A NEW APPROACH FOR EVALUATING THE CONDITION OF CABLE SYSTEMS AND ESTIMATION OF REMAINING LIFE TIME OF MV UNDERGROUND POWER CABLES

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ABSTRACT

This study focuses on one of the key questions of underground distribution network operators. How can the remaining life time of underground power cables be estimated? The answer to this question is explained by a new approach of KEPCO Korea. When combining VLF Tan Delta (TD) and Partial Discharge (PD) diagnostic it is possible to identify and localize weak individual spots along a cable. After weak spots are cleared, the general aging condition of the cable can be judged and the Remaining Life Time can be estimated. The implementation of this approach in the KEPCO Distribution Networks is illustrated in a practical case study. A new tool for asset managers is available and it is expected that it will help to further develop the preventive maintenance approach by power utilities all around the world.

INTRODUCTION

The importance of a healthy and reliable medium voltage cable network is today well understood by the cable operators. When planning the maintenance of these networks, distribution system operators (DSO) have to manage the conflicting requirements of scarce resources, high standards in terms of supply security and the issue of networks that become older and more complex. In addition, the energy transition towards renewable energy sources pushes underground cable networks to their limit.

Very Low Frequency (VLF) Monitored Withstand Diagnostic was found to be a very effective tool for evaluating the cable condition and deciding the urgency of partial or sectional replacement. The estimation of the remaining life time of a cable is the challenging key for DSOs in order to manage investments and resources.

In Europe it can be assumed that the average costs for laying a new cable route is in the range of € 300,000 per 2 - 3 km. Commonly the life time of a XLPE cable can be assumed with 30 to 40 years. A precise diagnostic tool allows categorising an old cable to be in healthy condition and the cable can therefore remain in place within the network for further 10 years, the extension of the service life time of the particular route can be quantified by 25% of the initial investment cost. In case this counts for several cable routes, savings of many € 100,000 per year are possible. The application of the best cable diagnostic tool available today and result – based diagnostic knowledge are the fundamentals for finding weak cable sections which can be replaced individually, instead of replacing the entire routes.

CONDITION BASED ASSET MANAGEMENT

Categorising underground cables based on the cable condition has become possible during the past years by application of VLF cable diagnostic techniques. In 2013 IEEE 400.2 [1] established comprehensive evaluation criteria for categorising various cable types into different condition status categories namely “No action required”, “Further study advised” and “Action required”. The evaluation criterion is mainly based on VLF Tan Delta diagnostics. This enables the DSO to perform a condition based asset management strategy categorising the cables depending on their condition (Figure 1).

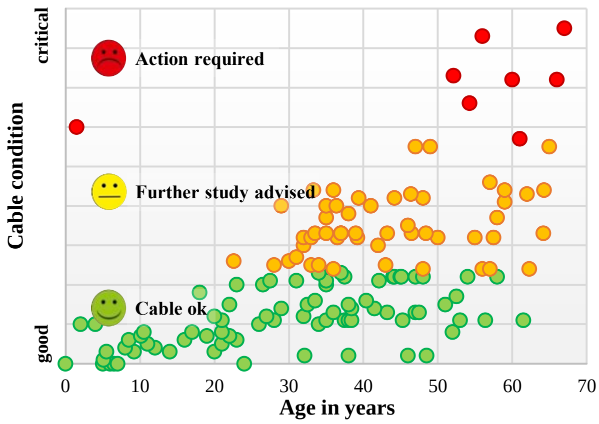

Figure 1: Distribution of cable condition versus duty period

The international guide for field testing IEEE 400.2-2013 [1] is proven to be useful for the basic categorisation, yet having its limitations. These limitations need to be considered in this regard, that for aged cable networks, the yellow range indicated in Figure 1, “Further study advised” is understood to be wide and may categorize cables with general aging condition and not very severe weaknesses. But cables with singular weaknesses that may turn into potential defects are categorised into the same group. Despite this the cable will not be categorized as a cable in severe condition. This may lead to unpredicted cable breakdowns.

