Budapest University of Technology and Economics
Department of Electric Power Engineering

Development of cable diagnostic methods

Thesis booklet

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1 Introduction

Almost all electrical equipment (e.g. transformers, circuit breakers, cables, etc.) contains electrical insulating material that enables the safe operation of that equipment. In my research, I focused on cables.

During their service life, insulations can be subject to a wide range of environmental and ageing effects (e.g. moisture, heat, radiation, mechanical vibration, etc.), which cause irreversible changes in the insulation, leading to a reduction in the lifetime of the insulating materials. The ageing of different types of insulation typically differs from each other, and may even vary depending on the aging processes (e.g. heat, stress, radiation, etc.) as well. Therefore, there is no single diagnostic method that could be applied for all insulation types as a best solution [1–3].

As a result of advances in insulation technology, a number of insulation diagnostic methods have been developed to determine the condition of electrical insulations [4–6]. Of particular importance is the development and application of non-destructive diagnostic techniques. Our department has been involved in research on these methods for decades, with significant results [5, 7, 8]. The need for new insulation diagnostic methods is typically influenced by two effects. The first is the appearance of new types of insulation in the electrical grid (e.g. cross-linked polyethylene), and the second is the transformation of the electricity grid e.g. due to the rise of distributed generation.

2 Motivation

2.1 Mixed Paper Insulated Lead Covered and Cross-linked Polyethylene Cables

With the gradual introduction of new types of insulation and the consequence of continuous improvements over time, it is not uncommon to have three or more different types of insulation in service simultaneously in a medium voltage network [9]. In practice, this can make diagnostic tests difficult, especially if the various differently insulated cables are located within the same section, as the electrical properties of these cables are typically very different.

In my research, I have developed a method for diagnosing mixed cable sections containing oil-paper and cross-linked (XLPE) and linear polyethylene (PE) insulation, which are currently widely used throughout Europe. This method is based on the extended voltage response method. Mixed cable sections are common and often difficult-to-diagnose elements of medium voltage electrical networks.

2.2 PVC insulated cables

PVC insulated cables, despite their electrical parameters not being the best, are used in many applications in the electric power industry, e.g. nuclear power plants, low voltage distribution grid cables, etc. so their condition testing is still an important field today. Two of the most important ageing processes of PVC insulated cables are dehydrochlorination and plasticizer evaporation [10]. Previous researches have shown that the increase in the initial slope of the discharge voltage obtained from voltage response measurement on PVC insulation is proportional to the thermal degradation of the insulation, with which the effect of dehydrochlorination can be well monitored [8, 11].

During artificial thermal aging the temperature is usually kept constant and lasts for hundreds or even thousands of hours. This is not even close to stress that occurs under real conditions where thermal stresses due to overloading occur periodically: not with constant temperature and not for hundreds of hours.

By conquering more and more land, distributed power generation on the low voltage distribution grid is posing new challenges to the cable network, whereby the non unidirectional power flow can result in overloading of certain sections of a cable line, reducing the lifetime of its insulation. Due to the increased loads resulting from these changing conditions, cables can be overloaded and their insulation subjected to higher stresses, which can reduce their lifetime [12, 13], e.g. the lifetime of medium voltage PILC cables can be less than halved according to a recent study [14]. The impact of distributed generation on the different elements of the grid is nowadays a highly researched area, with several ideas for protecting cables (e.g. by using batteries in electric cars to avoid overheating, etc.) [12, 15]. However, the impact of such short term thermal overloads is still one of the less researched areas.

In the other part of my work, I investigated the effects of short-time thermal overloads on PVC insulated distribution grid cables and PVC insulation films of known composition. During the research I was looking for electrical parameters that are indicative of the effects of short duration thermal ageing (e.g. from overloading) on PVC insulation. Knowledge of this relationship could form the basis for an asset management system for electricity utilities that would allow more accurate condition assessment and more efficient operation.

