ESSENTIAL STRATEGIES FOR THE REMAINING LIFETIME ESTIMATION OF THE MV CABLE SYSTEMS

Dr. Ivana MLADENOVIC  
Chair of Electrical Energy Systems, University of Erlangen-Nuremberg – Germany  
ivana.mladenovic@fau.de

Dr. Christian WEINDL  
voltage divider, rectifiers, transformer  
christian.weindl@fau.de

Thomas SCHARRER  
Thomas.scharrer@fau.de

ABSTRACT
In a long-term accelerated aging experiment on brand-new and differently pre-aged medium voltage cables, diagnostic parameters like dissipation factor and partial discharges have been measured daily and collected in a sophisticated data bank. In addition, extensive studies have been carried out in regular time intervals to determine the influence of variable test conditions on the dielectric parameters. The formed data bank counts over 1TB of data correlating the cable condition with diagnostic parameters and additionally test conditions like temperature or voltage. With the results of the aging experiment, a comprehensive database was developed. By the application of newly developed methods of data evaluation and statistical methods, it is enabled to make a prognosis of the cable’s remaining lifetime.

In this article, the process of artificial ageing and data acquisition during the ageing experiment will be briefly presented. Furthermore, some preselected experimental results demonstrating the dependencies of the diagnostic parameters on test conditions will be shown. In the following, the main focus will be on a novel method for the determination of the most probable remaining lifetime. The principles of this approach will be pointed out. Finally, a solution for the application of the approach for remaining lifetime estimation to field measurements will be presented.

INTRODUCTION
Although medium voltage (MV) cable systems are the biggest capital and the main source of faults and supply interruptions in the MV networks, they have reached in high percentage (in some power networks up to 60%) a critical and predefined lifetime. The today’s developments of the power grids can be characterized for many countries and especially for Germany by a continuously increasing integration of renewable energy sources resulting in a reinforcement of the load and the load fluctuation. In this way additional stress factors become operative that could influence the remaining lifetime of the already longstanding cable networks.

In the recent years, several key methods for the determination of cable condition have been proposed. However, influenced by numerous factors and test conditions, the cable condition can only be assumed with by diagnostic parameters with a partial reliability and mostly without the final intention to predict the remaining lifetime.

In order to identify the dependencies of the diagnostic parameters on the electrical as well as on the environmental test conditions and this all in correlation with cable’s condition and its remaining lifetime, a long-lasting aging experiment on MV paper insulated lead-covered (PILC) cables has been carried out. Even they have been partially replaced by cross-linked polyethylene (XLPE) cable types in many countries, this long-standing cable type is still very present not only in Europe. The stated aim of this project was to estimate a most probable time to the next cable failure (characteristic life time of cable) based on substantiated measurements of suitable diagnostic parameters. In order to find a method, which enables this approximation, it was necessary to define the physical background of the processes that are present in the cable insulation during the ageing process.

ARTIFICIAL AGEING EXPERIMENT
In the first phase, a fully automated and integrated cable accelerated ageing system (ICAAS) has been developed, realized and verified, [1][2][3]. It realizes accelerated, artificial but realistic ageing (50Hz, up to more than 600A at a maximum ageing voltage level of up to 50kV) with freely definable ageing parameters and load profiles. The SCADA (system control and data acquisition) system comprises the entire system operation and control of the ageing conditions and an extraordinarily accurate measuring i.e. monitoring (e.g. partial discharges (PD) and dissipation factor) of the diagnostic parameters on each cable sample on pre-definable voltage and temperature levels and in regular time intervals. In this way a unique knowledge databank was evaluated and many additional features for data selection, mathematical and graphical analyses and correlation were developed. A partial view over some of the ageing and protection components (resonant system, overvoltage protection, voltage divider, rectifiers, transformers for thermal stress) of the ICAAS system and the cable samples is shown in figure 1. Most of the hardware and software components were specifically developed, designed, constructed and approved in university workshops and laboratories.

