EXPERIENCES OF IN FIELD MEASURED DISSIPATION FACTOR ON MV PILC CABLES AT 50 HZ

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ABSTRACT

In the past several years, a significant amount of diagnostic data has been collected under known and adjustable test conditions, with the purpose of improving the diagnostic possibilities for medium voltage (MV) paper insulated lead covered (PILC) cables. Beside the complexity of the interpretation processes by itself, an additional challenge of onsite measurements is the investigation of mixed cable lines, as the analysis of the results is proven to be difficult. Moreover, when interpreting the measured values, i.e. diagnostic parameters, the problem often arises that different applied diagnostic criteria (e.g. in case of dissipation losses comparison of: absolute value, hysteresis, dependency on testing voltage) result in different statements. In this paper, empirically determined dependencies of the diagnostic parameter (in front of all the dissipation factor on test conditions) as well as the results of the in-field measured values and suggestion for their interpretation are presented.

INTRODUCTION

The components and equipment used in electrical energy systems have, compared to those used in other technologies like information technology or automotive technology, an extraordinary long lifetime. The amortization period for system's components like transformers is usually planned being several tens of years. This results in a quite heterogeneous age distribution of the electrical equipment, illustrating the historical and technical developments which lead to today's power grids [1].
Regarding the MV grids, PILC cables are to be found in wide parts of the urban power distribution systems, with already remarkable operation history often of over 50 years, even though they were replaced since the 90`s by XLPE (cross-linked polyethylene) cable types. Therefore, this type of cable and the corresponding sleeves and terminations are expected to be increasingly a source of failures and outages.
As the deregulation of Europe's electricity market is accompanied by changes in the electrical grids, economical aspects begin to dominate the asset management and maintenance planning. Furthermore, load profiles are changing and loads are increasing with high fluctuations, as a result of the increasing number of renewable energy sources, especially in medium and low voltage level. This results in an accelerated ageing of the electrical equipment and remarkable reducing of the remaining service lifetime. Therefore, alternative maintenance strategies have to be considered in contrast to the today mainly used failure based maintenance. By the means of a condition based maintenance strategy, equipment which diagnostic criteria reach critical values could be replaced or maintained in advance, i.e. before an upcoming incidence. Of the highest importance are here the information about the equipment's condition and its accuracy.
Obtaining such information is only feasible if intelligent diagnostic systems are developed and deployed, which use a fundamental knowledge database, consisting of critical limits of the diagnostic criteria, dependencies of the involved parameters, their characteristics and their correlation. Besides these empiric results, data from field measurements can contribute to applicability and transferability of the results.
As evaluation criteria, the partial discharge (PD) characteristics and intensities, as well as other dielectric values are often considered. As the latter, the dissipation factor tan(δ) and its behavior is often analyzed, even though its complex dependencies on environmental and test conditions like e.g. the temperature of the examinee or the test voltage could not be assumed as well known.

BASIC INFORMATION

Dissipation Factor

The dielectric in an insulation system can often be represented by a capacitor C_{Iso} and a conductance value G_{Iso}, connected in parallel (Figure 1, left), resulting in a complex admittance given by:

$$\underline{Y}_{Iso} = G_{Iso} + \mathrm{j}\omega C_{Iso} \ . \qquad (1.1)$$

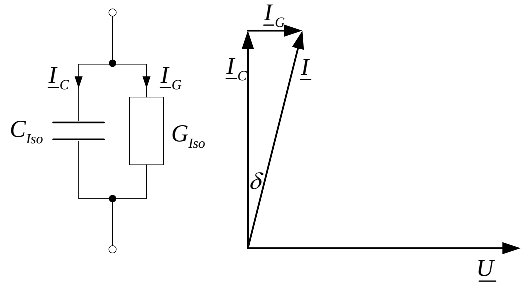

Figure 1: Equivalent circuit for a lossy dielectric and corresponding complex phasors

The capacitance value is given by the capacitance defined by the geometry of the electrodes and the dielectric permittivity. The ohmic portion describes the losses in the dielectric. The dissipation factor tan(δ) is obtained by calculating the tangent of this angle minus 90°, which is also called loss angle δ:

$$\tan\left(\delta\right) = \frac{I_G}{I_C} = \frac{G_{Iso}}{\omega C_{Iso}}. \quad (1.2)$$

The losses in the dielectric and thereby also the dissipation factor are composed of different portions:

- Polarisation losses: $\tan(\delta_{pol})$
- Conductivity losses: $\tan(\delta_{con})$
- Ionisation losses: $\tan(\delta_{PD})$

These accumulate to the total dissipation factor which could be measured and evaluated at a given frequency. Polarisation and conductivity losses are determined by the movement of polarised molecules, ions or electrons. The mobility of these particles is dependent on temperature and the strength of the applied electrical field, i.e. testing voltage. Additionally, if there is a significant PD activity this could also manifest in the dissipation factor as the part of the ionisation losses is increased.

