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On-Line Cable Diagnostic Possibilities in an Artificial Aging Environment

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Abstract. Since more than a decade the development of reliable and accurate diagnostic tools for power cables is in the centre of interest of scientists and power utilities. With the developments in our power systems, like the increasing feed-in of renewable energy sources, several issues could be additionally generated, such as extreme concurrence factors, short- and long-duration variations, voltage imbalances, waveform distortions, voltage fluctuations and power frequency variations. These impacts affect the aging rapidity of the electrical equipment and finally of the entire the electrical distribution network. Using appropriate diagnostic methods, it is possible to determine the electrical equipment's condition. The significance of the results depends on the quality of the measurement system and of the data interpretation. Based on these results, a reliable maintenance and investment strategy could be made, and the reliability of the grid could be improved. With this goal, an accelerated aging project for MV PILC (paper insulated lead covered) cables was started. A specially designed aging system for the accelerated aging of MV cables has been developed to point out the most relevant aging parameters, their limits, their development and to upgrade the accuracy of the MV cable diagnostics in this way. In this paper, the diagnostic possibilities, mainly the dielectric loss factor measurement and its dependence on environmental influences are presented.

Key words

diagnostics, aging, cable, partial discharge, loss factor.

1. Introduction

Cables and their equipment represent one of the major investments for power supply companies. In addition, cables and sleeves are a frequent source of damages and accordingly a source of network faults and supply discontinuities. Since unexpected cable faults in MV cable networks appear more frequent, a lot of scientific research has been directed to determine the remaining cable life time (time to the first failure). In many cases only partial discharge measurement and analyses are used for the prediction of failures, their localization and selective replacement of defective cable sections. Thus far there are some diagnostic systems on the market developed for XLPE (cross-linked polyethylene) cables. In case of lead shielded cable types, these prediction systems do not deliver reliable prognostic data because the physical and chemical backgrounds are not comparable. In the future,

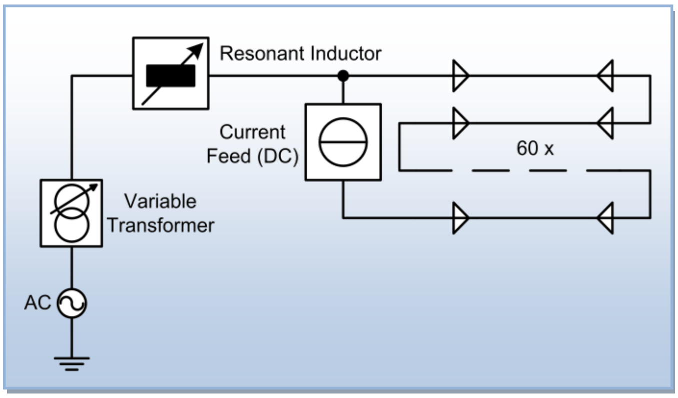

Fig. 1: Simplified structure of the ICAAS

the specific losses in the insulation system and therefore the loss-factor could be utilized as an indicator for the quality and status of the isolation material. Besides the PD-level-analyses, loss-factor measurements and other more specific and sophisticated criterion could build up a fundamental basis for the development of an accurate remaining lifetime diagnostics. Unlike to XLPE-cable analyses, where the PD-level is already a significant indicator for the cable status, PILC cables need an additional criterion. Because of their physical characteristics, the PD-

Fig. 2: The test site: cable samples, current transformer and rectifier, voltage source

ratio at discrete voltage levels or inception voltages on its own may not give a reliable impression of the actual aging status. Therefore, the accurate determination of the loss factor is of greatest interest and has to be achieved by the use of sophisticated acquisition systems and mathematical algorithms.
In 2006, a new and worldwide unique accelerated aging project for MV cables has been started. The final goal of this project is to define the suitable parameters that describe the aging process of PILC cables. Furthermore, the accuracy of the measurement system must assure the reliability of the formed database. Besides the resolution and precision of the acquisition system and the continuity of the aging and the subsequent monitoring process is of highest importance. In this paper, the diagnostic possibilities are presented, which mainly are partial discharge and loss factor measurements and their dependency on environmental influences like e.g. the operating voltage or the cable temperature.

2. Physical Backgrounds

Partial discharges (PD) are localized, dielectric breakdowns of small portions of solid or liquid electrical insulation systems under high or medium voltages. In high and medium voltage networks specific diagnostic measurements and/or a monitoring of the devices (such as power cables, power transformers, switchgears, motors, generators, etc.) can be used to acquire the equipment's status, health and rest-lifetime. Partial discharges occur as insulation starts to deteriorate and once prevalent, become a predominant source of insulation breakdowns. The uncontrolled PD activity could finally lead to a catastrophic failure, which can cause external equipment damage, fires and loss of revenue due to an unscheduled outage.

