Insulation Reliability of Superconductive Cables

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Abstract- High current capability, good integration in urban area and zero external magnetic field are advantages of HTS cables that make them interesting for implementation in the Netherlands. So far experience with HTS cable projects is good, but still limited. Yet there is a need for a proper testing practice. Due to limited operational experience, various aspects remain to be studied. This paper focuses on electrical testing of electrical insulation, the application of power laws and the length effect. These issues are yet to be resolved, but the paper discusses their background and uncertainties. This may give direction to the ongoing studies in order to assure quality of HTS.

I. INTRODUCTION

High Temperature Superconductive (HTS) conductors, insulation for cryogenic systems as well as cryogenic systems for providing the required low temperature conditions have developed such that adequate grid components can be constructed. To date, the main superconductivity applications are medical equipment (mainly Magnetic Resonance Interferometry scanners) and large R&D facilities such as CERN and ITER. In these fields superconductivity enabled features like very intense magnetic fields that cannot be achieved with conventional copper windings. The vast application majority uses Low Temperature Superconductors (LTS) as yet, but with HTS becoming both better in quality and production more economic, superconductive components not only start to form an alternative for LTS in the existing applications, but also start finding their way into the electric power grid. Three types of equipment appear the most attractive: Fault Current Limiters (FCL), transformers and cables. With FCL and transformers the cooling is concentrated at a limited location and therefore easier to realize. Nevertheless, cables appear to be faster introduced despite the need of a more extended cooling system.

A. Advantages of Superconductive Cables

Superconductive cables feature several advantages over conventional cables. Three advantages of superconductive cables are very relevant to transmission grids: an enhanced current capability; a strongly reduced thermal interdependence with other infrastructure; and a strongly reduced external magnetic field.

As in many countries, there is a growing demand for undergrounding overhead lines (OHL) in urban areas. Though OHL are a very economical solution, such circuits require a relatively large right of way due to EM fields and visual impact. The favored alternative consists of underground cable circuits. However, at extra high voltage (EHV) levels such as the 380 kV OHL system in the Netherlands, present on-shore XLPE insulated cable technology reaches its practical limits of current capability. The reason is that the conductor diameter is limited to allow reeling for road transport. On the other hand, EHV requires thicker electrical insulation, which generally, also has a lower thermal conductivity and is less able to drain off the conductor heat. EHV and long cable length also require a higher capacitive current. This combination of effects limits the length and current capability of EHV cables. The enhanced current capability of superconductive cables can solve this.

Replacing OHL in urban areas by underground cable requires intertwining cables in the already dense underground infrastructures that consist of water pipes, gas pipes, sewage systems, telecom cables and lower voltage cable systems. Generally, HV and EHV cables need to drain off their heat which requires crucial space that may be a problem. For HTS cables the thermal interdependence with other infrastructure is largely overcome by the cryostats that thermally insulate superconductive cables from their surroundings. Meanwhile there is also no need to drain off heat locally.

Both OHL and underground cable systems emit a magnetic field. Cable phases can be closer together which reduces the area where magnetic fields may exceed the limit of 100 µT or the presently used level of 0.4 µT for OHL at areas where children may reside. For (E)HV cables generally single phase cables are used. With superconductive cables the earth screen can be used as a return conductor which compensates the magnetic field of each phase conductor. As a result superconductive cables prevent external magnetic fields.

B. The Supernet NL project

The above mentioned advantages led to the definition of the Supernet NL project in the Netherlands. The project aims at laying a HTS 110 kV cable with a length of about 3.4 km. The purpose of the project is to demonstrate to what extent HTS cables can be incorporated in the existing grid and are ready to compete with XLPE cables at the top of the market. If the demonstration is successful, HTS cables become a realistic option in future cable laying projects. So, the project is rather a qualification project than a technology pilot project; it aims at Technology Readiness Level (TRL) 8 up to 9, i.e. a product qualified in an operational environment or product up to being a successfully implemented serial product.

The project is supported by the Dutch Ministry of Economic Affairs and concerns various work packages where the utility TenneT works together with universities and expert partners to mobilize expertise for decision-making. The knowledge partners in the consortium are TU Delft for electric and magnetic behavior, University of Twente for cryogenic aspects, HAN University of Applied Science for monitoring and sensing, IWO (Institute for Science and Development) for reliability and availability, RH Marine for system integration aspects.

C. Concerns with Superconductive Cables

Concerns with superconductive cables at this stage relate to the pricing of superconductive systems on the one hand and to uncertainties and inexperience with the required cryogenic system and with electrical testing on the other hand.

As for pricing, at this stage a ceiling is set not only for a go/no-go decision, but particularly to promote the design of an economically realistic HTS cable solution that can earn a place in the market and the grid based on added value.