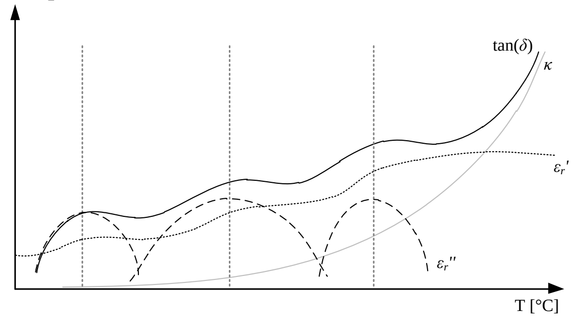

Figure 2: Dependency of the dissipation factor tan(δ), conductivity κ, real part ε_r' and imaginary part ε_r'' of the complex permittivity on temperature

The dependency of the dielectric parameters on temperature is shown in Figure 2. Conductivity κ increases because of the increased mobility of the (polarized) molecules as more charge carriers own the required activation energy E_a to overcome the potential barrier [2].

The fraction of the loss factor caused by conductivity $\tan(\delta_{con})$ therefore rises constantly with temperature:

$$\tan\left(\delta_{con}\right) = A \cdot e^{\frac{-E_a}{kT}} \quad (1.3)$$

with the constant coefficient A, the Boltzmann constant k and the absolute temperature T [3]. The imaginary part of the dielectric constant ε_r'', which is a measure for the losses in the dielectric, shows local maximums at resonant temperatures. The reason for this behavior might be e.g. humidity in the insulation material. The real part, ε_r' that complies with the known dielectric constant, is increasing stepwise at concrete temperatures because of the increasing dipole mobility. Towards higher temperatures it begins to fall again because the thermal molecular movements act against the electrical field.

Composition of cable lines

In today's MV grids, in most cases mixed cable lines are present, which are at least composed of cables with different age, mostly even of different cable types. If maintenance tasks have to be done on PILC cables, XLPE cable types are usually used with the corresponding transition joints as replacement. Thereby, additional issues could arise, like the drying-up of insulated PILC parts, which are not refilled by the terminations.

Investigating a line which is composed of several sections with different properties, an equivalent circuit shown in Figure 3 in accordance to Figure 1 has to be considered:

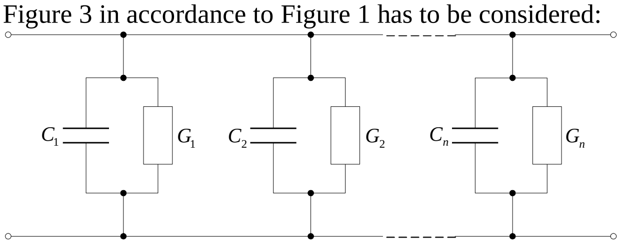

Figure 3: Equivalent circuit for the insulation of a mixed cable line for low frequencies

The complex admittance of the whole line is given by:

$$\underline{Y}_{ges} = G_1 + G_2 + \ldots + G_n + \mathrm{j}\omega\left(C_1 + C_2 + \ldots + C_n\right) \quad (1.4)$$

and for the dissipation factor under consideration of the linking of the parallel circuits:

$$\tan\left(\delta_{sum}\right) = \frac{G_1 + G_2 + \ldots G_n}{\omega\left(C_1 + C_2 + \ldots + C_n\right)}. \quad (1.5)$$

This equation shows that it is not possible to calculate the dissipation factor of a single part of the line with the help of the dissipation factor of the complete line. This is especially a problem when XLPE cable types are present. These have a low dissipation factor of less than $1 \cdot 10^{-3}$ and could therefore influence the measurement result up to it is meaningless [4][5]. If the dissipation factor of the line's fractions that are to be eliminated is considered as known, the dissipation factor of the remaining parts, e.g. the PILC cables can be calculated.