COMBINED CABLE DIAGNOSTIC

Considering that XLPE cables have been installed since the early 1980’s, many of those cables may have reached a duty period (DP) of 35 years and more. Today the critical question on the remaining life time of cables is raised everywhere. KEPCO Korea (Korean Electric Power Corporation) has addressed this question during the past years to their research group and found a unique solution and answers to this question.

Cable joints with Partial Discharge activities as well as joints with water ingress need to be addressed differently compared to cables with healthy joints. The judgement of Remaining Life Time can be influenced significantly by Partial Discharge activity with the result of an unprecise failure prediction. In order to identify and localize these critical joints, KEPCO as well as many other utilities make use of the comprehensive diagnostic tools VLF Tan Delta (TD), Partial Discharge (PD) diagnostic, Monitored Withstand Diagnostic as well as Time Domain Reflectometry (TDR). The smart combination of these methods allows localising all weaknesses along a cable at a reduced voltage stress level during VLF diagnostic. Singapore Power Grid [2] identified, that VLF Tan Delta combined with a sensitive TDR approach is a very efficient tool to localize joints with water ingress. VLF based diagnostic tools offer the big advantage, that even at low voltage application (up to 1.1 x U_o only, where 1.0 x U_o is equal to phase to ground voltage) very meaningful diagnostic results can be achieved and the cable condition can be evaluated. For aged medium voltage cables it is essential to keep the voltage stress during the diagnostic measurement as low as possible [3]. This low stress application differs greatly compared to a standard VLF Withstand Test. Here it shall be stated once again, that cable diagnosis is used to evaluate the cable condition aiming to avoid any life limiting voltage stress. The VLF Withstand Test as well as the Monitored Withstand Test (MWT) uses much higher test voltages with the aim of detecting weak spots by initiating a cable breakdown.

CASE STUDY

The following example [4] describes a diagnostic result, conducted on a 22 kV XLPE cable of 322 m length and a single joint at 97 m. The TD diagnostic result (Figure 2) allows understanding that the two phases L1 and L2 are in good and stable condition.

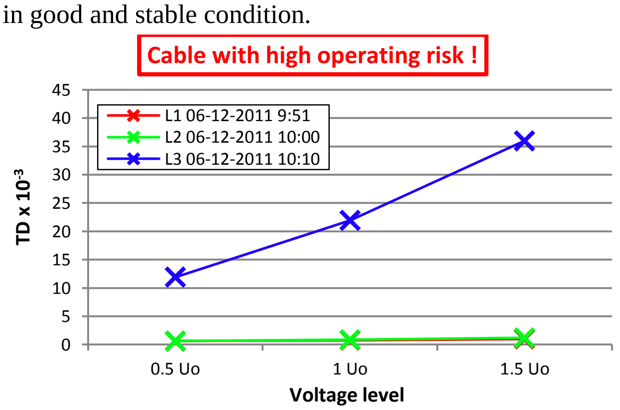

Figure 2: Result of initial Tan Delta diagnosis, 06.12.2011

This" result is confirmed by the Partial Discharge measurement showing no PD activities on L2 and L3.

The Tan Delta diagnostic result of L3 indicates very severe condition caused by water ingress in a joint indicated by the trend pattern of the TD diagnostic result. Due to this indication, PD activities in L3 might be affected by the presence of water in this joint.

PD activities are localized in L1 at a joint at 97 m (Figure 3) with a Partial Discharge Inception Voltage (PDIV) at operating voltage level.

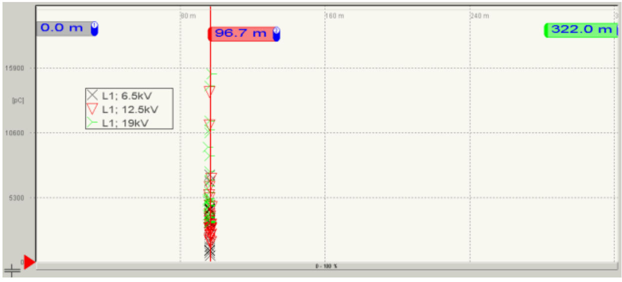

Figure 3: PD measurement result, PD in L1 at a joint (97 m), 06.12.2011

By means of the application of a very sensitive TDR measurement, in L3 an irregular impedance change at the wet joint at 97 m can be identified (Figure 4).

