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Thermal Limit of XLPE insulation: Is 90 still the magic number?

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SUMMARY

The conventionally accepted maximum operating temperature of XLPE insulated power cables in “normal operation” is 90°C as per IEC 60840 and IEC 62067. This limit has been in place for many decades, while the technology has continued to evolve and mature from the invention of XLPE in 1963, through to the highly robust and reliable cables being manufactured today. As time passes, the original rationale behind such limits can become obscured. The aim of this paper is to highlight the various reasons behind the existing limits, to consider them again in the light of present-day knowledge and experience and assess whether the technology has more to offer going forward.

The IEC standards specify only a single option for the maximum conductor temperature, with the same value used for both continuous and short-term operation. Looking to other standards, it is common to allow a short period of operation above the 90°C specified by IEC. For example, in the US market an emergency operating temperature of 105°C is permitted, and similar allowances are made in standards in Japan. These elevated operating temperature regimes were originally put in place with reference to the requirements of grid operators, rather than the performance limit of the cable system itself. This raises a number of questions, such as: could the cable actually tolerate elevated temperatures for longer periods? What are the actual limits, and what physical phenomena are involved in setting these limits? This becomes particularly interesting for systems which might be required to support high loads, but for limited and well-defined time periods, such as those connected to sources of renewable power generation.

In setting the permissible operating temperature, there are many considerations to make. Thermal ageing of the insulation material itself is only one of these, in reality comprising a number of linked issues from long term effects on the polymer structure itself to the depletion of anti-oxidants. Thermal and mechanical impacts of elevated temperatures are often coupled with the electrical behaviour of the system, especially at interfaces; a classic example here is the impact of thermal expansion and contraction on the interface pressure, where the electrical

strength of interfaces can be reduced if the pressure drops beyond a certain threshold. All of these factors need to be considered holistically when determining the permissible operating temperature of the cable circuit.

Our paper attempts to map the range of factors of relevance in assessing if conductor temperature higher than 90°C is feasible for more than the limited “emergency operation” defined in some standards. Crucially we seek to highlight what may have changed over the decades since the original 90°C limits were set and propose the steps which could be taken to expand the functionality of XLPE insulated cables into the future.

KEYWORDS

Temperature, Crosslinked-polyethylene (XLPE), Qualification Testing

1. INTRODUCTION

As the size and scale of cable projects has continued to increase, both within transmission grids and links to remote generation such as windfarms, the industry has delivered many innovations to increase the amount of power which can be transferred at each voltage level. This has been achieved in many ways, with examples varying from larger cable sizes to low loss Milliken conductors, novel sheath bonding arrangements, low loss metallic armour packages, ever more sophisticated thermal analysis and improved geophysical surveys to gather more refined data on site conditions.

Despite all of these innovations, one thing has remained constant. The maximum permissible operating temperature of XLPE insulated cables under normal conditions has been 90°C for many years, in fact many decades. Going back beyond the 1990s, the “magic number” 90°C is quoted. This motivated us to ask the question: is this 90°C still the best value to use? Under what circumstances could a higher value be utilised? In the modern power system, does “normal operation” really bear much relation to continuous operation at the same temperature for the full asset life, and are we therefore being too conservative?

On this basis our paper is not intended to provide a definitive answer, rather to provoke discussion in the community and encourage cable designers to revisit the work done in the past when developing new innovations. In Section 2 a short historical perspective is given, looking back to the early days of XLPE cable development. The wording in relevant standards is reviewed in Section 3, focusing in particular on cases where “emergency” operation at higher temperatures is permitted. This is followed by a short overview of the main temperature dependent properties of XLPE, as well as the implications of the maximum operating temperature on the design of the accessories. The paper ends by considering what might have changed, in terms of the cable itself and the way it is used, since the 90°C limit became common place. We also pose some thoughts about what might need to be done to enable the use of higher operating temperatures, including areas where further research and service experience would be needed.

