A Statistical Approach for Condition Evaluation and Residual Lifetime Estimation of MV Power Cables

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Abstract – **The general idea of preventive maintenance approach allowed most of the asset managers of power utilities to understand that a condition based maintenance approach is the only way to recognize aging effects and weak points, replace the weak cable sections and finally guarantee a distribution cable network condition with high reliability. This paper describes the new approach of statistical estimation of the remaining life time of power cables that allows operating underground cables to the operational limit.**

Keywords – **Asset Management, Loss Factor Tan Delta, Life Time Estimation, Medium Voltage Power Cables, VLF Diagnosis**

I. 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. Commonly the life time of a XLPE cable can be assumed with 30 to 40 years. A precise diagnostic tool allows categorizing 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 today's best available cable diagnostic tools and result evaluation knowledge are the base for finding weak cable sections which can be replaced individually, instead of replacing the entire routes.

II. CONDITION BASED ASSET MANAGEMENT

Categorizing 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 categorizing 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 δ diagnostics. This enables the DSO to perform a condition based asset management strategy categorizing the cables depending on their condition (Figure 1).

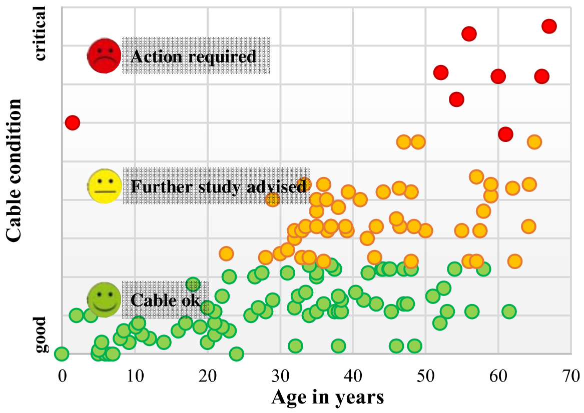

Figure 1: Distribution of cable condition versus duty period

The international field guide IEEE 400.2-2013 [1] is proved to be useful for the basic categorization, yet having its limitations. 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 also cables with singular weaknesses that may turn into potential defects 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.

III. EXTENDED CABLE CONDITION MARKER

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.

It has been understood instantly, that cable joints with partial discharge (PD) activities as well as joints with water ingress need to be addressed differently compared to

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cables with healthy joints. The judgement of remaining life time can be influenced significantly 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 TanDelta (TD), Partial Discharge (PD) Diagnostic, Monitored Withstand Diagnostic as well as Time Domain Reflectometry (TDR). The smart combination of these methods allows localizing all weaknesses along a cable at a reduced voltage stress level during VLF diagnostic (Figure 2). Singapore Power Grid [2] identified, that VLF TanDelta 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 compared to a VLF Withstand Test. Here it shall be stated once again, that cable diagnostic 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) use much higher test voltages with the risk of a cable failure at a weak spot.

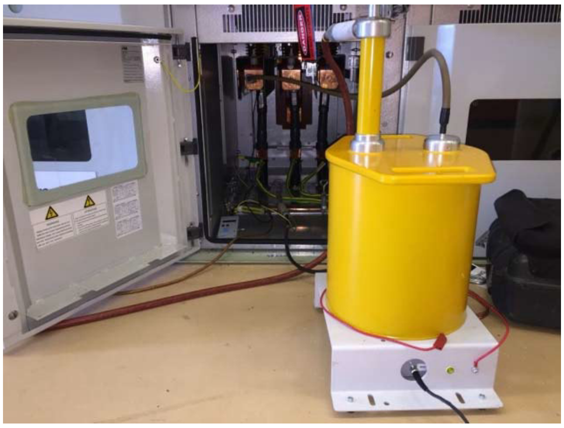


Figure 2: Combined VLF TD and PD diagnostic, field application

The methodology to address the question regarding the remaining life time was developed by KEPCO analyzing their extensive VLF TanDelta 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 TanDelta.

It is preferably defined in the time stability of the loss factor figures TD. The stability of the TD figures combined with the trending direction can be analyzed. This requires highest accuracy of the TanDelta testing device providing accurate and stable TD values of at least 1x10^{-5}. The graph in Figure 3 shows a TD diagnostic diagram with TD 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.

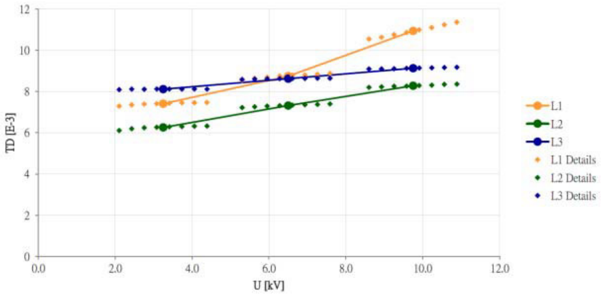


Figure 3: Ref. 3536, TD pattern of water tree aged cable

As per KEPCOs publication [4] the complex TD pattern consists of Standard Deviation STD, Skirt value offering the trend characteristics, Delta Tan Delta DTD as indication of TD versus voltage rise and Mean Tan Delta MTD. These characteristics can be converted into a 3 dimensional vector where each cable is represented by a single R-value. [4]:

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

Figure 4 shows the cloud of 45,000 TD diagnostic data points in a 3 dimensional graphic. The right top corner is the area defined as economic limit, where cable failures are likely to happen and a reliable operation cannot be expected any longer. The yellow triangles indicate cables that failed during operation.