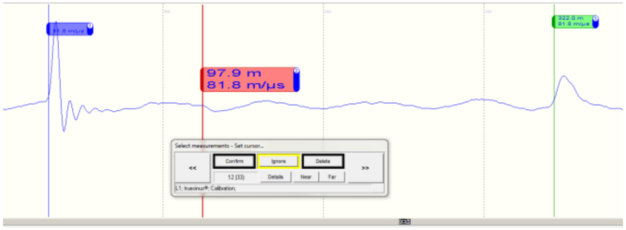

Figure 4: TDR record L3, indication of wet joint at 97 m

L2 and L3 do not show any PD activities which correlates with the fact that wet joints usually do not show partial discharge activity.

These results of a combined cable diagnosis identified and localised the presence of water in the joint (Figure 5).

Figure 5: Joint dissection, water ingress in L3

After joint replacement, the repeating VLF Tan Delta diagnostic showed stable and much lower TD values (Figure 6) compared to the initial measurement (Figure 2). L1 and L2 are confirmed being in good condition. L3 improved a lot, but the general aging condition according to IEEE 400.2 is still categorised as "in high operating risk".

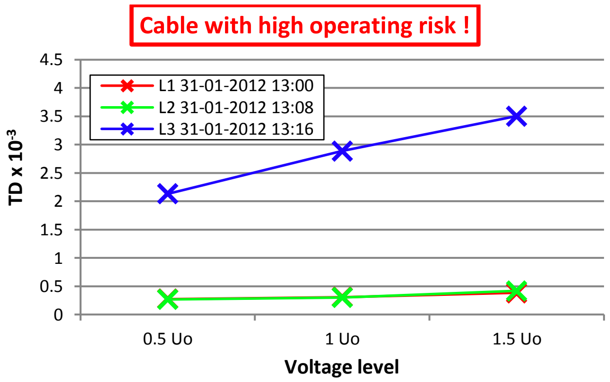

Figure 6: Tan Delta result after joint replacement 31.01.2012

All joints and terminations were free of PD activities after the successful joint replacement. It can be concluded that the general condition of the cable insulation itself is reflected by the TD measurement. In this case the rules of common practice recommend repeating the diagnostic measurements after a few years. It is a big challenge to understand how long the cable may still remain in service with reliability. This difficulty was the initial motivation for KEPCO to study on a methodology to estimate the remaining life time of medium voltage power cables.

METHODOLOGY OF REMAINING LIFE TIME ESTIMATION

The methodology to address the open question on the estimation of the Remaining Life Time (RLT) of underground cables was developed by KEPCO Korea analysing their extensive VLF Tan Delta diagnostic field test results collected over many years. Contrary to many utilities as well as IEEE [1], KEPCO identified that the key parameter of VLF Tan Delta is the time stability of the loss factor figures of Tan Delta. The stability of the Tan Delta figures combined with the trending direction can be analysed. This requires highest accuracy of the Tan Delta testing device providing accurate and stable Tan Delta values of at least $1x10^{-5}$. The graph in Figure 7 shows a Tan Delta diagnostic diagram with Tan Delta values at three defined voltage levels comprising eight measuring points per voltage level. The three phases and especially L1 show an increasing trend characteristic indicating the presence of water tree aging.