2. HISTORICAL PERSPECTIVE

XLPE insulated cables have been in use for over 60 years, starting at distribution voltage levels. For a time the development of both PE and XLPE insulated cables continued in parallel, before XLPE gradually became the dominant material. As early as the 1970’s, extensive work was done to characterise the behaviour of different XLPE materials as a function of temperature. Work by St-Onge et al produced a summary of how the electrical, thermal and mechanical properties of XLPE varied with temperature [1]. An interesting conclusion at that time (largely in the context of distribution systems) was that "*it appears reasonable to question the present emergency operating temperature of 130°C and to investigate if higher temperatures could be envisaged*". The paper notes that the emergency operating temperatures had "*been established several years ago and need re-evaluation*". A review conducted by Eichhorn [2] and published in 1981 built upon the earlier work from [1] by including additional examples from different XLPE materials which displayed slightly different behaviour.

The concept of emergency operating temperatures as high as 130°C (distribution) and 105°C (transmission) had already entered the standards in some countries by the 1980s (elaborated further in Section 3 of this paper). Research was continuing into the high temperature behaviour of XLPE, exemplified by the "HT84" workshop in Clamant, France in 1984 [3]. Further research began to identify wider cable system issues which might prove limiting, for example work by Buchholz et al from 1993 raised the issue of more complex thermomechanical behaviour, in particular with reference to the interaction between the insulation system and the metallic screens [4]. Work by Fletcher on a similar topic also posed the question of whether emergency operating temperatures of up to 110°C might be more appropriate within the distribution system [5]. Examples such as this underline the fact that the appropriate operating temperature must be considered in cognisance of the full cable system, and that it is not dictated by the insulation materials alone. That said, it is now almost half a century since some of the early works were performed and it seems appropriate to consider what has changed.

3. STANDARDS

3.1 IEC

The primary IEC power cable standards (IEC 60840 [6] and IEC 62067 [7]) specify only a single option for the maximum conductor temperature, with the same 90ºC value used for both continuous and short-term operation. The only exception is for short circuit calculations, which are out of the scope of this discussion. During pre-qualification testing, the heating cycle voltage test requires the conductor temperature to reach 0-5ºC above the normal operating temperature, while for the shorter type test it is 5-10ºC.

3.2 US standards

In the US market, both the AEIC CS9 [8] and ICEA S-108-720 [9] standards permit a period of "emergency operating temperature" at 105ºC, with the restriction that this operation should not be for more than 72 hours duration on average per year and not exceeding 216 hours in any 12-month period. AEIC CS9 Appendix D specifically notes that "*the above requirements are based on the purchasers power system operating needs*". An explanation is provided that the 72 hour emergency duration is related to the average time to recover from a forced outage affecting equipment other than cables. This statement implies that it is not really the performance limit of the cable system, but that the limitations were set to ensure that certain power system conditions could be overcome. AEIC CS9 further suggests means of verification of emergency temperatures by testing, with a number of adaptions to heat cycle voltage tests to cover the higher temperatures.

3.3 Japan

In Japan, there is similar provision for a brief period of operation at a higher temperature of up to 105ºC in JEC-3408 [10].

3.4 France

In France, Section 2 of standard NF C-33-253 [11] permits overload operation at up to 10ºC above the normal operating temperature of 90ºC, subject to the same annual restrictions that the use of this should not exceed on average 72 hours per year or 216 hours in the same 12 month period.

3.5 Summary

Even from the brief review presented here, it is apparent that many countries allow XLPE cables to be operated at temperatures beyond 90°C, typically up to 100-105°C, for a short period of time. Although 72 hour periods are very short compared to the full life of the cable, they are still long compared to the thermal time constant of the cable itself. To better understand the true performance limit of XLPE, it is important to consider how the material properties change with temperature, and which of these are short term or long term phenomena. This is discussed in detail in the following section.

4.0 TEMPERATURE DEPENDENT PROPERTIES OF XLPE

In considering any increase to the existing conductor temperature limit, it is vital to pay close attention to how the properties of the XLPE vary with temperature and the significance of this for the response of the cable system in service.