3 Theses

Thesis I

> **By investigating the time constant distribution of polarization processes on thermally aged mixed cable sections consisting of oil-paper and cross-linked polyethylene sections of different lengths, calculated from the results of extended voltage response measurements, I found that the effect of the cross-linked polyethylene cable section on the time constant distribution of polarization processes is negligible. When determining the time constant distribution of the polarization processes, it is sufficient to consider the cross-linked polyethylene section with its capacitance. Thus, from the results of the extended voltage response measurements, the condition of the oil-paper section can be determined and its thermal degradation can be monitored.**

Related publications: (J2), (J5), (C2), (C3), (C5), (C6)

Diagnostic methods based on voltage response have been proven very effective to investigate the general condition of oil-paper insulated cables and have been used for several decades [4, 16, 17]. In the case of mixed sections, two different solutions based on voltage response have been reported so far to determine the condition of the oil-paper part [18–20]. However, these methods have only been validated in a laboratory study on a small sample size (1-2 cables) and few mixed section ratios (1-2 different ratios), and the applicability of the methods under multiple ageing conditions has not been investigated [18–20]. A limitation of the voltage response based method [18] is that it can only be applied when the length of the oil paper section is not in the range of 20-40%. The limitation of the p-factor-based method [19, 20] is that the effect of moisture content have not been investigated although the p-factor is dependent on it. Both methods use a single number to indicate the progress of thermal degradation and therefore do not take into account the higher information content provided by the polarization spectrum [21, 22].

A cyclic laboratory ageing test was carried out on medium voltage oil-paper insulated (PILC) cables. On four different samples, with three different proportions of XLPE+PILC mixed sections, I have demonstrated by measurement results that the XLPE section is substitutable as a capacitor in terms of voltage response.

From the results of the extended voltage response method, I determined the time constant distribution of the polarization intensity, the polarization spectrum, using an iteration method. I found that, despite increasing the fraction of the XLPE cable, the spectra varied only in the intensity of the polarizations, but not in the time constant distribution of the spectrum, or to a negligible extent. Consequently, the spectral calculation method I have presented is suitable for the diagnostic investigation of mixed XLPE and PILC cables with different oil-paper fractions. The spectral calculation method can be used to detect the thermal ageing of the oil-paper section for the oil-paper fractions that occur in practice. This is because the increase in the intensity of polarization processes with small time constants, i.e. the shift of the polarization spectrum towards smaller time constants, is an indicator of ageing of oil-paper type insulations [23] and this is found by the algorithm for all fractions, cables and ageing states.

Thesis II

> **I developed a new diagnostics system of deducted quantities for evaluating the results of loss factor measurements on electrical insulations in the frequency range 20 Hz...500 kHz. By applying the new deducted quantity indicator system to PVC cable and insulation samples subjected to laboratory ageing simulating short-term thermal stresses, I found that short-term thermal overloading of PVC insulations can be detected by these indicators and the degradation that occurs can be monitored in a non-destructive manner. The results were validated by mechanical Shore D hardness measurements on the samples**.

Related publications: (J1), (J3), (J4), (C1), (C4)

Short-term (3-6 h) cyclic thermal ageing was performed on PVC insulated distribution network cable samples and PVC insulation samples of known composition, at several different temperatures on the cable samples. The results of the measurements demonstrated that short-time thermal ageing has an effect on the condition of PVC insulated cables. I defined deducted quantities, which I compared with the duration of ageing and the Shore D hardness of the samples using correlation analysis. Based on this analysis, I found that the short-term thermal ageing of PVC is well tracked by the voltage responses and other measured data.

I have shown that it is possible to choose better quantities for following short-term thermal aging than the Shore D hardness that has been proven to follow effectively the effect of long-term thermal ageing. The findings have been also confirmed by known composition PVC insulation films. I found that the best quantities are proportional to the dissipated power generated in the dielectric between 20 Hz and 500 kHz, hence the short-term thermal ageing can be well monitored by these indicators.