AGING EXPERIMENT

In the context of the research project "Determination of the remaining life time of PILC cables by the means of a PD and dissipation factor diagnosis", a system for accelerated and artificial aging of MV cable samples has been developed and realized [6]. During this several years lasting project, a large number of ca. 15 m long PILC cable samples with different operational history (brand new cables to cables, which were in operation for 40 years) have been examined. Therefore, a significant result is assured by a great spreading of the investigated age classes. The examinees run through a complete, accelerated life cycle until they fail during the test with daily diagnostic measurements. That means the actual condition of every cable sample is determined by a PD and dissipation factor measurement and recorded at several

voltage levels and at mains frequency. In addition, temperature scans are performed regularly, during which the cables' temperature is raised, beginning from ambient temperature up to ageing temperature, with continuous measurement of the diagnostic parameters. These temperature-voltage scans, together with the regular measurements, deliver a huge amount of PD and dissipation factor values that draw an exact image of all cable samples' lifetime until their failure.
In Figure 4 dissipation factor characteristics of a strongly- and medium pre-aged cable sample are shown exemplarily.

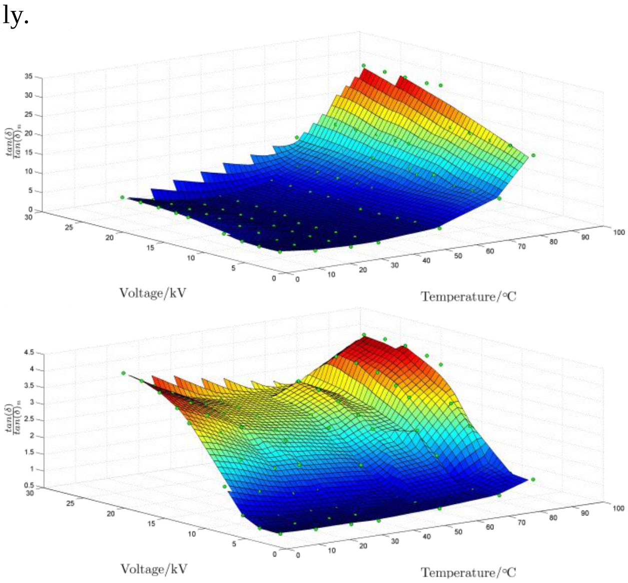

Figure 4: tan(δ) fingerprints of a sample that has been in operation for over 40 years (top) and of a sample that has been in operation for over 20 years (bottom)

The upper part of Figure 4 visualizes the dissipation factor data of a cable which has been in operation for 40 years. The dissipation factor tan(δ), relative to the dissipation factor of new cable tan(δ)$_n$ at room temperature, shows a strong dependence on temperature and a slight dependence on the test voltage. The lower part of Figure 4 shows the data for a sample which has been in operation for over 20 years in the same manner. The absolute values of the dissipation factor are obviously smaller with dominant voltage dependency. Despite of this fact, the samples of the older age class failed first.

FIELD MEASUREMENTS

Conception

The measurement equipment, methods and principles developed for the mentioned ageing experiment have been further improved, adjusted and partly re-designed for the purpose of the field diagnostic measurements, and comply therefore with those, used for monitoring and diagnostics during the aging experiment in laboratory. The generation of the test voltage is accomplished by a resonant system at mains frequency, so that previously selected lines in the medium voltage level (20 kV) can be tested with a multiple of the nominal voltage. The measurement unit is working on test voltage level and is placed on a mainly capacitive coupling device, which is simultaneously used as a voltage divider. From the so determined voltage and current values, a sophisticated algorithm calculates the dissipation factor with highest precision of better than $1 \cdot 10^{-5}$. The communication with the control computer, which also stores the at different test voltages measured values in a database, is accomplished via a fibre optics connection [8].

Results

In a first test series a total of 10 cable lines have been investigated. The range of measured objects reaches from lines, which consist solely of PILC cables up to those, were the original cable type was replaced by XLPE cable types more than 50%. Beside the mixed structure regarding cable type, also a very broad range of different cable generations was present. The main focus was put on PILC cable lines, since it was expected that they represent the weakest part in the cable lines.