4.1 Influence of PE grade

A major advantage of XLPE over previous insulation systems is its higher thermal stability, while e.g. the previous generation of mass-impregnated non-draining cables – which relied on a combination of wound paper tape and an insulation liquid – suffered from increased void formation during cooling periods and subsequent failure as temperatures increased [12]. However, while PE was a suitable base material due to its low dielectric permittivity and loss in combination with high breakdown strength and low cost, the latter by virtue of being a polymer in widespread use in a number of industries, it is still limited by its melting point and thermal stability. Depending on the grade of PE used, PE is stable until around 85ºC for typical low-density PE with melting points between 105 and 110ºC for most commercial grades, the melting point increasing to 130ºC for high-density PE and with some grades such as ultra-high molecular weight PE (UHMWPE) having melting points above 150ºC [13]. This relates to the number of branches that split from the backbone of the ethylene chain, the more and longer the branches, the lower the density and subsequently melting point. This also puts a practical limit for operating temperatures of any PE-based material, where UHMWPE once processed can be found to have no higher melting point than types of HDPE, especially when blended with other polymers [14, 15].

4.2 Crosslinking mechanism

PE can be crosslinked with several different routes, such as peroxide cure or by grafting silanes onto polymer chains, thus the use of moisture-based cure [16]. By the mid-seventies increased use of XLPE for higher voltage cables with increasingly thicker insulation led to advances in manufacturing technology, primarily to reduce the time required for vulcanisation and alternative methods of XLPE production were developed [17]. Studies into the thermal and electrical behaviour of service-aged XLPE cables during the 1980’s [18], showed that it was possible to measure volatile by-products resulting from peroxide crosslinking and that several overtemperature events were required to remove all volatiles. The further development of different industrial methods to crosslink cables allowed comparison of resulting insulation morphology with results indicating that wet and dry crosslinking processes created structures where the void volume for dry crosslinked cables was smaller by three orders of magnitude than that of steam crosslinked cables [19]. Contemporary investigations into thermal behaviour as a function of crosslinking density reported that increased the levels of crosslinking density reduced the resultant melt temperature [20].

Regardless of the type of crosslinking, the resulting polymer will have a glass transition temperature related to the melting point of the base polymer. Consequently, different grades of XLPE can have very different available operating temperatures. Yamada et al demonstrated in 2003 the peak temperatures for the melting points of conventional XLPE and heat-resistant XLPE to be 103ºC and 123ºC respectively [21]. Thus, while it makes sense to limit the operational temperature of conventional XLPE to 90ºC to allow for a certain headroom, the so called heat-resistant XLPE could feasibly be operated at temperatures of up to 110ºC for short durations.

4.3 Importance of the glass transition

The risks of operating XLPE near or above the glass transition arise from a number of material parameter changes, such as the thermal expansion of XLPE, reduction of mechanical strength, the drop in thermal conductivity and the increase of electrical conductivity, just to name a few.

Early work on XLPE showed the drastic difference in thermal expansion between XLPE and adjacent metals (copper, aluminium, lead and their alloys). As shown in [22], conventional XLPE can expand by more than 10% in the range between 80ºC and 100ºC, while copper or aluminium expand less than 3% in the same temperature range.

The same work also measured a drastic reduction in thermal conductivity between 90 ºC and 129 ºC by about 18%, from 0.28 W/Km to 0.23 W/Km, while the same material would still have 0.32 W/Km at 30ºC. With the glass transition from a glassy to a rubbery state at higher temperatures also comes a reduction in the mechanical strength of the XLPE [23, 24].

For HVDC systems it is well-known that, since the electrical conductivity increases with operating temperature, the local electric field across the insulation is not constant due to the temperature gradient from conductor to the outer sheath. With heat-resistant XLPE, these effects are significantly delayed, which is why e.g. Yamada [21] suggested that 20ºC higher operating temperatures are feasible. Results for laboratory ageing on XLPE has shown that thermal treatment at or above the peak temperature of the glass transition affects several dielectric properties, such as permittivity and dielectric losses, but not in an easily predictable fashion [25].

4.4 Summary

From the brief discussion above, it is clear that while it is easy to talk of XLPE in generic terms, the real situation is more nuanced. Depending not only on the exact grade of base PE and the exact crosslinking method and extrusion process utilised, duration and effectiveness of the de-gassing process, both positive and negative trends in material properties can be observed as a function of temperature. While the above review is in no way exhaustive, it is clear that the capability of some XLPE materials will be higher than the existing IEC standards suggest. The question is, to what extent can this be quantified?