The dielectric loss angle is an index of the insulation quality. The tangent of this angle is defined by the quotient of active power *P* and reactive power *Q*:

$$\tan(\delta) = \frac{P}{Q} \tag{1}$$

It is called the dielectric loss factor. An ideal capacitor would consume only reactive power and thus would own a zero sized loss factor. An ideal resistor would consume only active power and would have an infinite loss factor. The equivalent network of cables' insulation can be represented by resistive and capacitive elements. During operation and over the years, the resistive components and also the loss factor increases for most isolation systems [8].

3. System Structure

The accelerated aging of the cable samples is accomplished by a combined dielectric and thermal stress. Dielectric stress means up to four times the nominal voltage, generated by a resonant system which works at mains frequency (50 Hz). Therefore, a variable inductance was constructed with an inductivity of more than 500 H. It forms a resonant series circuit with the cables' capacities. The voltage excision is the desired aging voltage. Thermal stress is applied by a specially constructed current transformer, which feeds in about two times nominal current on high voltage level. The cables themselves are situated in a fully air-conditioned container. All components of the ICCAS build up an fully automatic and remote-controllable accelerated ageing system. It facilitates the control, acquisition and measurement of about 100 analog and digital input and outputs values. All relevant parameters, like e.g. voltages, currents, temperatures, characteristic ageing values and security information are acquired, evaluated and stored by this central control system.

4. Diagnostic Measurements

A. PD Measurement

The data acquisition for the PD measurement and the loss factor measurement are based on a high speed data acquisition card. The PD impulses are measured at selective nodes. They are transferred and into a voltage equivalent signal by suitable analogue circuits. This signal is acquired with the highest available sample rate and processed by software subsequently. The PD impulses result in an equivalent peak to peak voltage (V_{pp}). The time response of the signal is stored for later evaluation purposes. Regular measurements on a calibrated reference generator approve that the background noise level is much lower than 50 pC (Pico Coulomb). Actually, discharges of ca. 5 pC can be detected and distinguished from the noise level.

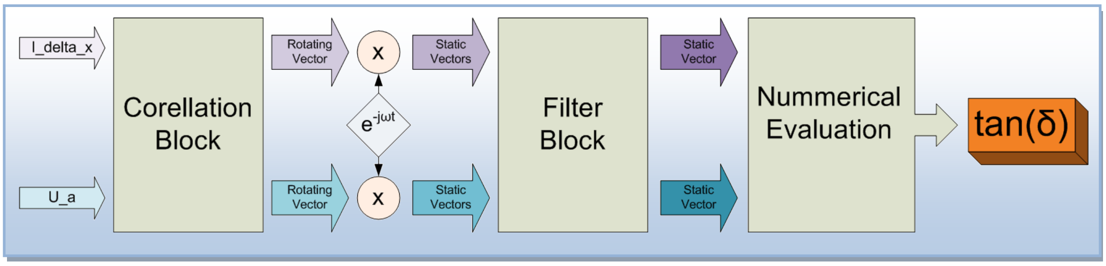

Fig. 3: Loss factor measurement algorithm

B. Measurement and Determination of the Loss Factor

For the determination of the loss factor, the aging voltage and the leakage current through the insulation (see fig. 3) are measured simultaneously at a constant and high sample rate for a couple of 50Hz periods. The values are subsequently used to build up complex rotating vectors. Therefore, the signals are correlated with themselves and split into orthogonal components. These resulting rotating

vectors are comparable to space phasors, calculated for three phase systems. They are then transformed into a rotating coordinate system and further transferred to suitable designed FIR-filter groups, which deliver a stable output signal for the following determination of the loss factor, see fig 4.
The reachable accuracy on repeated measurements of the tan(δ) evaluation using the method described above is better than 10^{-5}, which is an excellent value for a 50 Hz system in field operation. All measurements are adjusted to specially defined and premeasured HV-capacitors, using a high-accuracy calibrated Schering bridge.

C. Performance

During the diagnostic measurement cycles, a high amount of data accumulates. Therefore, the acquisition hardware had to be chosen very carefully. This resulted in a high measurement and data processing performance. 540 PD measurements and 300 loss factor measurements can be carried out in a time of ca. 20 minutes at the highest achievable accuracy. Thereby, an amount of ca. 3 Gigabytes of PD data is acquired and recorded on hard disk. Afterwards, this data is compressed by an LZW algorithm, transferred via FTP to an offsite server and imported into an SQL database. This database will form, together with the aging operation values (i.e. temperatures, voltages, currents), the foundation of all further data processing and evaluation.

