Thermal Ageing of XLPE Cable Insulation under Operational Temperatures – Does It Exist?

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Abstract

Thermal ageing of power cables may cause premature breakdown if the cables are operated at elevated temperatures, a relation usually described by Arrhenius' law. The purpose of the present study is to investigate if any significant ageing takes place under normal operational temperatures. The investigation shows that thermal degradation at these comparably low temperatures is hardly reported and seems not to be of practical concern to transmission system operators. This may be the result of a conservative mind-set during the dimensioning of power systems, here in the case of power cables, which means that the lines are generally lightly loaded. Based on the literature found or, to be more precise, on the literature not found it seems to be very difficult to determine that thermal ageing should be problematic for operational power cables at all, in particular as compared to laboratory investigations at very high temperatures, where thermal ageing clearly takes place. To this conclusion contributes the fact that failure statistics do not correlate failures with severity of loading, and that the laboratory studies (which mostly conclude thermal ageing to be problematic) exposes the materials to unrealistic conditions.

1. Introduction

Transmission cable manufacturers usually recommend a maximum conductor temperature of 90°C for cross-linked polyethylene (XLPE) cables for the entire lifetime of the cables. This limitation is enforced by well-known ageing processes of the insulating material as it, through many experimental studies e.g. [1]-[6], has been proven that the electrical and mechanical properties of XLPE degrades fast at high temperatures. Dimensioning the conductor of cross-linked polyethylene (XLPE) power cables is based on the requirement of a maximum temperature of 90°C during normal operation. Of course, economics play a role as well and continuously elevated temperatures in a cable will be non-acceptable just for this reason. But under emergency load and in failure situations, the limits could be reached, depending on conductor dimensioning, grid properties and cooling conditions in the actual case.

The aim of the present literature study is to investigate if operational temperatures of XLPE cables can be related to and, in particular, have been reported as causing increased failure rates, when the XLPE insulated cables are operated in common power systems. The focus in this study is on the cable as a component, which means that temperature dependent failures of accessories are not included, hereunder joints, terminations, etc. Regarding joints at distribution level, it is known that temperature variations can cause thermo-mechanical loads, increasing the failure risk in the component.
Other cable phenomena such as water trees are also not included in the investigation, even though their nature might be dependent on thermal conditions as well.

The goal here is to investigate if the temperature of power cables is a problem when operating under real life conditions, or if temperature limitations are based on tradition-related operation policies where considerable safety margins are standard. Investigations of temperature based ageing should include both the impact of high peak temperatures and also the accumulated ageing under normal temperature variations. Temperature variations are considered as being more relevant for accessories.

2. Temperature Dependent Insulation Properties

The limitation of 90°C is the result of extensive studies of the different material properties of XLPE and their dependency on temperature.

The thermal response of material properties can in general be divided into two categories. Firstly, some properties, such as the tensile strength and the electrical resistivity of materials, are reversible. These types of properties typically experience an immediate change when applying a temperature change, however when reversing the temperature after a short period of time the properties may return to their original values.
Secondly, some properties are non-reversible and an example is the breaking of crosslinking covalent bonds in XLPE Such changes typically require longer time scales to evolve and are thus often referred to as thermal ageing resulting in permanent changes of the mechanical and electrical properties.

Most important for cable performance is of course the AC and impulse breakdown strength. These properties are in [2]-[6] shown to be highly dependent on the temperature and it is found that both immediate and long term effects must be considered when designing XLPE insulated cables. The studies show that the AC breakdown strength of XLPE is observed to immediately drop by one third when the temperature is raised from 25°C to 90°C, and similarly the impulse withstand voltage decreases to approximately half its value.

Regarding the reversible mechanical properties, it is shown in for instance [1] that the immediate response of XLPE to temperatures above 100°C is a significant decrease in the tensile strength, which means that the cable may experience breakdown caused by direct mechanical failure when subjected to high losses.

In order to prevent such premature breakdowns (mechanical, electrical or combined), cables are usually dimensioned such that the critical temperatures are newer exceeded. Even when failures in the transmission and distribution systems are experienced, the Transmission System Operators (TSOs) require the conductor temperature to be within the acceptable limits. Cables will thus, because they must be able to carry extra load in case of failures, for far most of the time operate well below their thermal rating of 90°C.