Thesis III

By using extended voltage response method to investigate the aging of PVC insulation samples subjected to cyclic thermal aging tests, I proved that the plasticizer loss of PVC — which is the dominant degradation process of PVC insulations — can be followed by the value of the initial slope of the return voltages. The amount of plasticizer remaining after thermal ageing is proportional to the initial slope of the return voltage. The results have been validated by mechanical methods, namely by Shore D hardness measurements and dynamic mechanical thermal analysis (DMTA).

Related publications: (J1), (C1), (E1)

PVC is a brittle polymer that is made suitable for use as cable insulation by the addition of plasticizing additives [10]. Previous researches have shown that mechanical measurement methods such as elongation at break or indenter-type measurements can be used to monitor the effects of thermal ageing on PVC insulation [24–26]. These methods, however, typically damage the insulation, since, for example, the measurement of elongation at break requires sampling from the cable insulation.

I have developed a method to infer, in a non-destructive manner, the reduction of the plasticizer content of PVC annealed with the plasticizer additive dioctyl phthalate (DOP). By means of this method the determination of the glassy state of PVC is possible, which in practice warns of the end of the mechanical lifetime of PVC insulation.

Short-term (3-6 h) cyclic thermal ageing was performed on dye-free insulation samples made of PVC with different plasticizer contents. I have demonstrated with measured results that the effect of ageing can be well monitored for insulations with a hardness of cable sheathing or higher using the extended voltage response method. An increase in the time constant of an intense polarization process, i.e. a shift towards a higher time constant in the polarization spectrum, was clearly observed with decreasing plasticizer content on the samples having the same hardness as cable sheaths.

It was found that in the transition state between the glassy or glassy and highly elastic states of PVC, the slope of the return voltages measured by the extended voltage response method varied in proportion to the PVC plasticizer content. Shore D hardness measurements and dynamic mechanical thermal analysis of PVC (DMTA) were used to verify the proportionality of the slope of the recovery voltages with the PVC plasticizer content.

Publications

Articles Related to Theses

Articles in International Journals

(J1) G. M. Csányi, S. Bal, Z. Á. Tamus, "Dielectric Measurement Based Deducted Quantities to Track Repetitive, Short-Term Thermal Aging of Polyvinyl Chloride (PVC) Cable Insulation", *MDPI Polymers*, vol. 12, no. 12, p. 2809, 2020. (IF: 3,426, Q1, Scopus, WoS)

(J2) Z. Á. Tamus, D. Csábi, G. M. Csányi. "Characterization of dielectric materials by the extension of voltage response method." *Journal of Physics: Conference Series*, vol. 646, no. 1, p. 012043, 2015. (Scopus, WoS)

(J3) G. M. Csányi, Z. Á. Tamus, P. Kordás, "Effect of enhancing distribution grid resilience on low voltage cable ageing", *IFIP Advances in Information and Communication Technology*, vol 521 pp 300-307, 2018. (Scopus)

(J4) G. M. Csányi, Z. Á. Tamus, Á. Varga, "Impact of distributed generation onthe thermal ageing of low voltage distribution cables," *IFIP Advances in Information and Communication Technology*, vol. 499 pp 251-258, 2017. (Scopus)

Articles in Hungarian Journals

(J5) G. M. Csányi, Z. Á., Tamus. "Elemi polarizációs folyamatok vizsgálata", *Elektrotechnika*, vol. 11-12 pp. 17-19, 2019.

Conference Papers

(C1) G. M. Csányi, Z. Á. Tamus, "Effect of short term thermal aging on PVC films by the extended voltage response measurement method", in *DIAGNOSTIKA '20 - Conference on Diagnostics in Electrical Engineering (CDEE)*, Pilsen, Czech Republic, 2020.

(C2) G. M. Csányi, Z. Á. Tamus, "Modeling of insulations by the results of voltage response measurement", in *ISH 2015 : 19th International Symposium on High Voltage Engineering*, Pilsen, Czech Republic, 2015.