Within the long-lasting project, several groups of MV PILC cables of different generations have been artificially aged. Hereby, the tan(δ) and the PDs have been regularly monitored over the complete lifetime of
the accelerated aged samples. Additionally, measurement cycles with varied temperatures and variable voltages (so called parametric studies) have been accomplished in regular time intervals. All measurements were carried out at the network frequency of 50 Hz.

Figure 1. Partial view over ICAAS

In order to get an information over the cables’ condition during their complete lifetime, as well as to analyze the development of the electrical and diagnostic parameters in different age-stages, different generations of cable samples have been used. Thus, beside the brand new cables, also cables that were in field operation for up to 45 years have been artificially aged. An overview over cable samples within the thermal thank is shown in Figure 2.

Figure 2. Cable samples in ICAAS (top open)

In figure 3 a structural chart of the complete ageing experiment and one single day is presented. The ageing process is interrupted in case of the daily diagnostic monitoring measurements – diagnostic cycles, parametric studies (marked as PS), or if one of the cables fails. In the last case, time is needed to remove or replace the affected cable sample (marked as FR) before the artificial ageing can be proceeded.

Beside the regular daily “diagnostic cycles”, which consist of several reference measurements and measurements of tan(δ) and PD on different voltage levels at the predefined ageing temperature, also regular “parametric studies” have been carried out. Parametric studies are sets of measurements performed over a wide range of temperatures and voltages, which enable analyses of the dependencies of the diagnostic parameters on the test and cable conditions. These measurements were accomplished under defined and monitored environmental circumstances, at 50 Hz, and over selective test-voltage levels in the range from 0.4\(U_n\) to 2.2\(U_n\), and within a temperature range from 5°C to over 90°C.

Figure 3. Operation charts of the complete ageing experiment and of one single day

RESULTS OF THE EXPERIMENT

As described in figure 3, the ageing experiment started with a parametric study. The related 3D-plots of the diagnostic parameters over a variable voltage and temperature are called PD- or tan(\(\delta\))-profiles.

Figure 4. Selected and characteristic initial profiles of normalized tan(\(\delta\)) showing: a) temperature dependent loss maxima caused by polarization effects, b) dominant voltage or c) dominant temperature dependency
In figure 4, some typical dependencies of dissipation factor for brand new cables (a), or pre-aged cables (b) and (c) are presented. It can be seen that test conditions strongly influence tan(δ) (and also PD) and have to be considered during data interpretation. As a result of the ageing process the shape of these profiles developed in the course of the experiment so that e.g. loss maxima disappeared in the mainly increased values of the diagnostic parameters or caused by the physical impact of temperature fluctuations. Withal it was also shown that some temperature regions are not optimal for diagnostic measurements and also that a strong temperature dependency of tan(δ), what theoretically means increased conductivity, indicates strongly aged cables. Considering partial discharges, the principal conclusions can be similar. Moreover, even on ca. 13 m long cable samples no correlation between tan(δ), and PD-activity was recognized. [4][5][6].

Finally, as an indicator of the general cable condition, tan(δ) has been used for the development of a method for remaining lifetime estimation.

**NOVEL METHOD FOR DETERMINATION OF THE MOST PROBABLE REMAINING LIFETIME**

For a condition based asset management, the knowledge of the actual condition and the remaining lifetime of the asset is essential. The actual condition of the analyzed cable can be assumed using available diagnostic methods. However, due to the remarkable knowledge leakage in the interpretation of the measured parameters, the condition assumptions can be very unreliable. For this reason, there are still no methods available for the determination of the most probable remaining lifetime of cables or other systems.

As the stress is essential for the lifetime of the cable, the new approach has to regard the actual cable condition as well as the expected future stress factors. Therefore a method had to be found that provides reliable information about the actual condition of a probe and enables the prognosis of the remaining lifetime according to different stress scenarios.

As the general basis for the new method, the development of the dissipation factor during the ageing process has been used. Thereby, temperature and voltage levels had to be taken into consideration.

