Performance, Reliability & Remaining Lifetime Estimation of the MV PILC Cables

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Abstract— *Performance and characteristic features of any insulating material is evaluated by subjecting it, mostly in the form of specimens, to accelerated ageing. The object of interest in the here presented long-lasting ageing study is a multilayered insulation system of medium voltage paper insulated lead covered (MV PILC) cable. Under the influence of an electrical and/or thermal load, direct or alternating field, it behaves so multisided making reasonable only investigation on the real cable portions. In the experiment, sets of cable samples (MV PILC cables, 20 kV, Al core, each 13,5m long) with different service histories (20-40-60 years) as well as brand new and unused cables have been examined. Principles of the ageing process, physical and chemical changes of the insulation system under spectrum of stresses and their combinations have been studied. Based on an widespread databank, formed primary by a regular ageing and diagnostic monitoring under very different but definable test conditions, the process of ageing along with its expressiveness and distinctiveness through the variety of diagnostic parameters have been researched. Finally, ageing models and their parameters have been evaluated, and the probability of the failure based on diagnostic measurements has been classified. Moreover, formed knowledge databank is a fundamental source for further researches. Additionally, the developed ageing system can be applied in the future for parametric studies, investigations on physical dependencies and the artificial ageing of different newly developed or already known insulation materials and power components. It helps to improve the diagnosis and interpretation of field measurement data and enables the development of new diagnostic approaches, like e.g. a constant monitoring of the cable characteristics, leading finally to the principles of smarter networks.*

I. Introduction

During the field operation power equipment is exposed to numerous impacts that influence the ageing rapidity: load flow, voltage imbalance, short and long duration variations, transients, waveform distortion, voltage fluctuations, power frequency variations, etc. The major parts of the MV networks are cable systems, which are in the same time one of the main sources of the failures, networks interruptions and outages. On the other hand, cable systems represent a major capital investment and their condition is of significant importance for an effective maintenance planning and efficient asset management, [**1**][**2**]. For the evaluation of the condition of cables and network components, different electrical parameters could be measured by variety of diagnostic systems. Unfortunately, the reliability of many methods, diagnostic systems and the resulting status and remaining lifetime prognoses is mostly dependent on the experience of the conducting technicians and engineers and available knowledge databank. Especially in the case of PILC cables, there is a big knowledge leakage; even this cable type is the oldest in the today's MV power networks (almost 95% of the MV power cable networks of "NUON Infra Noord-Holland" are made up of PILC cables, [**3**], 65% in the network of one of the biggest energy supplier in Belgium, 56% in the urban area in Bayern (Germany), and ca. 50% in complete MV cable network of Germany, [**4**].

In order to form a comprehensive data bank, it is needed to measure different ageing parameters and cable's dielectric properties during the complete cable life and that all on numerous cables. Further, measured data should be classified with consideration of the dependencies on electrical and environmental parameters, and finally they should be correlated to ageing condition and to most probable but load-defined remaining lifetime.

Due to the very long lifetime of PILC cables, the data collection could be an extremely time demanding and cost intensive process. Therefore, an accelerated ageing experiment on the MV PILC cables, lasting over two years, with continuous measurements of the different electrical parameters and under different and controlled electrical and environmental conditions was performed.

In this paper the systematical approach to the artificial and accelerated ageing experiment, selected data correlations and interpretations, ageing characteristics and the significance of some of the diagnostic parameters are presented.

II. Demands and Opportunities of an Artificial and Accelerated Ageing Experiment

The ageing process of PILC cables proceeds due to the in front of all moisture presence within the paper i.e. cellulose and the temperature impacts. Under the influence of each of these two ageing factors water molecules are released, provoking a chain reaction which is amplified by higher temperatures (but lower than 200°C), [**5**]. Besides, strong influences on chemical processes within the PILC cable insulation, thermal cycling results in a partial thermal expansion and due to the incompatibility of the thermal factors of the materials, to a physical and irreversible expansion of the lead sheath. It enables moisture migration, leads to the melting and migration of the mass and enables a formation of voids. Electrical stress leads then to local overstresses creating optimal circumstances for the occurrence of partial discharges, a sequential puncture of paper layers and building of conductive carbonized channels - finally leading to a complete breakdown of the insulation system, [**6**].