5. Measurements

A. Environmental Influences

The environmental conditions and mainly the temperature have a strong influence on the electrical parameters of

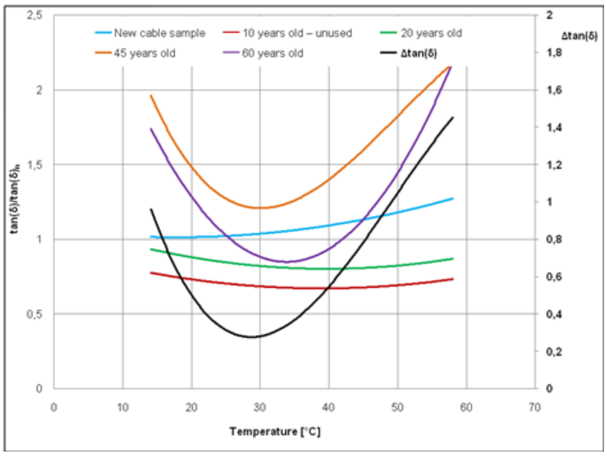

Fig. 5: Dependency of the dissipation factor on the temperature for different cable samples

electrical insulation systems and in this way on the diagnostic parameters like e.g. the PD values and the tan(δ).
It is known, that in the interval of 0-100°C the dissipation factor should have an minimum in the vicinity of ca. 40°C, and further rises with temperature, [10]. Since this dependency is influenced by the cable age and its status, it is even more complex to compare the measured values on different cable samples and temperatures and to make it applicable for future diagnostic researches. At the beginning of the main aging experiment, which should last for around two years in continuity, some dependences of the PDs, tan(δ) values as well as polarization and depolarization processes on environmental parameters have been researched and analyzed, [11].

B. Results

The cable samples are differently pre-aged: the range reaches from brand new cables, over 10 years old but unused cables, to 20, 45 and finally 60 year old cables. All shown measurements were performed under nominal

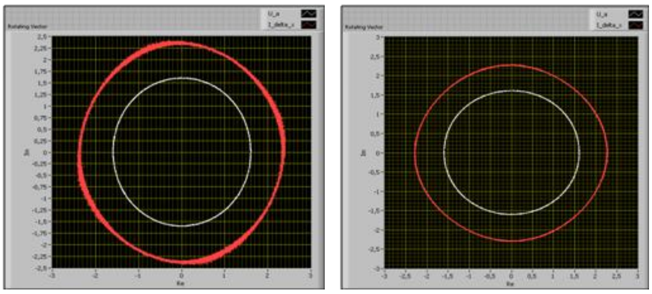

Fig. 4: One step in the process of determining the tan(δ) value: rotating vectors of the voltage U_a and current $I_{delta\,x}$ of a pre-aged cable (left) and a new cable sample (right)

voltage conditions: 20/11,5kV, 50Hz. The results are presented in fig. 6. The value $\tan(\delta)_n$, to which all measurements are related, is the loss factor of a brand new cable at 20°C. The shown curves are polynomial interpolated based on discrete measurement points in the temperature interval 14°C to 58°C.
Two principal groups of similar profiles can be distinguished. In one group are new, 10 years and 20 years old cables; in the other 45 and 60 years old cables.
Additionally, it could be concluded, that a suitable storage of cables (see 10 years old – unused cables) has no visible negative consequences on the shown temperature dependency of the tan(δ) values. A nearly similar dependence can be stated for the brand new samples and the tan(δ) values are even smaller. The main aging experiment will show, if the tan(δ) of brand new cable samples is slightly higher at the beginning of the operation interval until the mass is equally allocated through the paper and the insulation layers and the entire insulation is uniformly formed out. In contrast to these cable samples, the older cables in this experiment (45 and 60 years old) show a strong dependency of the tan(δ) on the temperature. It is significant, that the minimal tan(δ) values are measured around 30°C. According to the shown and very different dependencies, it can be stated, that not every cable temperature is optimal or even adequate for the diagnostic measurements, since the sensibility of the diagnostic method could also show the above dependency on the temperature. Actually, the measured aberration of the tan(δ), marked out as

$$\Delta \tan(\delta) = \max(\tan(\delta)) - \min(\tan(\delta)) \quad (2)$$

on each measured temperature, is minimal in the range of 30°C. Therefore, the sensibility of diagnostic measurements would have a minimum in this temperature range. In field measurements, the temperatures of the ground, surrounding the cables can easily reach this region, espe-