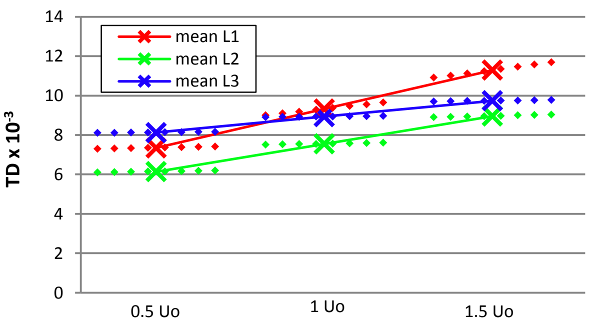

Figure 7: Ref. 3536, Tan Delta pattern of water tree aged cable, three voltage levels with eight consecutive measurements

As per KEPCOs publication [5] the complex Tan Delta pattern consists of Standard Deviation STD, Skirt value offering the trend characteristics, Delta Tan Delta DTD as indication of Tan Delta versus voltage rise and Mean Tan Delta MTD. These characteristics can be converted into a three dimensional vector where each cable is represented by a single R-value. [4]:

$$R = \sqrt{TD_{norm}^2 + DTD_{norm}^2 + skirt_{norm}^2} \qquad (1)$$

These R-values are shown as an extract of in total 45,000 Tan Delta diagnostic data points in a three dimensional cloud (Figure 8). The right top corner is the area defined as economic limit, where cable failures are likely to occur and a reliable operation cannot be expected any longer. The yellow triangles indicate cables failures during operation.

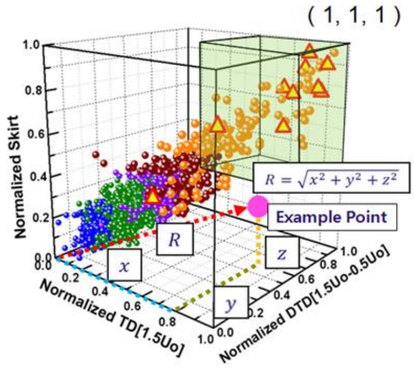

Figure 8: 3D graphic of R values and cable failures [5]

LIFE TIME ESTIMATION

The statistical approach of estimating the Remaining Life Time of cables is based on the statistics of 15,000 cable circuits measured, providing 45,000 data points. This data set may be concluded as the largest VLF Tan Delta data base worldwide. Thereby extensive field VLF diagnostic measurements were carried out.

Figure 9 illustrates the life time assessment approach based on one example. KEPCO's statistical evaluation offered insight that cables below 13 years in service commonly do not show aging. Accordingly, a

Degradation Starting Point (DSP) can be defined. This is the point, where aging is expected to start. The economical limit is set at a level where cables statistically failed and are expected to fail any moment. In order not to reach this level, a safety margin is determined by the DSO. This level is defined as Critical Point (CP).

In a simplified model the Y-axis shall be scaled from 0 (new condition) to 10 units (maximum range of Tan Delta considered). Based on this assumption, an example of calculation can be presented. The statistical DSP of the cable network is 13 years. The limit of economical operation is 8 per unit. The DSO defined the critical cable condition point including a safety margin at 7 per unit. When reaching the Critical Point (CP), the end of life time is considered.

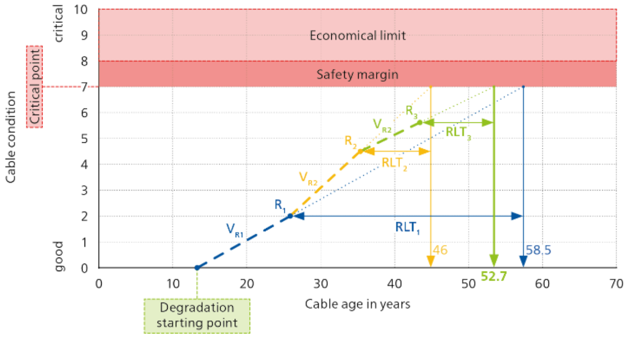

Figure 9: Estimation of Remaining Life Time at different testing points

Example: A cable tested after a duty period of 26 years is diagnosed at a level of aging condition R_1 scaling to 2.0 units. The aging speed can be calculated as R_1 over the aging period being the duty period minus the degradation starting point. Consequently, an average aging speed of 0.15 units per year can be calculated (2). The Remaining Life Time (RLT) based on the statistical aging speed is calculated by extending the same aging speed (V_R) until reaching the Critical Point (here $CP_1 = 7$). Following this, the Remaining Life Time (RLT_1) with reference to the DSP would be 32.5 years (3) and reaching a total life time of 58.5 years.