Line ID	10030	10034	20039
Number of sections	5	16	3
Percentage PILC	100%	48%	95%
Oldest section	1960	1959	1960
Youngest section	1991	2011	1996
Average age PILC	1966	1967	1965
Length of line	834 m	1396 m	450 m

Table 1: Line information for the presented data

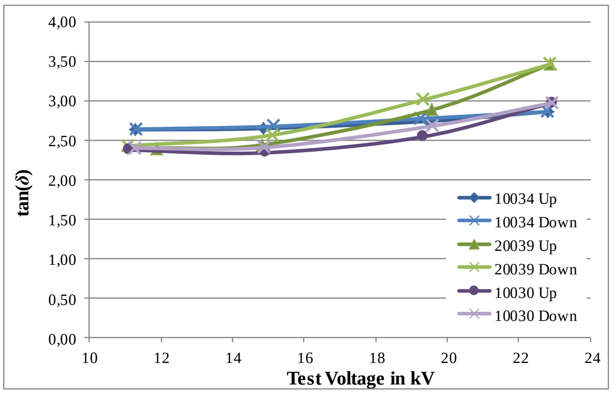

Figure 5: Raw dissipation factor values of selected lines

Table 1 shows the information of the measured cable lines, which uncorrected, raw dissipation factors are presented in Figure 5. When comparing these values to the under consideration of the lines' structure corrected values (Figure 6), clear differences are to be noticed. As expected, line 10034 with the most significant PILC percentage is influenced the most. It also comes apparent, that the curves measured with rising voltage are not the same when decreasing test voltage. This behavior called hysteresis is more distinct at lines 10030 and 20039 than at line 10034 that shows higher absolute values than the remaining lines. These show in contrast a bigger dependency on the test voltage.

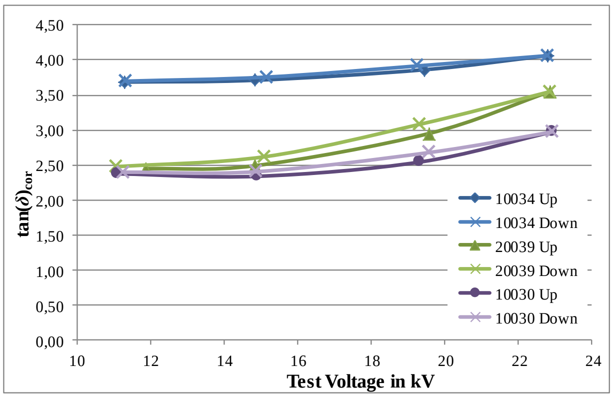

Figure 6: Corrected dissipation factor values of selected lines

Depending on the interpretation, different statements concerning the actual condition and the expected remaining lifetime could be made. Thus, an increased dependency on test voltage or also an increased hysteresis could indicate a bad cable condition. But this statement is in conflict to the result one could obtain observing the absolute value. Finally, only a comparison and the correlation with the data gained by the aging experiment enable a differentiated analysis and interpretation with respect to a plurality of parameters [7].
Based on this and including the characteristics of the PD magnitude and density, it is possible to improve the diagnostic reliability. That means, recommendations for the replacement of a critical cable portion could be made, or the time period for a repetitive measurement could be suggested. The data and results of the repeated measurements could additionally be used to gain insight in the aging development and characteristics. By storing them in a database system, the so achieved outcomes can not only be used for the measured lines itself, but also for other, afterwards measured lines. Also here, the extremely comprehensive, previously conducted, empirical parameter studies can be used to interpret the measurement and environmental parameters and find a suitable normalization to eliminate dependencies on these.

CONCLUSION

The data gained by the aging experiment provides an important contribution to the interpretation of the in-field measured values. These are not in every case directly and primarily suitable as a diagnostic parameter, since they are dependent on several testing and environmental conditions, e.g. cable temperature, test voltage and composition of the measured cable line. To give more accurate statements on the actual condition, additional parameters and their in the aging experiment determined dependencies are required. This is especially important if different diagnostic criteria (hysteresis, dependency on test voltage, absolute values) deliver a diverging image of the equipment's condition. Particular challenges are mixed cable lines because the diagnostic parameters depend on the composition of the line. Here, not only the used cable types, but also their length and their corresponding service age play an essential role. According to the diagnostic result, it is possible to control the period for a repeated measurement. In addition and with respect to the PD behavior, recommendations for the replacement of a short part or the whole line could be stated. In this way, dissipation factor and PD measurements at 50 Hz could make an important contribution to the establishment of condition based principles for maintenance strategies and to the improvement of distribution grids, resulting in a better service security und increased reliability.

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