In order to accelerate these processes, simultaneous thermal and electrical overstresses are necessary. For a monitoring of the ageing progression appropriate measurement, data acquisition and data storage systems are needed. Therefore, a fully automated and integrated cable accelerated ageing system (ICAAS) have been developed, realized and verified. It realizes: accelerated and artificial but realistic ageing (on 50Hz) with freely definable ageing parameters and load profiles, observation of the ageing condition and proper system operation, extraordinarily accurate measuring i.e. monitoring (e.g. tan(δ) measurement on 50 Hz with remarkable accuracy of more than $1\cdot10^{-5}$) of the diagnostic parameters on each cable sample on pre-definable voltage and temperature levels and in regular time intervals, forming of an unique knowledge databank and many additional features for data selecting, graphical presenting, analyzing and correlating etc.

The developed system is capable to provide more than 600A at a maximum ageing voltage level of up to 50kV. A partial view over some of the ageing and protection components (resonant coil, overvoltage protection, voltage divider, rectifiers, transformer for additional thermal stress) of the ICAAS system and the cable samples are shown Figure 1. Most of hardware and software components were especially developed, designed, constructed and approved in university workshops and laboratories, [**7**]-[**11**].

Figure 1. Partial view over some of the ageing components of the ICAAS system and the cable samples

The sets of cable samples in the ICAAS are divided into three groups dependant on the applied stress: only thermally, only electrically and simultaneous thermo-electrical ageing. In this way the knowledge of the impact of the different physical stresses on the insulation deterioration and lifetime consumption should be improved. Moreover, beside unused cable samples (brand new and for 10 years stored – delivered directly from cable manufacturer) there are also samples that were in field operation for 20, 40, 45 and up to 60 years (delivered and installed by a power-distribution utility). The ageing parameters have been carefully selected in a nine months lasting pre-test (of up to over 100°C and voltages up to three times the nominal voltage), which was in the same time used to prove the functionality of the complete ageing system, [**12**].

Beside regular daily measurements of dissipation factor (tan(δ)) and partial discharges (PD), regular parametric studies have also been carried out. They concern the behavior of the electrical properties i.e. diagnostic parameters in the range of predefined and steady cable temperatures (app. 10-85°C) and voltages (0,4-2,2 times nominal voltage),[**13**]-[**15**]. Moreover, during the ageing experiment numerous DC measurements like return voltage or polarization/depolarization current measurements (RVM and PDC, respectively) were carried out, [**6**][**16**]. Thus, the behavior of the material's electrical properties under homogeneous DC field and capability of the DC diagnostic systems have been studied. The influence of the environmental parameters – especially temperature and humidity, and test parameters – e.g. polarization voltage and/or time, grounding point, etc. on the reliability of the measurement and consequently consistency of its statement have been analyzed. All executed measurements have been used for the purpose of the determination of detoriation or consumption levels of the insulation material, its electrical parameters in different age-stages (capacitances and resistances symbolizing polarization effects and conductivity), defining of the life/ageing models, and correlating of the diagnostic parameters under specific test conditions to most probable remaining lifetime. Some selected inserts and outcomes of the numerous experiments have been presented in this paper.

III. DIAGNOSTIC PARAMETERS OF THE PILC CABLES AND INFLUENCING FACTORS

An electrical field applied to a dielectric causes a moving and arranging of polarized molecules, ions and, in principle, of all charge carriers within the insulation material. Several electrical and environmental parameters, like frequency and strength of the applied electrical field and the temperature of the dielectric, have significant influence on charge mobility and hence the relative permittivity and conductivity.

Applying of an alternating field on a dielectric will result in dissipation losses, which can be described as a sum of the dissipation losses due to the polarization processes, conductivity and partial discharge activity. The principal temperature characteristics, by constant strength and frequency of the field) of basic dielectric parameters (conductivity ν and relative permittivity $\underline{\varepsilon}_r = \varepsilon_r' + j\varepsilon_r''$) and dissipation losses are shown in Figure 2.

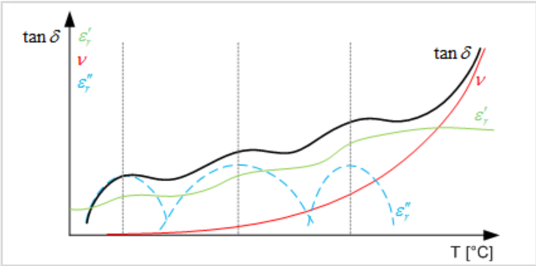

Figure 2. Principal temperature influence on the basic dielectric parameters and dissipation losses.