In addition to the immediate changes of the material properties of XLPE caused by high temperatures, some long term effects have also been observed in different studies.

This ageing process includes broken chains in the polymer, oxidation, darkening of the insulation, poorer mechanical properties and finally increasing the probability of breakdown with increased failure rates as a consequence.

It is e.g. in [6] shown that both the electrical breakdown strength and the tensile strength of XLPE decrease to 50% of its original value when continuously exposed to 110°C for 10000 hours.

Such non-reversible responses to high temperatures are generally denoted thermal ageing.

The conventional way of analysing thermal ageing of XLPE is to assume the ageing as being caused by a first order chemical reaction and the rate with which this ageing will progress is generally modelled with Arrhenius' law (1), [7]-[8].

$$k(\theta) = A \cdot exp\left(\frac{-E_a}{R \cdot \theta}\right) \quad (1)$$

where $k(\theta)$ is the reaction rate with temperature θ, E_a the activation energy necessary to initiate the reaction, R the gas constant and A is called the frequency factor (a material specific constant).

Similar to the electrical properties, the mechanical properties will also be affected by the thermal history. In [1] is shown that thermal ageing steadily decreases the tensile strength (at least up to the 5000 hours testing period) for temperatures above 80°C.

3. Thermal Ageing of Power Cables in Service and under Laboratory Conditions

This section investigates failures and ageing as reported from power cables in service and tries to relate the findings to the thermal conditions.

The methodology used for finding the answer to this challenge has been an investigation of failure statistics and other publications concerned with power cables which have been aged in power systems or have been exposed to conditions similar to what is experienced by cables in power systems.

In Denmark, the Danish Energy Association has collected failure statistics on power cables in transmission and distributions systems for several years. Internationally, such information can be found in Cigré publications, [9]. However, neither of these datasets contains information, that would allow us to correlate load with failure rate, and it is thus not possible to determine if the failed cables in the statistics have been loaded harder than the non-failed cables. Furthermore, possible failures caused by excessive temperatures are impossible to distinguish in the failure statistics from cables where the failure is caused by other material related problems such as material contamination, etc. Especially at lower voltage levels where many material related failures are results of water treeing, the failure statistics become useless for obtaining knowledge about thermal ageing of power cables.

It has to be mentioned that the failure statistics also include the early and less successful cable designs, with steam vulcanized polymer and those with semiconductive layers based on graphite, known to have high failure rates due to a generally poor design.

In order to address these shortcomings in the failure statistics, the authors searched for alternative literature which addresses thermal ageing of cables aged in power systems. It seems that such studies are scarcely represented in the available literature databases; however some attempts on quantifying thermal ageing of cables which have been in operation, were found. E.g. [10] uses X-ray Photoelectric Spectroscopy (XPS), Oxidation Induction Time (OIT) and Differential Scanning Calorimetry (DSC) for determining the ageing condition of a field aged 13.8kV distribution cable, which had experienced a joint failure. It is concluded that excessive temperatures have increased the oxidation level in a short part of the cable (close to the failed joint), which may be an indication of thermal ageing. It must though be noticed that the cable failed due to a fault in an accessory, and it can thus not be determined if the increased oxidation level would become

problematic in the future. It is furthermore not known to which degree the cable was loaded, and it is thus not possible to determine if the cable has been subjected to excessive temperatures.
This pattern repeats in all research reports which have been found during the search for relevant literature.
The problem is that reported analyses of XLPE degradation is not correlated to the loading which the cable has been subjected to, and it is thus not possible to determine if potentially poor material properties are the result of high temperatures, or if identical cables which have been loaded lighter will show the same state of material degradation.

The authors will not exclude that there is more information available, but according to our findings, the most promising way to make proper correlation between operational temperature and thermal ageing is via laboratory experiments.

The main challenge regarding thermal ageing based on laboratory experiments is scaling and accelerated ageing. In many studies the XLPE samples are subjected to temperatures above 100^{o}C, which means the experimental conditions are not realistic anymore.

