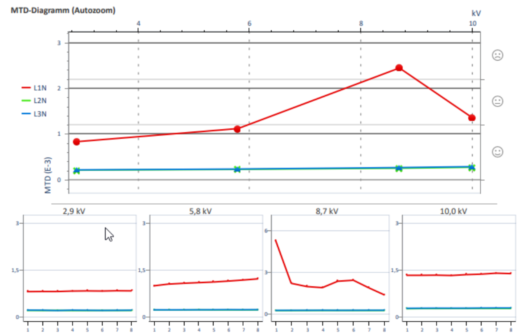

Figure 16 TD characteristic, indicating high water tree aging

In case of a VLF withstand test using 3.0 x Uo the cable would have failed after a few minutes.

Instead, the comprehensive result analysis with statex® revealed, that if no VLF test is done and therefore no intentional stress is applied, the cable can stay in reliable service for another 8 years. A remeasurement would be recommended after 4 years [Figure 17].

Summary

Phases	Index R	Stat. remaining life time	Next measurement
L1	0,531	8 Years	22.03.2026
L2	0,010	> 30 Years	22.03.2032
L3	0,010	> 30 Years	22.03.2032

Figure 17 statex(r) summary, remaining lifetime, example 2

From financial point of view, the lifetime can be extended by 8 years which equals to at least 60.000 EUR.

Recommendation

The modern approach of cable diagnostics as preventive maintenance method shall replace the conventional approach of cable replacement after a fixed service lifetime. Cables face completely different aging models depending on many parameters. Today, there are no models to estimate the aging condition based on load scenarios, earth fault current influence, temperature influence and many other factors.
Using the combined diagnostics technology of tan delta and partial discharge measurement is the only method to understand the aging condition of a cable. The estimation of the remaining lifetime of a cable is a new approach that originates from a huge practical database and has proven to be the tool to save a huge amount of money and allows investment planning for replacement of underground cables. When considering the average extension of live time of the cables that are already 40 – 50 years old for 10 or more years, every utility can easily understand that the saving potential is reaching millions of Euros while the investment is comparably low [Figure 18] . [6]

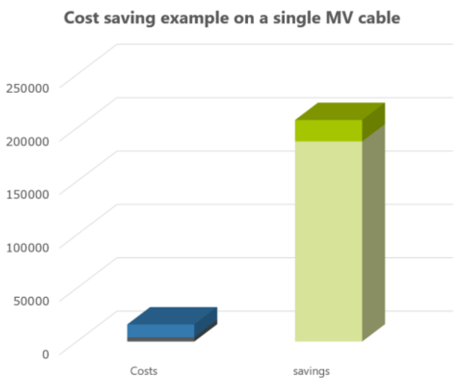

Figure 18 Cost saving example on one particular cable

Summary

Cable diagnostics applied in a comprehensive way opens new possibilities for power utilities to cope with the increasing pressures that arise from many points of view. Diagnostics are more than just performing diagnostics measurements. A key factor for success is the implementation of a standard operating procedure that includes the procedure of diagnostic measurement and a comprehensive evaluation logic with a clear action plan that is tailored to the cable network. The estimation of the remaining lifetime with highest reliability allows investment planning while the reliability of a cable network can be improved. BAUR provides the complete solution, based on precise technology, know-how and experience. BAUR, your home of diagnostics.

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