Primarily, with increasing temperature the AC conductivity rises exponentially, according to Arrhenius low, and also the relative permittivity through amplified charge mobility. The activity of PD, if any, will change according to ideal gas and Paschen's law. Also, conductive carbonized channels within insulation, if present, will develop faster leading to the complete breakdown of the insulation. As to be seen in Figure 2 there are “resonant temperatures” that vary for different resonant mechanism and/or molecules’ structure.

Moreover, PDC and RVM are also strongly influenced by temperature variations. For example, the starting value of the polarization current increases due to the increased of the relative permittivity and ending value due to the increased conductivity.

Analyzing the influence of the test voltage, it can be assumed that with increasing voltage the value of the diagnostic parameters (tan(δ), PD, RVM PDC) generally rise due to an increasing number of ions - an enhancement of polarization losses and a rise of the conductivity (energy of the charge carriers). The function of the polarization current will change in a way that the starting value is slightly enlarged in comparison to ending value which rises proportionally to the conductivity increase.

The presence of moisture within the insulation increases the conductivity and polarization processes (polar molecules of water with much higher relative permittivity) and has an exceptional effect on insulation performance, diagnostic parameters and their dependencies (on temperature, voltage and/or frequency). The amount of moisture by brand new PILC cables is directly dependent on manufacturing process (e.g. time and pressure in the phase of paper drying).

IV. Parametric Studies and Distinctiveness of the Diagnostic Parameters

Individuality and complexity of the e.g. temperature and voltage dependencies of diagnostic parameters have been confirmed by more than 200.000 single measurements which have been carried out on the artificially aged cable samples [**13**]-[**15**].

Summarized, the behavior i.e. profiles are so individual that they differ for even each core of the same three-core cable – initiated already during the manufacturing process. Besides, 10 years of storage does not influence the insulation properties as well as ageing rapidity significantly. Unused cables have also shown an improvement of the cables electrical properties in the first phase of ageing process that is distinctive for a bathtub curve.

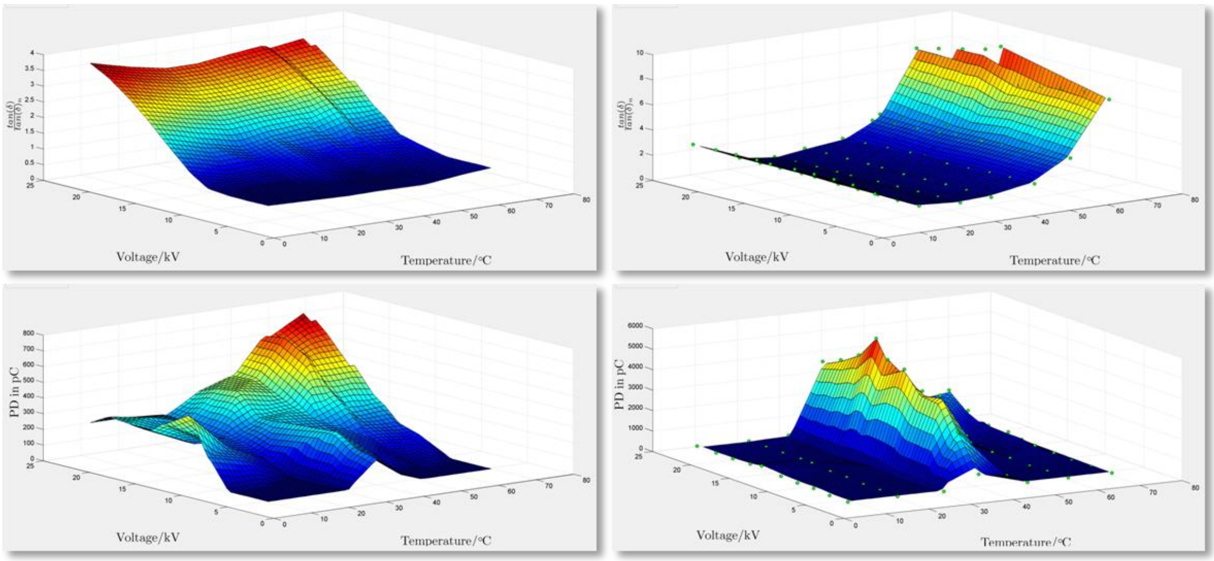

Figure 3. tan(δ) and PD profile-characteristic of medium aged (left) and unused (right) cable sample (tan(δ)$_n$ stands for brand new cable under nominal temperature and voltage occasions)