In the following determination of all necessary parameters (which is essentially a recursive process) needed for the definition of the ageing factors and the ageing models, the principal development of the dissipation factor during the accelerated ageing process will be shown.

**Summarized Aging Time (SAT)**

In figure 5, the development of the dissipation factor during an ageing interval, at the main ageing temperature and for different voltage levels of an exemplary cable sample is shown. Every measurement value can be correlated with a specific time to failure for the analyzed cable sample. Faults in other simultaneously aged samples lead to unavoidable interruptions in the ageing process of the rest of the samples. Therefore, the artificial aging (like the ageing in the field) cannot be considered to be a constant and continuous process. In order to eliminate the ageing interruptions and even to weight the changes of the ageing conditions and the resulting factors, a mathematic method has been developed that allows an transition of the real ageing time in an effective ageing time at normalized conditions, the so-called summarized aging time (SAT), [6]. In this way, it is possible to analyze the tan(δ) development under constant ageing conditions and without interruptions, what represents the bases for the further development of ageing models.

**Aging Models**

In the ageing experiment, three different types of stress have been applied on comparable cables which means on cable samples with identical operation history in the field (identical generation). In other words, for the evaluation of their effect on the aging rapidity and for the determination of the parameters of the particular aging models, the cable samples have been separated into three ageing groups according to the three types of stress. That means that they have been exposed to electrical, thermal or combined electrical and thermal stress. In this way it was possible to determine the parameters of the different ageing models and finally to analyze and formulate the influence of the thermo-electrical stress on the dissipation factor and the remaining life time. Inverse power law and Arrhenius-model have been used for the description of electrical and thermal aging respectively. For the combined thermal and electrical stress several super-positioning models have been considered, [6]. Both the ageing models and the most suitable super-positioning model contain parameters, whose values are firstly unknown. The data of the aging experiment provide the basis for the determination of these parameters. Additionally, a functional dependency of the tan(δ) development under test conditions has been defined, figure 6.
Figure 6. Exemplary development of the normalized tan(δ) within the ageing process and best-fit curve of aging model (sample was partially pre-aged in the field)

The developed ageing model is based on a further developed approach, which considers the statistical behavior of the relevant measurement values of the majority of the test field. Now it is possible for any selected or measured tan(δ) value to predict its further development under defined stress conditions.

In the next phase, the results have to be transferred to field measurements and field conditions. For this purpose it was necessary to define the ageing factor, a parameter that describes the rate of ageing acceleration between experimental and field conditions. [6].

Ageing Factor

The accelerated ageing leads to a strongly reduced lifetime in comparison to field conditions. By the usage of ageing factors, the summarized ageing time can be converted into field conditions. The complex methods for the determination of the (nonlinear) aging factors have also been developed and are shown for a simplified and linearized approach in figure 7.

Figure 7. Simplified visualization of the determination of an ageing factor

Cables from different ageing groups i.e. life consumption levels (C1, C2 and C3) will have different values of a diagnostic parameters (DiPa) for t=0, where cables with a longer operation history show higher DiPa values. After the time Δt₂ the cable C2 will reach a value that cable C3 reached after some time Δt₁. Thus, if Δt=Δt₂-Δt₁, the ageing factor AF could be calculated as:

\[ AF = \frac{L_2 - L_3}{\Delta t} \]

where \( L_3 \) and \( L_2 \) stands for the time in field operation for exemplars 3 and 2 respectively.

METHOD FOR CORRELATION OF EXPERIMENTAL DATA WITH IN-FIELD MEASURED DATA

Once the parameters of the ageing models and the ageing factor have been determined, it is possible to make lifetime predictions in the ageing experiment and to transfer them to field measurements. To explain the process of this crossover, figure 8 will be used.

The development of the dissipation factor during the cable life can be divided into three characteristic sections. In the first section, the dissipation factor increases before it falls slightly. The changes of tan(δ) that can be stated in the second section, are very small. Dissipation factor nearly keeps its value from the end of section one. In contrast, a strong incline of dissipation factor can be seen in the third section, where the development of tan(δ) can be described by a best-fit curve (see figure 6).