(C3) G. M. Csányi, Z. Á. Tamus, "Investigation of Dielectric Properties of Mixed PILC and XLPE Cable Insulation by the Extended Voltage Response Method", in: *2017 6th International Youth Conference on Energy (IYCE)*, Budapest, Hungary, 2017.

(C4) G. M. Csányi, Z. Á. Tamus, T. Iváncsy, "Investigation of Central Frequency and Central Loss Factor Values on Dioctyl-phthalate (DOP) Plasticized PVC films", in *DIAGNOSTIKA '18 - Conference on Diagnostics in Electrical Engineering (CDEE)*, Pilsen, Czech Republic, 2018.

(C5) G. M. Csányi, Z. Á. Tamus, T. Iváncsy, "Investigation of dielectric properties of cable insulation by the extended voltage response method", in *Proc. of DIAGNOSTIKA '16 - Conference on Diagnostics in Electrical Engineering (CDEE)*, Pilsen, Czech Republic, 2016.

(C6) G. M. Csányi, Z. Á. Tamus, "Elemi polarizációs folyamatok vizsgálata továbbfejlesztett teljes feszültségválasz módszer segítségével", in *IX. Mechwart András Ifjúsági Találkozó*, Debrecen, Hungary, 2019.

Other

(E1) G. M. Csányi, "Polarizációs folyamatok hőmérsékletfüggésének vizsgálata", MSc Thesis, Budapest University of Technology and Economics, Hungary, 2015

Articles Not Related to Theses

Articles in International Journals

(J6) Jaroslav Hornak, Pavel Trnka, Petr Kadlec, Ondrej Michal, Václav Mentlík, Pavol Šutta, G. M. Csányi, Z. Á. Tamus, "Magnesium Oxide Nanoparticles: Dielectric Properties, Surface Functionalization and Improvement of Epoxy-Based Composites Insulating Properties", *MDPI NANOMATERIALS* vol. 8, no. 6, 2018. (IF: 4,032, Q1, Scopus, WoS)

Conference Papers

(C7) G. M. Csányi, Z. Á. Tamus, "Investigation of Polarization Processes on Thin PVC Film Insulations by the Comparison of Frequency Domain Spectroscopy and Extended Voltage Response Measurements", in: *2017 6th International Youth Conference on Energy (IYCE)*, Budapest, Hungary, 2017.

(C8) R. Egyed, Z. Á. Tamus, G. M. Csányi, T. Iváncsy, "Testing of high voltage cable lines by damped ac technique – a case study", in *Proc. of DIAGNOSTIKA '16 - Conference on Diagnostics in Electrical Engineering CDEE 2016*, Pilsen, Czech Republic, 2016.

(C9) Z. Á. Tamus, G. M. Csányi, Á. Szirmai, A. Nagy , "Insulation Diagnostics of High Voltage Equipment by Dielectric Measurements – Hungarian Research and Experience", in *International Scientific Symposium "Electrical power engineering 2016"*, Varna, Bulgaria, 2016.

(C10) Z. Á. Tamus, G. M. Csányi, "Laboratory investigation of a service aged HV cable termination", in *Jicable'15 - 9th International Conference on Power Insulated Cables*, Paris, France, 2015.

(C11) Z. Á. Tamus, G. M. Csányi, G. Tomon, "Investigation of temperature dependence of DC diagnostic tests on LV PVC insulated cables", in *Jicable'15 - 9th International Conference on Power Insulated Cables*, Paris, France, 2015.

(C12) G. M. Csányi, Z. Á. Tamus, "Temperature dependence of conductive and polarization processes of PVC cable", in *Electrical Insulation Conference (EIC)*, New York, USA, 2014.

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(C14) P. Kordás, Z. Á. Tamus, G. M. Csányi, "Elosztott energiatermelés által okozott termikus túlterhelések vizsgálata a kisfeszültségű elosztókábelekre", in *VIII. Mechwart András Ifjúsági Találkozó*, Visegrád, Hungary, 2018.

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