Typical Temperature-Voltage (TU) profiles of tan(δ) and PDs of a brand new and medium aged cable sample are shown in Figure 3. It can be noticed, that used cables show in front of all a voltage dependency, but mostly not initiated by PD activity. In the case of brand new cable samples, the temperature dependency is more dominant, and although the PD activity increases with temperature the resulting losses are not sufficient to be visible in the tan(δ)-characteristics, assuming due to the increase of PD magnitude with the temperature and not the repetition rate. Moreover, the temperature region of 20 to 40°C seems to be predestinated for resonant occurrences. Even more, it was shown in [**15**] that tan(δ) value is the less sensible on cable condition exactly in this temperature region. Therefore, it is not recommendable to carry out any diagnostic dissipation factor measurements when the cable temperature is within this interval.

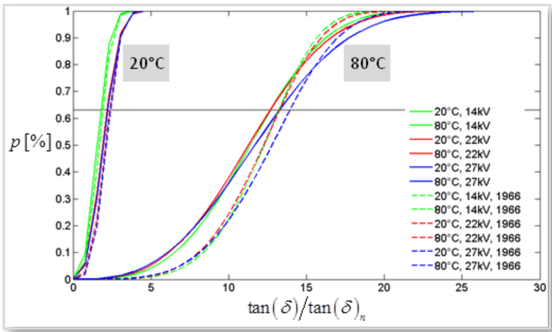

Figure 4. Weibull plot for variable tests conditions and for all failed cables or one cable generation (1966)

The Weibull plots in figure 4 show the distributions of cable failures over the normalized dissipation factor for variable test conditions. It can be noticed that test voltage does not influence the Weibull curves significantly. Also, there is no strong curve deviation comparing Weibull plot of one cable generation to all failed cables. The dominating influence factor is the temperature, showing more suitable test (diagnostic) conditions in higher temperature regions due to a better value allocation. Experimental results have also shown that lower temperatures are suitable for diagnostic measurements, too. Anyway, regarding to Figure 4 and Figure 5, the critical $\tan(\delta)/\tan(\delta)_n$-interval measured at 20°C is 1,8-2,4, and at 80°C is 13-14.

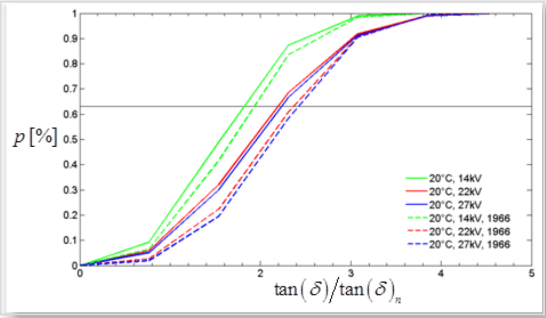

Figure 5. Weibull plot for 20°*C*, variable test-voltage and for all failed cables or one cable generation (1966)

In addition to the dissipation factor measurements, also diagnostic DC measurements (RVM and PDC) which are as well a good identifier of general insulation condition, have demonstrated significant dependencies. The influences of numerous factors on these measurements have been investigated with the goal to find optimal (or even unsuitable) test conditions. Additionally secondary condition indicators, like e.g. the p-factor (figure 6) have been determined and verified. Analyzing the return voltage curves, the main time constants of the paper and the mass can be specified, showing the moisture allocation between paper and mass on variable temperatures. Moreover this information can be helpful to analyze the functional dependencies of $\tan(\delta)$ and other insulation properties. The entire data ($\tan(\delta)$, RVM and PDC) deliver the basic information to define the parameters of the theoretical equivalent circuits of the PILC cable insulation system together with its nonlinear characteristics.

