# Reliability considerations of electrical insulation systems in superconducting cables

Gholizad, Babak; Ross, Robert; Koopmans, G.; Mousavi Gargari, S.; Smit, Johan; Ghaffarian Niasar, Mohamad; Meijer, C. G.; Bucurenciu, A. M.

**DOI**
10.1109/ICPADM.2018.8401183

**Publication date**
2018

**Document Version**
Final published version

**Published in**
12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)

# Reliability Considerations of Electrical Insulation Systems in Superconducting Cables

B. Gholizad[1], R. Ross[1,2], G. Koopmans[3], S. Mousavi Gargari[2], J. J. Smit[1,3], M. Ghaffarian Niasar[1], C. Meijer[4], and A. M. Bucurenciu[4]

[1] TU Delft, Mekelweg 4, 2628 CD Delft, Netherlands
[2] TenneT TSO, Utrechtseweg 310, 6812AR Arnhem, Netherlands
[3] IWO, Zweerslaan 46, 6711GG Ede, Netherlands
[4] RH Marine Netherlands B.V. , Jan Evertsenweg 2, NL-3115 JA, Schiedam, Netherlands

*Abstract-* **Advantages of HTS cables are higher current carrying capability, very low thermal interaction with underground infrastructures, and very low external magnetic field designs. These advantages make them interesting for implementation in dense urban areas. There are several experiences worldwide with HTS cables at various voltage levels, but the long-term experience is still limited. As a result, various aspects of HTS performance, such as long-term reliability, are unclear and further study is required. This paper provides an overview of insulation materials, background, and uncertainties of recommended electrical insulation testing. The application of power law and the length effect will be discussed. This discussion may help to give direction and assure the quality of HTS cable for ongoing studies.**

## I. Introduction

Higher demand for electrical power and access to renewables require higher power transfer capability of the power system. The power transfer capability of the power system in HVAC and HVDC transmission system mainly depends on surge impedance and resistive losses of the system, respectively. In urban areas, the transmission system is possible with HV and EHV cables, while about overhead lines (OHL) disputes arise due to the higher right of way, the visual impact and EMF [1] and [2]. On the other hand environmental issues of gas insulated and oil-filled lines restrict their application and a polymeric insulation system with lower thermal conductivity remains the main choice. EHV cables require thicker polymeric insulation, and therefore the cables will have less ability to drain off the conductor's heat. In order to reduce the generated Joule losses of the cable, limits apply to the conductor engineering current density. Also, the diameter of the conductor is limited because of transportation requirements.

The higher engineering current density of high-temperature superconducting tapes (HTS cable) overrides the values of conventional conductors (i.e. Cu and Al) by an order of magnitude. Moreover, the increasing quality of HTS tapes and almost the absence thermal interaction between the HTS cable and existing underground infrastructure enables the integration of the HTS cable in the power system [1]. Due to several successful demonstrating HTS cable project worldwide and the experience of the manufacturers, the HTS cable system is going to be commercialized [3]. The application of an HTS cable system requires specific HV testing and measurement techniques to test its components. However, the field experience with HTS cable is not sufficient yet to provide a statistical base for testing [1]. As for testing, Cigré released recommendations for testing HTS cable, technical brochure TB 538 [4]. More recently, IEC TC90 working group released the committee draft of IEC 63075 standard for testing HTS cable based on TB 538, IEC Standard 60840, IEC standard 60141, IEC standard 62067, and Cigré TB 538.

However, the foreseen applications of the HTS devices is not just the cables, but may also include superconducting fault current limiters, superconducting transformers, and rotating machines. At the moment, two active working groups of Cigré, WG D1. 64 and WG D1. 69 are studying the electrical insulation techniques and guidelines for testing techniques of HTS devices, respectively.

This paper discusses the long-term property of the HTS cable insulation system, and how the present testing addresses the aging behavior of that insulation in cryogenic temperature.

## II. Insulation System Behavior at Cryogenic Temperature

Aging in the polymeric electrical insulation is defined as the irreversible changes in the polymeric dielectric material structure due to chemical and physical degradation processes [5]. These changes increase the chance of failure with time. The major aging mechanisms in polymer insulated cable operated in dry condition are caused by the electrical, thermal and mechanical stresses applied to the insulation system.

It is agreed that the chemical degradation rate in HTS cable is very slow and negligible because of the cryogenic temperature (77 K) [6]. However, electrical insulation in the terminations experiences a temperature between cryogenic temperature and room temperature, therefore, a chemical degradation mechanism still could deteriorate the insulation at that location; also the large temperature difference (~230 °K) at cooling down and warming up could deteriorate the cable mechanically by means of cracking or tape migration [7].