In [11], small scale model sized samples of XLPE cables were exposed to thermal and electrical conditions comparable to what is experienced by cables in transmission systems. It is found that even for continuous exposure to 90^{o}C and a normal electric field; the cable insulation will have relatively high breakdown strength, which converges with time towards a constant threshold value (7.9 kV_{rms}/mm). This indicates that cables may age to a certain level where after further thermal ageing is not measurable in the electrical properties.
The study of [11] differs from other studies by including ageing data for cables being continuously exposed to relatively low temperatures (in the range of what is experienced in real transmission systems). It is found that the combined electro-thermal stresses at 20^{o}C and 60^{o}C result in minimum breakdown strengths of 11.5kV_{rms}/mm and 9.8kV_{rms}/mm respectively. It is noticed that these breakdown fields are fairly high, especially when considering that a typical 170kV cable may be exposed to field strengths of only 7.6kV_{rms}/mm, [12]. It should be noticed that the quality of the XLPE used in [11] is unknown, and a direct comparison between the quantities given in [11] and [12] can thus not be made.
One additional comment about the breakdown strengths found in [11] should be made. It is observed that the breakdown strength decreases as a function of time in the entire temperature range from 20^{o}C to 90^{o}C.
This means that even unloaded cables will experience exponentially decreasing breakdown strengths, from 28kV/mm to 11.5kV/mm over a six year period.
This data shows that ageing of XLPE is an inherent material property that will be experienced by cables even when they are unloaded. It can on this background be argued that even though deterioration is more pronounced at elevated temperatures, most of the ageing is an inevitable and inherent material process, at least for the cables investigated here.

4. Discussion

The well-known challenge between real world operational conditions and accelerated laboratory tests becomes noticeable, because:

- It is difficult to perform laboratory ageing experiments without increasing the temperature above realistic operating values; while laboratory experiments indicate considerable ageing mainly at such high temperatures.
- On the other hand failure statistics, and related reports, are based on cables which in general have been lightly loaded; and these reports show no indication of thermal ageing being a problem for cables subjected to realistic operating conditions.

The second statement is based on the search through many databases for available literature, for proof that thermal ageing constitutes a problem for cables in operation in distribution and transmission grids. It turned out that most data publically available has been collected under laboratory conditions, and it is thus difficult to make conclusions about operational conditions. The study of [11] though has interesting results as it attempts to expose model sized cables to realistic conditions. It is found that the converging breakdown strength at 20^{o}C is not even twice the converging breakdown strength of 90^{o}C, and it may thus be assumed that thermal ageing is a negligible phenomenon in real operational transmission cables where temperatures are always kept below 90^{o}C.

From the observations made in this paper, it may be considered if power systems, in an ageing perspective, can be loaded harder than what is presently the standard. It should though also be remembered that other problems than thermal ageing may arise when increasing the temperature, possibly setting limitations on the allowed operational temperature.

5. Conclusion

This study has investigated if elevated conductor temperatures presently affect the reported failure statistics of XLPE insulated power cables. Many studies have shown that high temperatures affect the lifetime of XLPE, however an increased failure rate of power cables, caused by elevated temperature, seems not to be reported as a problem in real life operation of transmission systems.
The challenge in the analysis of thermal ageing brought into daylight also in this study is between laboratory studies, where cables are subjected to unrealistically high temperatures in order to increase the ageing rate,

and the real operational conditions. One laboratory study is concerned with the investigation of XLPE at operational temperatures. It is shown that long term exposure to elevated temperatures does not affect the breakdown strength of XLPE significantly more than if the material is aged at room temperature.

The concerns about thermal ageing of XLPE must, based on the findings in this paper, be seen as a topic of mainly academic interest for the time being, as operational power cables are generally lightly loaded. These findings opens for taking a closer look at increasing the utilisation of power cables as the drawn conclusions suggest that system operators might be too conservative when dimensioning and operating their cables.

It should though be noted that increasing the utilisation of cables might require the investigation of other problems than thermal degradation of XLPE. Highly varying temperatures may for example lead to thermo-mechanical movement in joints and terminations, which can cause premature breakdown. The study of such phenomena is left for future research activities to investigate.

The present work should mainly be considered as stimulation for further discussions regarding thermal conditions of modern XLPE cable systems.

6. References

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