$$V_{R_1} = \frac{R_1}{DP_1 - DSP} = \frac{2}{26-13} = 0.15\ a^{-1} \quad (2)$$

$$RLT_1 = \frac{CP - R_1}{V_{R_1}} = \frac{7-2}{0.15\ a^{-1}} = 32.5\ a \quad (3)$$

This calculation is based on the initial diagnostic measurement. It is advisable to repeat a diagnostic measurement after 5 to a maximum of 10 years. The implemented logic allows continuing and refining previous diagnostic results. In this example, the cable would be retested after 36 years in operation gaining an aging condition of R_2 of 4.5. The precise and corrected aging speed V_{R2} with reference to the first measurement result R_1 indicates that the actual aging speed is either increased due to different load condition or the cable condition is weaker compared to the statistical average.

$$V_{R_2} = \frac{R_2 - R_1}{DP_2 - DP_1} = \frac{4.5-2}{36-26} = 0.25\ a^{-1} \quad (4)$$

$$RLT_2 = \frac{CP - R_2}{V_{R2}} = \frac{7-4.5}{0.25\ a^{-1}} = 10\ a \quad (5)$$

With an aging speed of 0.25 per year (4) the refined Remaining Life Time is resulting to 10 years (5) and reaching a total life time of 46 years. This scenario could have the consequence of reduction of load in order to keep the aging lower and extend the life time further. With reference to the result 2, a retest would be schedule after further 8 years. The retest after 44 years delivers a condition value of 5.7 and redefines the aging speed V_{R3} (6) indicating that the aging speed reduced as consequence of the lower load stress. The RLT_3 (7) is calculated to 8.7 years. Summing up, the cable will reach an estimated duty period of approximately 53 years.

$$V_{R_3} = \frac{R_3 - R_2}{DP_3 - DP_2} = \frac{5.7-4.5}{44-36} = 0.15\ a^{-1} \quad (6)$$

$$RLT_3 = \frac{CP - R_3}{V_{R_3}} = \frac{7-5.7}{0.15\ a^{-1}} = 8.7\ a \quad (7)$$

RESULTS

This life time estimation approach has been implemented in KEPCO in 2015. The cable diagnostic data collected until 2015 only comprised comparable 22.9 kV XLPE cables with similar type of cables, installation condition as well as joints. Due to this, by 2015, the world's largest VLF Tan Delta database of 15,000 cables with approx. 5,000 circuit km and comparable test results had been accumulated in the diagnostic database. In order to evaluate the logic of categorizing the cable condition and estimating the Remaining Life Time of these circuits, a direct comparison with IEEE 400.2-2013 (Figure 10) evaluation criteria was done.

When using the evaluation criteria according to IEEE 400.2 -2013 field guide, out of the 15,000 cables, 255 km would be categorized as "action required". This is the highest category, where cable breakdowns have to be expected.

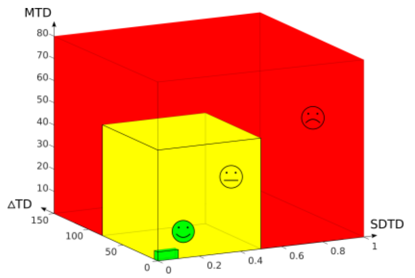

Figure 10: 3D illustration of IEEE 400.2-2013 evaluation logic [1]

The evaluation of the same database using KEPCO's new life time estimation logic only judged 54 km as cables with remaining life time of less than two years. This leads to the assumption that according to IEEE 400.2-2013 field guide criteria, 201 km would have been replaced if they were not yet in a very critical condition. The study further revealed that the average life time in comparison to the IEEE 400.2-2013 field guide could have been increased by 11 years. Referring to the cost saving calculation also mentioned in the introduction section of this paper, this approach achieved the actual cost saving of USD 1.4 million in 2015 itself. The cost saving is based on avoiding 200 km cable replacements immediately and offers the possibility to take advantage of increasing their life time to the naturally given limit.