The black line in figure 8 describes the development of the dissipation factor of the cable in the ageing experiment. The red line symbolizes the value of dissipation factor at the end of the life time, the so-called critical dissipation factor \( \tan(\delta)_{cr} \). \( \tan(\delta)_{cr} \) has been determined by means of Weibull distribution (for appropriate temperature region).

Figure 8. Interpretation of the \( \tan(\delta) \)-measurements in field and lifetime prediction

Using the best-fit curve, the time to failure can be determined for any measured dissipation factor in region III. As the value of dissipation factor does not change its value significantly in region II, the worst case scenario has to be regarded, which is based on the assumption that the measured value lies at the beginning of region III respectively the final stage of region II. Now it is possible to apply the fitting curve from the ageing experiment and calculate the time when the critical dissipation factor under test conditions would be reached. The expected development of tan(δ) is shown by the blue line in
Thus the time to the next most probable failure, can be calculated by means of a previously defined functional dependency as:

$$t_{cr} = \frac{1}{b} \left( \frac{1}{\tan \delta_{cr} - a} \right) - \frac{1}{b} \left( \frac{1}{\tan \delta_m - a} \right),$$

where $\tan(\delta_{cr})$ represents the measured dissipation factor, and $a, b$ and $c$ are previously determined parameters of the fitting function, [6].

This time can then be scaled by ageing factor $AF$ to calculate respective time to failure under average ageing conditions $t_{av}$:

$$t_{af} = AF \cdot t_{cr}$$

and corrected in similar way for some other predicted load occasions:

$$t_{corr} = AF_{load} \cdot (AF \cdot t_{cr})$$

where $AF_{load}$ is the previously determined ageing factor for particular predicted load occasions.

The calculated time to failure is now the time, within at least a further diagnostic measurement should be repeated. The procedure has to be repeated until some predefined $\tan(\delta)$ value is reached, or the time intervals between two measurements are so reduced that further diagnostic measurements would not be reasonable. This is the final phase of the cable life i.e. a replacement should be scheduled.

CONCLUSION

For the implementation of condition based asset management and maintenance planning in distribution power networks, information about power equipment condition and prognosis of its remaining lifetime is of highest importance. Most diagnostic systems and tools available on the market can assume partial aspects of the equipment condition, which validity is often based on the experience of the operator and without consideration of the influence of the test parameter as e.g. temperature and voltage levels.

In order to develop methods for a remaining lifetime estimation, a long-lasting aging experiment on MV PILC cables has been performed and a sophisticated data bank has been built up. Based on numerous data, describing the behavior of the electrical and diagnostic parameters of the particular cable at different test conditions and different stages of component life, numerous statistical and mathematical analyses have been performed. The complexity of the diagnostic parameter dependencies is briefly shown on the example of the dissipation factor for differently pre aged cable samples and is considered in all further data analyses.

For the determination of the remaining lifetime, a novel approach has been developed which is presented in this article. It includes the determination of the ageing factor of the artificial ageing system, the evaluation of the critical values of the diagnostic parameters and the parameters of the aging models, the determination of the fitting curve describing the development of the diagnostic parameters during the ageing process and finally the development of methods to apply the results in field measurements. Based on the determined ageing models assumptions of the effect of increased load conditions on the cables’ remaining lifetime can be determined. These are fundamental data for the network planning and the network development and further improvements of the maintenance and asset management strategies.

Finally, this approach for the determination of the cable condition and its remaining lifetime is also applicable on other components of electrical power systems. In order to verify the developed approach and models, a follow-up project has been was initiated. For that purpose, a novel mobile diagnostic system was developed and integrated into a testing van for intensive field measurements and a correlation of field and laboratory data.

Acknowledgments

The authors would like to thank the following cooperating companies for the financial and organizational support of the entire project: N-ERGIE AG (Germany), N-ERGIE Netz GmbH (Germany), N-ERGIE Service GmbH (Germany), Bayerische Kabelwerke AG (Germany).

REFERENCES