cially for cable tracks which were heavily loaded directly before the diagnostic measurement. Further investigations on all cable samples in the main aging experiment are necessary to deepen the knowledge about the dependencies and the physical backgrounds.
In addition also some other phenomena have been noticed. As an example, fig. 4 shows the current $I_{delta\ x}$ and the voltage U_a as rotating vectors for two different aged cable samples. On the left picture, a rather strong presence of PDs can be notified on the red current curve, manifesting as a slight ripple. The brand new cable on the right does not show a comparable amount of discharges. The later monitoring of the PDs, its PDIV (partial discharge inception voltage) and intensity in the main aging experiment will show if there is a comprehensive dependency of PD on the temperature and/or the age of a paper insulated system.
During the artificial aging process, all dependencies presented here will be monitored for a large number of cable samples with very different operation histories and ages. Therefore, statistical influences and inaccuracies will be eliminated widely. In addition, the effect of the physical aging process on the measured loss factor and PD values and other diagnostic key values will be further carried out. In this way the reliability of the rest lifetime prognoses under different environmental or thermal conditions will be improved.

6. Conclusion

The status and the condition of the MV networks and especially cable systems can be analyzed by a measurement of characteristic aging parameters like PD-intensity and loss factor values. To determine the typical levels of these parameters, an artificial and accelerated aging system for MV cables has been developed and realized. In this way, all relevant aging parameters should be monitored, interpreted and the cable status should be estimated. In this paper, the PD measurement and the loss factor measurement equipment and algorithms are presented. Especially the loss factor determination represents a unique algorithm with highest accuracy and highest reliability.
Furthermore, the principal dependencies of the loss factor on the cable temperature were investigated for a moderate temperature range. It is obvious, that older cables have a stronger temperature dependency than brand new or stored cable samples. The very different characteristics of the tan(δ) for different aged cable samples clearly illustrate the difficulties for the interpretation of the results from diagnostic field measurements under incomparable environmental conditions.
Based on the continuous and sample-wise monitoring of the PD and the loss factor values, their development during the aging process and the dependency on environmental influences, an aging database will be built up. This database will be the foundation for the determination of the relevant electrical, physical and chemical parameters and for further developments of cable diagnostic methods and mathematical aging models. On behalf of the created database, criteria for the development of a calculation and diagnostic system for field studies should be derived. Therefore, a condition-oriented maintenance strategy and asset management is made possible and the investment planning can be improved. Moreover, this is one way to increase the power quality and reliability in today's MV distribution networks.

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References

[1] Mladenovic I., Weindl Ch.: "Determination of the Characteristic Life Time of Paper-insulated MV-Cables based on a Partial Discharge and tan(δ) Diagnosis", 13th International Power Electronics and Motion Control Conference (EPE-PEMC 2008)
[2] Freitag, C.: „Entwicklung und Implementierung eines Steuerungs-, Regelungs- und Messsystems zur Realisierung einer automatisierten Versuchsanlage für die beschleunigte Alterung von Mittelspannungskabeln", Diploma Thesis, University of Erlangen-Nürnberg, 2008
[3] Imcorp - Instrument manufacturing company, „IMCORP Teilentladungsmessverfahren als Zustandsdiagnose für Mittel- und Hochspannungskabelanlagen", Feb. 2003
[4] Mladenovic I., Weindl C., Freitag C.: "New System for MV-Cable ageing under controlled conditions", CIRED 2009, Prague (Czech Republic)
[5] I. Mladenovic, Ch. Weindl: "ICAAS – Integrated System for lasting Accelerated Aging of MV Cables, Data Monitoring and Acquisition", CEIDP 2009, Virginia Beach (USA) 2009
[6] I. Mladenovic, Ch. Weindl: Determination of the Environmental Conditions for the Accelerated Ageing of MV-PILC Cables, 9th International Conference on Properties and Applications of Dielectric Materials 2009, IC-PADM 2009, July 19-23, 2009, Harbin, China
[7] „Zustandsorientierte Instandhaltung von Mittelspannungsnetzen", Forschungsreport, FGH - Forschungsgemeinschaft für elektrische Anlagen und Stromwirtschaft, 2002
[8] Lecture Script „Hochspannungstechnik", Dr.-Ing. C.Weindl, Erlangen, 2010
[9] C. Freitag, I. Mladenovic, Ch. Weindl: Fully Automated MV Cable Monitoring and Measurement System for Multi-Sample Acquisition of Artificial Aging Parameters, ICREPQ 2010, 23-25 March, Granada Spain, 2010
[10] M. Ohlen, P. Werelius: "Dielectric Frequency Response and Temperature Dependence of Power Factor", ISEI 2010, San Diego, USA, 2010
[11] Ch. Weindl, I. Mladenovic: "Development of the p-factor in an Accelerated Ageing Experiment of the MV PILC Cables", ICSD 2010, Potsdam, Germany, 2010