5.0 IMPLICATIONS FOR ACCESSORIES

When qualifying cable products at Um>36kV (i.e. in accordance with IEC 60840 or IEC 62067), the qualification regime requires a test of the full cable system, rather than just the cable itself. If higher conductor temperatures are to be used, careful consideration must be given to what needs to be qualified to achieve the desired functionality.

5.1 Technical Challenges

Many of the temperature dependent properties discussed in Section 4 are also critical when designing cable accessories; failing to evaluate the thermal response of the cable and accessory together could lead to poor service experience. We focus here only on the interaction between the cable and the accessory, primarily at the interface; the response of the accessory itself is a separate scope and indeed could fill a separate paper.

One of the major challenges to overcome is that of differential thermal expansion. Section 4 noted that the thermal expansion coefficient for XLPE can increase significantly above 80°C. Accessories must be capable of withstanding the compressive stress placed on them by the expanding XLPE, but arguably the greater risk comes when the cable system then cools. It is essential that sufficient interface pressure is retained after numerous heat cycles. Failure to achieve this leads to an electrically weak interface and a heightened risk of partial discharge inception, resulting in degradation that may prevent the cable from achieving its design life.

Reduction in the mechanical strength of the cable insulation itself, coupled with the outward radial pressure exerted on the accessory, also raises the prospect of creep of the cable insulation which could adversely affect the integrity of the interface.

It is worth stressing that these considerations do exist already at the existing 90°C operating temperature limit, with many accessories containing different materials that do not respond in the same way as XLPE. Therefore any move to increase the conductor temperature is primarily amplifying a known problem which must already be assessed carefully by accessory designers.

Before considering in detail all of the types of accessory we should examine carefully the actual needs case for higher temperatures at the accessories. While the cable must be treated as a system, is it reasonable to assume that all parts of that system have the same thermal requirements?

5.2 Thermally limiting locations

Although most standards treat the entire cable system (including accessories) as having the same operating temperature limit, the actual operating temperature is rarely constant along the route. Therefore, is it actually necessary to uprate the operating temperature of the entire system inclusive of all accessories?

- Terminations are often installed in locations where the cooling is via the air; those installed indoors could be climate controlled to some extent, and the cable phases are typically separated which reduces mutual heating effects. The cable directly approaching the termination is rarely a bottle neck to begin with, with a possible exception of solidly bonded cases with large phase separations and hence large metal screen currents.
- Joints occur relatively frequently in onshore cables, but the increase in phase spacing in the joint bay (a natural consequence of the physical working space needed to install the joints) means that in some cases they may already operate cooler than the cable outside of the joint bay. If the joint bay is not thermally limiting, then no action might be needed.
- In offshore cables, the most common locations for thermal limits are at the landfall, at the crossing of another asset, or in features such as J-tubes. In almost all of these cases,

accessories can be avoided by design. Individual delivery lengths of submarine cable can exceed 25km, and on an AC system the distribution of reactive power along the length means that loads will be lower than the maximum on large parts of the route. Arguably repair scenarios might be adversely impacted if repair joints needed to be moved away from a “high temperature” zone, but the economics and practicalities of this can be readily assessed and contrasted with the merits of using a higher conductor temperature.

On this basis, there is a strong argument to say that for many applications higher temperatures could be limited to parts of the route without accessories, meaning that only the cable itself must be qualified to the higher temperature.

6.0 WHAT HAS CHANGED?

6.1 Cable Production

Arguably there have been massive developments in the quality control processes within cable production, as well as the input materials. Awareness of the effects of external contaminants coming from the factory floor, as well as effects of by-products due to reactions of the chemicals involved in the cross-linking process itself, have been growing since the 1970’s, with constant improvements to the material quality and materials processing over the decades. The latter are typically managed during a lengthy degassing process. Since the late 1990’s and the year 2000, with the installation of the first XLPE HV cables rated for 500kV [26], so-called “superclean” or “ultra-clean” XLPE with focus on smooth interfaces between semicon and insulating layers has become prevalent. The number of patents related to ultra-clean or high-purity XLPE has consequently been increasing steadily since the early 2000s, reaching a peak from 2017-2019. Materials development led towards closed-loop production processes with tight control of processing parameters in order to minimise contaminants and pips, especially at the interface between the main insulation and semicon as well as accessories.