VERIFICATION OF STUDY

For approval of this calculation a further evaluation has been conducted. By 2015, approximately 11,000 km of 22.9 kV cable have been diagnosed. This represents approximately 25 % of the entire MV network in Korea.

Figure 11 shows the recorded failure statistics per year. The network failure rate of not yet diagnosed cables is rated at 3.37 failures per 1,000 km, which indicates a very healthy cable network. Cables with a duty period of less than 13 years indicate only 0.32 failures per 1,000 km. In reference to this excellent figure, cables that are judged with the KEPCO algorithm of estimating the remaining life time indicate a rate of 0.29 unexpected faults per 1,000 km only. The data shown in Figure 13 reveals the excellent condition of KEPCO's medium voltage cable network where cable failures rarely happen. Even though, the estimation of the remaining life time allows to judge that cables can be operated for different duty periods in close alignment of their aging condition.

	New cable < 13 years	Diagnosed cables	Not yet diagnosed cables
Failure rate (fault/1.000 km)	0,32	0,29	3,37

Figure 11: KEPCO failure rate per 1,000 km

Applying the KEPCO tool for estimation of the Remaining Life Time for the mentioned case study (IV) a clear indication is given. The evaluation according to IEEE 400.2-2013 for aged cables, the condition of all 3 phases would be "no action required" but a Remaining Life Time is undefined. With today's approach a clear figure can be identified. This particular cable would be judged to remain in service for further 4 years with consideration that the cable was tested 08.01.2019.

A retest is recommended in 2021.

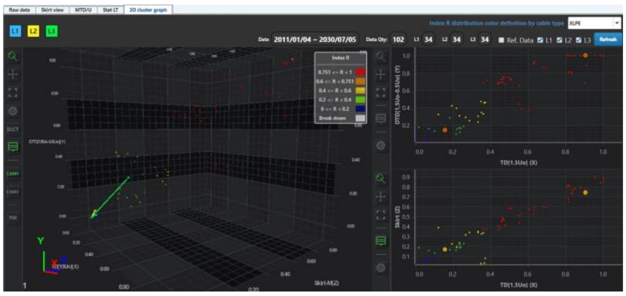

Figure 12 3D evaluation for TD data 31.01.2012, in reference to KEPCO data base

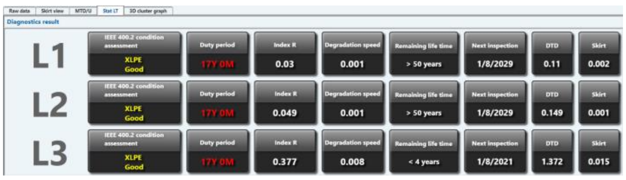

Figure 13 TD data 31.01.2012, estimation of Remaining Life Time for L3 judged with < 4 years; date of evaluation 10.01.2019

Power utilities aim for such a solution that allows scheduling maintenance and replacement work with respect to the real aging condition. If these figures are available for the entire cable network, a proactive preventive maintenance strategy can be established.

CONCLUSION AND OUTLOOK

The study reveals that there is a big potential in cost saving for distribution system operators in case the cable duty period can be judged correctly. The statistical approach done by KEPCO was possible, as the large amount of data can be grouped into a single characteristic group of homogeneous cables. The failure rate of diagnosed cable was reduced to a very minimum and proves the cable life time estimation approach. This cable life time estimation approach and its algorithm will be further studied. The life time estimation tool can be applied by other utilities for estimation of their cable network life time. The combination of VLF truesinus® diagnostic measurements combined with this powerful tool delivers the answer for estimation of Remaining Life Time of underground power cables and concludes for how long aged cables and cable sections can remain in service with high reliability.

ACKNOWLEDGMENT

The authors gratefully acknowledge KEPCO Korea for sharing their knowledge and experience and allowing developing a tool that for the first time offers the possibility of life time estimation of medium voltage underground cables that can be used by power utilities all around the world.

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