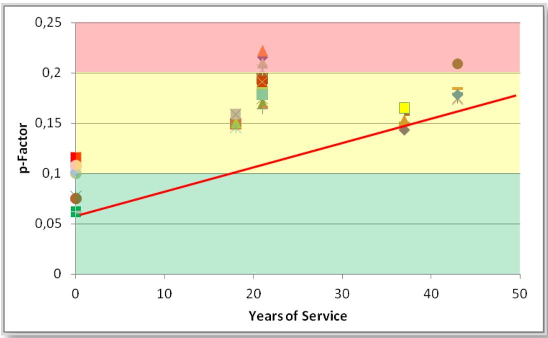

Figure 6. p-factor over years of service (green, yelow and red region simbolyse good, reliable, and critical condition respectively)

Moreover, based on RVM measurements, the activation energy for each cable sample can be determined particularly. Dependent on the insulation condition it varies as exemplary presented in Figure 7.

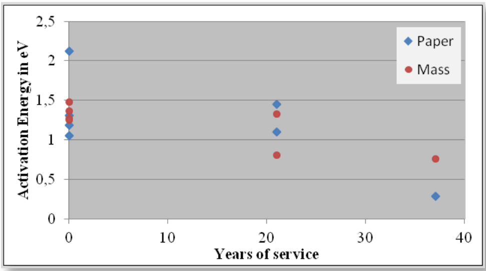

Figure 7. Activation energy for new, meadium aged and aged cable samples

Following the development of electrical and mechanical parameters of the mentioned three groups of cables (aged only electrically, thermally or combined), it can be concluded, that PILC cables predominantly age under the influence of temperature (it could result in thermal breakdown), except there is the PD activity which leads to the electrical breakdown. Therefore, the most relevant ageing model is Arrhenius, where is the value of activation energy determined from RVM of significant importance. These models could deliver very relevant information considering new trends in the power networks (change of the load profiles through the renewable power sources and developing of smart grids).

Additionally, some chemical analyses (like spectrum analyses or Fourier transform infrared spectroscopy) have been carried out on insulating mass (and mass/oil from terminators) in different consumption stages. Moreover, paper samples of different paper layers (closer to conductor or lead sheath) and of each failed cable sample have been taken and will be object of upcoming chemical and mechanical analyses.

V. CONCLUSION

In a long-lasting ageing experiment, the ageing characteristics and diagnostic possibilities of the insulation system of MV PILC cables have been investigated. The study could be divided in several phases: developing, realization and verification of the entire ageing system (ICAAS) and its hardware and software components; selection of the cable samples and installation in ICAAS; selection of the ageing parameters; ageing experiment with regular measurements of the diagnostic parameters; regular parametric studies on $\tan(\delta)$, PD, RVM, PDC in different stages of the ageing process; correlation between electrical, environmental and condition parameters; chemical analyses of the mass and paper samples; developing of the ageing/life models; reliability analyses, etc.

In the presented paper several research results are pointed out. Direct and derived parameters of the dissipation factor measurements deliver relevant information about the general insulation condition.

However, temperature and voltage conditions must be considered. The temperature region for 20°C to 40°C is indicated as mainly inappropriate for measurements of cable's electrical properties and therefore diagnostic studies. The insulations behavior under DC test conditions brings additional complex condition information which can be used to determine the nonlinear parameters of the equivalent circuit of the PILC insulation system. PD diagnostics deliver a unique information with a mostly local character and should be executed and interpreted independently to other diagnostic measurements since considerable correlations between PD activity and tan(δ)-TU profiles were not present.

Additionally, it was shown, that the thermal stress is the dominant ageing factor, except in presence of significant PD locations. The deterioration of the insulation performance is confirmed exemplarily through the activation energy, which was determined from series of RVM. Besides, the activation energy is one of the key parameters defining the thermal life/ageing models of PILC cable.

Finally, one of the major future research objectives is and will be the further interpretation and development of theoretical models describing the correlations between the data from the determined sophisticated knowledge databank. Moreover, the developed models and correlations will be verified through already started diagnostic field studies.

ACKNOWLEDGMENTS

The author would like to thank Prof. Gerhard Herold and Dr. Christian Weindl for their guidance and significant contribution in the project. Also, the author is thankful to the following cooperating companies for the financial and organizational support: N-ERGIE AG (Germany), N-ERGIE Netz GmbH (Germany), N-ERGIE Service GmbH (Germany), Bayerische Kabelwerke AG (Germany).

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