The cryogenic system is as yet unknown in the conventional grid. Its maintenance, efficiency and reliability (including testing) are subject of investigations.

As for electric testing, by far most of the pilot projects in the world were successful. However, compared to XLPE and paper-oil insulated cable there is too little experience with superconductive cable in practice to provide a statistical base for testing. Electric testing is the main focus of this paper.

II. TESTING

One of the work packages in the Supernet NL project is "Reliability and Availability". The aim is to achieve a similar quality as with the conventionally used XLPE insulated 110 kV cables. In the TenneT grid present cables are specified to endure at least 50 years of service. However the actual warranty period is limited and the quality is assured by testing.

The type testing of cable systems with extruded insulation in the voltage range 36-150 kV is described in IEC 60840 [1]. Testing of paper insulated cable is described in IEC 60141 [2]. For XLPE insulated cable it is hard to evaluate the 50 year long lifetime as no XLPE insulated EHV cables have reached this minimum lifetime. With paper insulation various cables have reached that lifetime successfully, but some cables failed to reach the expected life time. IEC develops a standard for HTS cable systems based on the standards above and two Cigré Technical Brochures 538 and 644 [3,4].

Various tests are described in [1] and [2]. Distinguished are:
- Routine test: on each manufactured component to check that it meets the specifications
- Sample test: on samples of completed cable or components at a specified frequency to meet the specifications
- Type test: on a type of cable system or cable or accessory to demonstrate satisfactory performance characteristics for application before supplying on a general commercial basis

- Pre-qualification (PQ) test and extended PQ test: on a type of cable system to demonstrate satisfactory long term performance of the complete cable system before supplying on a general commercial basis
- Test after installation: on a cable system as installed to demonstrate its integrity

These tests cover a wide range of aspects including non-electrical tests. The present paper particularly focuses on insulation and aspects to assess its reliability.

A. Insulation Ageing

The major aging mechanisms in XLPE insulated cable operated in dry condition concern electrical, thermal, mechanical and ambient stresses. It may be noted that in theory XLPE insulation is a homogeneous material though this may not be true in practice due to production flaws.

In accessories (joints and terminations) electric fields exist that are partly along interfaces of different polymeric materials. As a consequence interface discharging may occur which is an important failure mechanism in XLPE insulated cable systems. This mechanism can be enhanced by thermal and mechanical effects.

Older AC cable (and present DC cable) types often have paper-oil insulation. Such insulation systems are inherently a composite insulation of oil and paper. Discharges may occur in the insulation interfaces as an additional mechanism.

Intrinsic ageing and discharges in voids is common to all types of insulation. Various factors may influence this ageing.

B. Modelling of ageing

The rate of failure of many components with time follows a well-characterized pattern: an early high failure rate (child mortality), a period with low constant rate of failure (random failure or useful life) and finally a high failure rate near the end of the life (wear out) [5]. The hazard rate then shows a pattern that is known as the bathtub model.

Degradation mechanisms that can be regarded as weakest-link-in-chain processes normally follow a Weibull distribution model:

$$F(t) = 1 - \exp\left(-\left(\frac{t}{\alpha}\right)^{\beta}\right) \qquad (1)$$

with α and β the Weibull scale and shape parameter. Usually the three stages child mortality, random failure and wear out are related to the shape parameter values $\beta<1$, $\beta=1$ and $\beta>1$. Provided these processes compete in all products, the hazard rates can be summed to yield the well-known bath tub shaped hazard rate curve mentioned above. However, identifying child mortality with $\beta_{cm}<1$ often appears a misconception [6]. Child mortality products usually suffer from production and/or installation flaws that make them wear out considerably faster than products that are conform specification. This then means that $\beta_{cm}>1$, but particularly the observed α_{cm} is significantly smaller than the specified α and the intended operational lifetime. Such products usually form a sub-population that is soon extinguished (Fig. 1), but should have been removed by quality control, while the remaining batch lives longer.
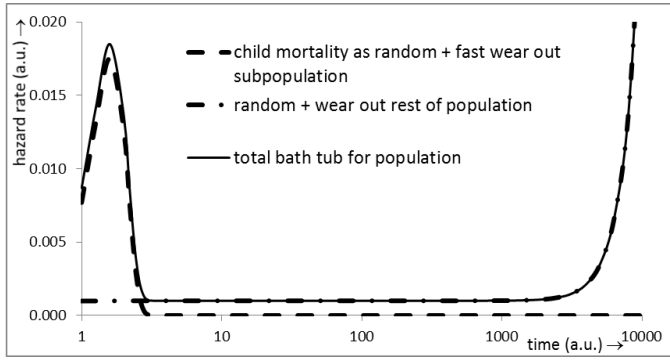
Fig. 1. Hazard rate plot of an example batch where 98% has a Weibull distribution of α=4000 a.u. and β=4.5 and 2% has α=1.75 a.u. and β=4. Both also feature random failure with α=1000 a.u. and β=1 (i.e. exponential distribution). The 2% form the child mortality subpopulation here. This bath tub is an often occurring alternative to the bath tub with β<1, β=1 and β>1 [6]. It typically features a finite hazard rate at t=0 and an early peak.