978-1-5386-5788-1/18/$31.00 ©2018 IEEE

Breakdown strength of liquid nitrogen ($LN_2$) as the impregnant and coolant in HTS cable for various conditions is reported in the literature [8] and [9]. It is found out that the breakdown field strength of $LN_2$ is comparable to the dielectric strength of insulation oil and can reach several tens of kV/mm [10]. However, the breakdown strength will vary, depending on temperature, pressure, area and volume effect, bubble formation, the geometry of the electrodes and partial discharge (PD) in $LN_2$. Lower operating temperature and higher pressure could increase the breakdown strength of $LN_2$ [11].

Breakdown strength of polymeric insulation materials at cryogenic environment are reported in several publications [6], [7] and [12]-[14]. It is reported that increasing the frequency will decrease the breakdown strength of material [7]. Also, the effect of tensile strength on the breakdown strength of the material for AC and impulse breakdown is quite small [13]. AC breakdown voltage of material impregnated with $LN_2$ depends on the pressure of $LN_2$. For pressures higher than 7 bar the breakdown voltage of the materials will be saturated [6]. The PD inception voltage of the composite insulation (solid material and $LN_2$) will increase with increasing $LN_2$ pressure [6]. Finally, the number of layers of the insulation sheets will decrease the breakdown strength of the insulation [14].

Electrical and mechanical (e.g. tensile and contraction of the material) stresses in the HTS cable are the main aging mechanisms and the chemical reaction has a negligible effect; but, all electrical, mechanical and chemical stresses should be considered for the termination. Careful design of the insulation system could reduce the aging of the insulation material and increase the lifetime.

## III. Lifetime Modelling of HTS Cable

Accelerated aging tests are carried out on the power cable to predict its life expectancy under in-service operating conditions on the basis of a reasonably short test time. The stress level is elevated, but not to the extent that the aging mechanism of the cable under actual service condition is altered [16].

Testing usually consists of a program of accelerated testing at enhanced stress levels being voltage amplitude at various voltage shapes, temperature etcetera. In the case of the conventional cable, subjecting the cable to enhanced electric field stresses is the most effective way [16].

In such accelerated aging tests, the control parameter $E$ (e.g. electrical stress) is used to determine the variable parameter $t$ (time to failure). The assumed relationship between $E$ and $t$ is the well-known power law (also called inverse power law, in short IPL). Through a power law, the testing time at such stress levels is usually translated into a lifetime at the rated stress level. The ruling equation is:

$$(E_{test})^p \times t_{test} = (E_0)^p t_0 = const. \quad (1)$$

With $E$ a specified stress, $E_{test}$ the stress level at testing, $t_{test}$ the testing duration, $E_0$ the rated stress level, $t_0$ the corresponding time at rated stress level, and $p$ the power or exponent of the power law. Granted the power law applies and given $E_{test}$, $t_{test}$, $E_0$, and $p$ are known the equivalent $t_0$ follows as:

$$t_0 = (E_{test}/E_0)^p \times t_{test} \quad (2)$$

Each type of acceleration can accelerate one or more aging mechanisms and will feature a characteristic exponent for that type of acceleration. One should be very careful with choosing the $p$-value in the IPL, where it strongly depends on the type of the insulation system and manufacturing process. Also, it should be based on experimental ground data and understanding of the aging processes that are active at the various stress levels [17].

If the IPL with electrical stress as the control parameter is deemed applicable, the exponent $p$ is estimated as follows. The test results are plotted in log(V)-log(t) coordinates, to which a straight line is fitted with slope -1/$p$.

IPL is extensively used in the conventional cable system and the values of $p$ for different degradation processes (using electrical stress as a control parameter) are obtained [5] and [16]:

1. for water trees $2 \leq p \leq 4$
2. for partial-discharge induced degradation $p$ is ~4
3. for contaminant effect in the polymer under dry condition $8 \leq p \leq 10$
4. for deterioration mechanisms in high-purity polymer cables with smooth extruded semiconducting shields $p \geq 15$

Exponent values are known for the electrical aging of conventional insulating materials and various cryogenic materials [18], but what exponent values should be adopted for systems is still a matter of study.

In the case of HTS cable, the $p$-value is very sensitive to the presence of PD [19]. The $p$-value equal to 50 in PD free PPLP insulated HTS model cable is reported in [20]. Besides, the enlargement law for scaling model cable to longer lengths of the cable is not well established [7].

New power system equipment design starts with model design. Model insulations are tested prior to the final design of the insulation. Then, several quality tests should be done to demonstrate and verify the quality of the design and production. And finally, the installed (assembled) system should be tested to check defects of the insulation system due to transportation and assembly. The stresses during the test programs should represent the characteristic stresses in service. The levels of stresses and testing duration are based on the lifetime modeling of the cable. These tests could be categorized as follows

- prequalification
- routine test
- sample test
- type test
- after installation test

There is no standardized test for HTS cable. Cigré TB 538 recommended different tests based on IEC Standard 60840 for cables with extruded insulation. IEC develops a standard for

HTS cable systems bases IEC standard 60840, IEC standard 60141, IEC standard 62067, and Cigré TB 538.