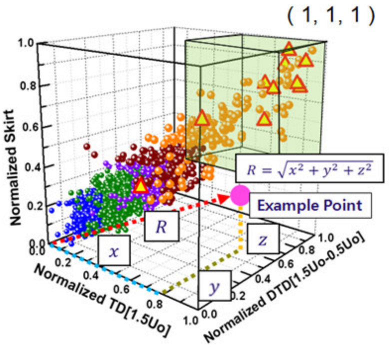


Figure 4: 3-dimensional graphic for R-values [4]

IV. 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 world's largest VLF Tan Delta data base. Therefore extensive field measurements were carried out (Figures 5, 6).

Figure 5: Field test condition, substation

Figure 6: Field test condition, pole mounted termination

Figure 7 illustrates an 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 be starting. 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 has been 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 TD considered). Based on this assumption, an example of calculation can be presented. The 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.

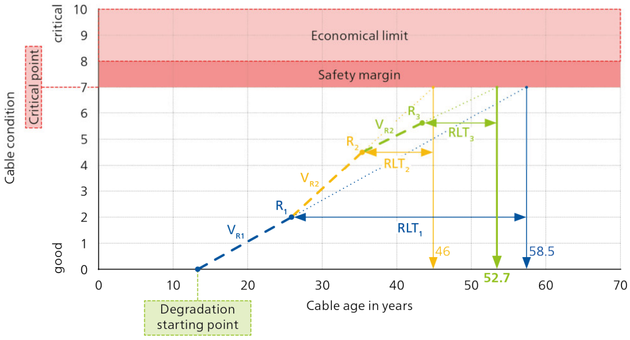


Figure 7: Estimation of remaining life time at different testing points

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. 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 CP1 = 7). Following this, the remaining life time (RLT) with reference to the DSP would be 32.5 years and reaching a total life time of 58.5 years.

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

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

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.

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

$$RLT_2 = \frac{CP - R_2}{V_{R_2}} = \frac{7-4.5}{0.25\ a^{-1}} = 10\ a \tag{5}$$

With an aging speed of 0.25 per year the refined remaining life time is resulting to 10 years 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} indicating that the aging speed reduced as consequence of the lower load stress. Summing up, the cable will reach an estimated duty period of 53 years.

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

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

V. 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 TanDelta database of 15,000 cables with approx. 5,000 circuit kilometers 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 8) evaluation criteria was done.

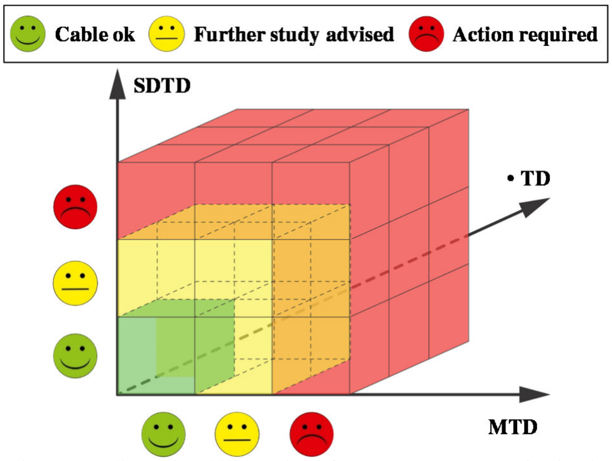


Figure 8: 3-dimensional illustration of IEEE 400.2-2013 evaluation logic

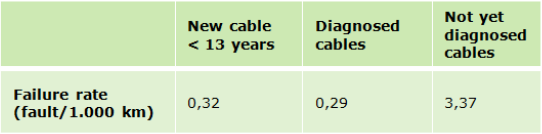
Estimating using the figures according to IEEE 400.2 - 2013 field guide, out of the 15,000 cables, 255 km would be categorized as "action required". This is the highest category, where cable breakdowns have to be expected.

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 even if they were not yet in a 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 to take advantage of increasing their life time to the naturally given limit.

VI. VERIFICATION OF STUDY

For approval of this calculation a further evaluation has been conducted. By 2015, approximately 11.000 kilometers of 22.9 kV cable have been diagnosed. This represents approximately 25 % of the entire MV network in Korea.

Figure 9 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.



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

Figure 9: KEPCO failure rate per 1,000 km

The data shown in Figure **9** points out 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.

VII. CONCLUSION & 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 has been reduced to a very minimum and proves the cable life time estimation approach is fully correct.

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 combined with this powerful tool delivers the answer to 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.

VIII. ACKNOWLEDGMENT

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

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