For single and multi-stress ageing the Weibull distribution can be often extended with one or multiple stress terms.

$$F(t,E,..)=1-\exp\left(-\left(\frac{t}{\alpha_t}\right)^{\beta_t}\left(\frac{E}{\alpha_E}\right)^{\beta_E}..\right) \qquad (2)$$

If all stress terms except the variable time are kept constant, then the equation can be rewritten in the single variable form of (1), where α then incorporates the other variables, scale parameters and shape parameters.

C. Accelerated ageing in testing

In order to perform type tests in a reasonable amount of time the ageing conditions are enhanced in order to accelerate ageing and represent operational life in a relatively short testing time. The test time with enhanced stresses should be as short as possible while preserving representative ageing of the cable under actual service conditions [7].

Testing usually consists of a program of enhanced stress levels like voltage amplitude, various voltage shapes, temperature etcetera. In the case of a conventional cable, subjecting the cable to enhanced electric stresses is the most effective way [7]. Using a range of stresses E_i will yield a range of times to failure t_i. Generally a well-known power law (PL) relationship (3) between the E and t is found (also called "inverse power law" if t and E are on different sides of the equation). The ruling equation is:

$$(E_{test})^p \times t_{test} = (E_0)^p t_0 = const. \qquad (3)$$

With E a specified stress, E_{test} the stress level at testing, t_{test} the testing duration time, E_0 the rated stress level, t_0 the corresponding time at rated stress level and p the power of the power law. If the PL applies, then plotting the test results of E versus t in a log-log plot yields a sloped straight line (Fig. 2). The power value p follows from the slope of the E-t plot. Once the value of power p is known a time to failure t_{test} at stress level E_{test} can be calculated back to a corresponding time to failure t_0 at rated stress E_0:

$$t_0 = \left(\frac{E_{test}}{E_0}\right)^p \times t_{test} \qquad (4)$$
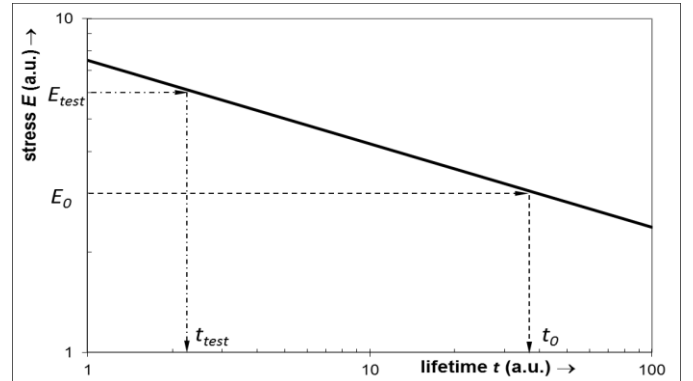

Fig. 2. Example of a power law relationship of (3). Enhancing the rated stress E_0 to the test stress E_{test} accelerates the time to breakdown from t_0 to t_{test}.

If a PL is known, but the test period t_{test} ends without failure the PL can still be used to calculate a t_0, which can be regarded as a warranted period without failure.

Various ageing mechanisms such as intrinsic insulation breakdown, partial discharge etc. can occur in a cable. Enhancing the stress can accelerate the various mechanisms to a different degree, i.e. each type of ageing mechanism, stress and material(s) combination will generally have its own p-value. Tests should therefore be well designed.

The PL is extensively used in the conventional cable system and p-values (using electrical stress as a control parameter) are obtained for the following degradation processes [7,8]:

- water treeing: $2 \leq p \leq 4$
- partial-discharge induced degradation: $p \sim 4$
- contaminant effects in polymer insulation in real cable under dry conditions: $8 \leq p \leq 10$ (often $p\sim9$ is taken as average)
- deterioration mechanisms in high-purity polymer cables with smooth extruded semiconducting shields: $p \geq 15$

Such p-values are usually determined by breakdown test with a ramped voltage, i.e. the electric stresses are linearly increased with time. Assuming a Weibull distribution as in (1), the p-values can conveniently be derived.