A prequalification test is part of standard tests, which demonstrates the reliability of the component for long-term use under normal operating condition. Such a test is absent in Cigré TB 538. The prequalification test is used in IEC Standard 62067 to compensate the lack of experience with extra high voltage XLPE cable.

Type Test in Cigré TB 538 is based on IEC Standard 60840 with an additional pressure test and vacuum leak tests. Cigré TB 538 specified maximum 10 pC as an acceptable level of PD measurement sensitivity in Type Test. The better sensitivity of PD measurement should assure the PD free operation of the cable during its lifetime. However, as discussed in [21], in IEC Standard 62067 the approach to calculating the stress levels in the prequalification test and type test is not consistent. In other words, type test does not qualify the electrical insulation system at an aging level equivalent to the designed lifetime of the cable.

## IV. Reliability COnsiderations of HTS Cable Insulation

The rate of failure of many components follows a well-characterized pattern: an early high failure rate (child/infant mortality), a long period with a low constant rate of failure (useful life) and finally a high failure rate near the end of the life (wear out) [12]. This pattern is well-known as bathtub model (Fig. 1).

For estimating the cable insulation reliability the results of accelerated aging tests on small samples should fit on the bathtub curve. Most often Weibull distribution is used for this fitting [15].

The cumulative distribution $F$ describes the failed portion of the population and reliability $R$ describes the surviving portion [15].

$$F(t) = 1 - \exp[-(t/\alpha)^{\beta}] = 1 - R(t) \quad (3)$$

where $\alpha$ and $\beta$ are the scale and shape parameter of Weibull distribution, respectively. The mean time to failure (MTTF) $\theta$ is:

$$\theta = \alpha \cdot \Gamma(1 + 1/\beta) \quad (4)$$

with $\Gamma(x)$ the Gamma-function. If $\beta$=1 then the Weibull reduces to the Exponential distribution [15]:

$$\beta = 1 \;\; \Rightarrow \;\; \theta = \alpha \cdot \Gamma(1 + 1/\beta) = \alpha \cdot \Gamma(2) = \alpha \\ \Rightarrow \;\; F(t) = 1 - \exp[-(t/\alpha)] \quad (5)$$

The Weibull density distribution *f(t)* describes how many failures occur per unit time. It is the derivative of the cumulative Weibull distribution. It is noteworthy that *F(t)* and *f(t)* may describe the complete asset population, but not necessarily the failure probability of an individual asset [15].

The hazard rate *h(t)* describes the failure rate of the surviving portion. If the assets cannot be distinguished, then *h(t)* is a measure that a randomly selected (yet operational) item fails per unit time [15]:

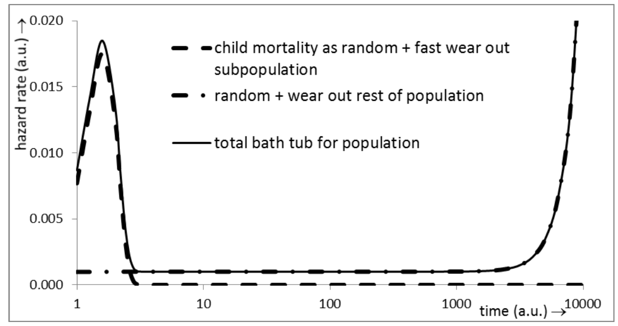


Fig. 1. Hazard rate plot of an example batch where 98% has a Weibull distribution of α=4000 a.u. and β=4.5 and 2% has α=1.75 a.u. and β=4. Both also feature random failure with α=1000 a.u. and β=1 (i.e. exponential distribution). The 2% form the child mortality subpopulation here. This bathtub is an often occurring alternative to the bathtub with β<1, β=1 and β>1 [15]. It typically features a finite hazard rate at *t*=0 and an early peak.

$$h(t) = \frac{f(t)}{R(t)} = \frac{\beta \cdot t^{\beta - 1}}{\alpha^{\beta}} \quad (6)$$

It is often pointed out that *h(t)* increases with time when $\beta$ >1 indicating a wear out process; $\beta$ =1 indicates a random failure process (Exponential distribution) featuring a constant hazard rate; and that $\beta$ <1 indicates a child mortality process. However, child mortality processes do not need to have $\beta$ <1 in the Weibull distribution [15]. Many child mortality cases concern a subpopulation with lower strength than specified due to manufacturing defects (see Fig 1). This weaker fraction will fail early and dies out. This subpopulation may very well appear to have $\beta$ >1 and a very low $\alpha$ compared to the rest of the population [15].