6.2 Cable Monitoring

Optical monitoring of cable systems has also advanced considerably in recent decades. In addition to thermal data, modern fibreoptic systems can also return mechanical stress information, allowing differential thermal expansion to be monitored [27]. Improved monitoring reduces the need to limit cable temperatures during a design phase to 90°C to provide thermal headroom, as there is now live data relating to the operating conditions of the cable. It should be noted that there are limitations to fibreoptic measurements, in particular the coarseness of measurement interval (~10m) and range (<100km) which may be limiting for long submarine interconnectors. Nevertheless, the growth of real time thermal ratings systems demonstrates an increased confidence in the industry in the use of fibreoptic measurements [28] and gives the ability to actively protect the cable from elevated temperatures that might result from uncertainties in the thermal environment for example.

6.3 Numerical Modelling

In addition to more advanced monitoring capabilities, increases in computational power has led to advances in thermal and mechanical modelling providing insight into temperature and strain distributions throughout a cable and its accessories [29]. These developments are supported by improved information regarding cable installation conditions, for example with focused site surveys. There can therefore be greater confidence in assessing the impact of increased operating temperatures on cable systems using simulation, combined with the ability to propagate localised measurements from monitoring systems to a full distribution of temperature within a cable.

6.4 Installation Conditions

Perhaps one of the main reasons for the use of conservative temperature limits in the past was the uncertainty about how the cable really performed in the field. As noted in Section 6.2, as an industry we are now much better able to monitor the system and take protective action if needed. It is also important to remember that our ability to characterise the thermal conditions along the route has also improved dramatically, reducing the risk that the actual thermal resistance seen by the cable was higher than anticipated. This is especially true for long submarine cables, where advances in geophysical assessments, combined with the huge growth in service experience and therefore measured operating temperatures, reduces the risk that the cable could be exposed to unexpected thermal conditions.

7.0 WHERE DO WE GO FROM HERE?

We choose to end this paper with a question rather than a definitive conclusion. Having reviewed some of the main developments that might enable XLPE cables to operate at higher temperatures, it is apparent that there has been a significant body of work prior to the turn of the century but relatively little afterwards. In some ways, the concept of permitting cable temperatures higher than 90°C is not really new on the basis that many national standards have allowed 72 hour periods up to 105°C for many years. In the modern power system, perhaps we should reconsider what "normal operation" really means, and whether restricting the cable to 90°C is necessary.

Arguably any change would need to be made gradually and with great care, and with cognisance of the potential rewards relative to any increase in risks. On that basis, we propose that the first step is considering only the cable itself in the absence of any accessories for the reasons outlined in Section 5. Among the aspects that would need to be considered are:

- The permissible fraction of the cable life where temperatures above 90°C would be permitted and how that could be assessed
- Whether any changes to existing pre-qualification and type tests would be needed beyond increasing the temperatures during the heating cycle voltage tests.
- Any knock-on impacts on other cable system materials and how they might be assessed
- Acceptance criteria related to thermomechanical response, especially for cables with wire screens.

Any such development would need to be done carefully, driven by a functional analysis approach to identifying what impacts an increment in conductor temperature could have on the cable performance.

7.1 Research Gaps

In addition to the qualification aspects discussed above, the following gaps have been identified which merit further attention from the research community:

- Monitoring of very long cable systems, in particular gaining a full understanding of the uncertainty inherent in the measurements and how that needs to be factored in to cable system operation.

- Experimental evidence of the long term ageing behaviour of insulation interfaces under thermal cycling to build upon existing published work from modelling and smaller scale laboratory tests.
- Attention on how accelerated ageing tests can be applied to practical applications, focusing in particular on modern ultra-clean XLPE compounds. In particular this should focus on physical processes which might be triggered by the accelerated ageing tests, but which may be different in service at lower stress levels. This would facilitate assessment of how the periods at higher temperature might affect the ageing of the insulation, subject to the actual loads seen in the service life of the cable.
- Reassessment of the thermomechanical evidence published in the past and extrapolation (where possible) to the behaviour of modern systems.

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