Power values are known for electrical ageing of conventional insulating materials and also for various cryogenic materials [9,10]. For HTS insulation materials, p-values are considerably higher than $p\sim9$. These relate to intrinsic ageing and the presently developed IEC standard for HTS cable might seem to be quite severe, but other types of ageing may have lower p-values as shown above. The p-values for new systems and materials should be checked. Actually, the same holds for insulating materials that are further developed. The sensitivity to enhanced stress levels i.e. the p-value, may change with material development, even when the type of ageing is in principle the same. At this stage, R&D results are required to assess the sensitivity to enhanced test stresses.

In addition to the power law, also thermal excitation may accelerate degradation processes. Generally, it is assumed that chemical degradation in HTS cable is of minor importance because of the cryogenic temperature [11]. Still, if relevant, remaining life (and α) relate to an activation energy ΔH [12]:

$$t_{remaining} = A \cdot \exp(\Delta H / kT) \qquad (5)$$

Here, A is a (time) constant, T the absolute temperature and k the Boltzmann constant. The electrical insulation near terminations is exposed to non-cryogenic temperatures and HTS cable systems may be stronger influenced by thermal fluctuations. An important concern is the mechanical force on insulation tape due to thermal shrinkage and expansion in thermal cycling which as such is not covered by (5).

Frequency is also a stress parameter that can accelerate ageing particularly where zero-crossings and slope of the voltage matter. It is usually less efficient than voltage.

Other parameters that can accelerate ageing are pressure, area, bubble formation. These act on the coolant Liquid Nitrogen (LN_2). Part of these accelerated factors are typical for material research, but others are incorporated in type tests.

D. Cable length versus test sample length

Type tests are performed on complete installations consisting of cable lengths with minimum 10 m length. The minimum length between adjacent accessories is 5 m [1,2]. As type tests require that no breakdown occurs the above mentioned situation applies that no actual time to failure is determined and even with known PL no time to failure at E_0 is found. If also the p-value is not known, then the type test is hardly informative about minimum expected time to breakdown.

Provided testing is carried out and also an adequate PL is known, then a time to breakdown or warranted time without failure $t_{0,sample}$ is found for a test sample length L_{sample}. A circuit length of cable L_{cable} is usually much longer and is then likely to fail earlier at $t_{0,cable} < t_{0,sample}$. Provided ageing follows a Weibull distribution as in (1), it can be shown that:

$$t_{0,\text{cable}} = t_{0,\text{sample}} \cdot \left(\frac{L_{\text{sample}}}{L_{\text{cable}}} \right)^{1/\beta} \qquad (6)$$

The longer the cable circuit the more reliable a cable sample should be for statistical reasons. If the failure distribution is more complicated than in (1), so it may be in (6). This length effect is not as straight forward as it seems. A test length will generally contain at least 10 m cable, two terminations and minimum 1 joint. Scaling up to a full length cable increases the cable length and number of joints (albeit not in the same ratio), but not the number of terminations. Eq.(6) is therefore a simplification of the relation between sample and circuit. A type test and PQ test both aim at evidencing production reliability conform to existing experience. Both type testing and translation to long cable length are matters of study as yet.

III. DISCUSSION AND RECOMMENDATIONS

Although the experience with HTS cables is good, long term experience must grow. It is common practice to build on experience with previous generations of cables as [1] is founded on [2]. HTS cables resemble polymer insulated cables, but maybe even resemble more paper-oil insulated cable, as they have a liquid-taped composite insulation.

Besides the need for assuring the quality of the cryogenic system and complications at the temperature transition points there are a number of issues related to testing the electrical insulation components and cables in particular. Recognizing that there is a lack of data and knowledge on the behavior of dielectrics and electrical insulation systems at cryogenic temperatures, Cigré started WG D1.64 to: summarize the state-of-the-art; study HTS electrical insulation phenomena and major design and test issues for electrical insulation systems. The focus is not only on cables but also on other superconductive apparatus.

Based on the present analysis the following issues are recommended for further study in relation to Supernet NL:

- Which ageing phenomena need further attention in testing: intrinsic insulation strength, interfaces between LN_2 and insulation tape, effect of possible discharging in gaseous N_2 bubbles, etc.
- Effects on the insulation (e.g. cracking of tape) due to thermal contraction and expansion of the cable and the insulation itself when cooling down to cryogenic temperature respectively heating up to room temperature.
- Determination of p-values for power laws as well as enhanced stress levels to accelerate ageing in type testing
- Sensible mix of enhanced stress tests to cover realistic operational ageing.
- Length effect in relation to required stress levels.

For the moment the IEC draft HTS cable standard is the most practical way to assess cable quality, but access to other test data from R&D will be necessary to gain confidence in long-term performance. Additional material or ageing test results will most likely be required in the project.

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