To prevent as much as possible the child mortality installed in the power system precise quality testing plays an important role.

## V. Discussion

Published results of tests of model designs, demonstration projects worldwide, and continued operation of already installed projects could not make an experimental ground to model the lifetime and understand the in-service stresses of the HTS cables. In this situation, using available data of the conventional cables which could resemble the HTS cable is the most practical way to assess the quality of the HTS cable and build up the required actions and Standards. However, -questions were raised about the validity of assumptions even for present testing of conventional cables.

There are several issues related to the testing of the electrical insulation system in the complicated cryogenic environment. Most of the available publications address the test and successful operation of the electrical insulation samples in the laboratory testing facilities. Testing of complete cable systems needs more attention for the future work.

The following is recommended for further study:

- Exploring the dominant aging phenomena which need further attention in testing, such as intrinsic insulation strength, interfaces between $LN_2$ and insulation tape, the effect of possible discharging in gaseous $N_2$ bubbles, etc.

- Thermal contraction and expansion effects on the insulation (e.g. cracking of tape) due to the cooling down and heating up procedure, respectively.
- Determination of *p*-values for power law and enhanced stress levels in type testing.
- The relation between the length of the cable and stress levels of the insulation system.
- Testing of the cryostat and cooling system and lifetime estimation of it.
- Analyzing failure modes and repair strategy for different failures.

Generally, standardized tests are the most practical way to assess cable quality. In the case of HTS cable, besides the IEC draft, to gain confidence in long-term performance, access to more test data and further R&D is necessary. Additional material or aging test results of the insulation system will most likely be required in the future projects.

## References


[1] R. Ross, B. Gholizad, G. Koopmans, S. Mousavi Gargari, J. J. Smit, M. Ghaffarina Niasar, C. G. Meijer, A. M. Bucurenciu "Insulation Reliability of Superconductive Cables" *1st International Conference on Electrical Materials and Power equipment* (ICEMPE), 2017, Xi'an, China, pp. 20-23

[2] R. Zuijderduin "Integration of High-Tc Superconducting Cables in the Dutch Power Grid of the Future" Ph.D. dissertation, Dept. of Electrical Sustainable Energy, TU Delft, Delft, The Netherlands, 2016, doi:10.4233/uuid:7fd7e28a-f700-4da6-8daa-bc554de71390

[3] M. Noe, "Superconducting Cables" EUCAS 2017, 17-21 September 2017, Geneva, Switzerland

[4] "Recommendations for testing of superconducting cables" *CIGRE Technical Brochure 538, Working Group B1.31*, 2013

[5] R.J. Densley, R. Bartnikas, and B. Bernstein "Multiple Stress Aging of Solid-Dielectric Extruded Dry-Cured Insulation Systems for Power Transmission Cables" *IEEE Transactions on Power Delivery* Vol. 9 No. 1, pp. 559-571, January 1994

[6] H. Suzuki, T. Takahashi, T. Okamoto, and S. Akita "Electrical Insulation Characteristics of Cold Dielectric High Temperature Superconducting Cable" *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 9, No. 6, pp. 952-957, December 2002

[7] "Common characteristics and emerging test techniques for high temperature superconducting power equipment" *CIGRE Technical Brochure 644*, Working Group D1.38, 2015, ISBN: 978-2-85873-347-7

[8] I. Sauers, E. Tuncer, "Strategic Dielectrics R&D for HTS and other OE Applications", *DOE Peer Review*, 2008, available at http://web.ornl.gov/sci/fed/cryogenic/2009CDIPeerReview.pdf

[9] D.J. Swaffield, P.L. Lewin, G. Chen, S.G. Swingler, "Partial Discharge Characterization of Streamers in Liquid Nitrogen under Applied AC Voltages" *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 15, No. 3, pp. 635-646, June 2008

[10] J. Gerhold, "Potential of Cryogenic Liquids for Future Power Equipment Insulation", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 9, No. 6, pp. 878-890, December 2002

[11] S. Nishimachi, N. Hayakawa, H. Kojima, M. Hanai, and H. Okubo "Pressure and Temperature Dependence of Breakdown Characteristics of Sub-Cooled Liquid Nitrogen" *Annual Report Conference on Electrical Insulation and Dielectric Phenomena* (CEIDP), pp. 440-443, 14-17 October 2012, Montreal, QC, Canada

[12] E. B. Forsyth "The Dielectric Insulation of Superconducting Power Cables" *Proceedings of the IEEE*, Vol 79, No. 1, pp. 31-40, January 1991

[13] X. Yang, M. Song, K. N. Cao, D. D. Wang, and B. Wei "Dielectric Characteristics of Laminated Paper and Polymer Sheets Used for Lapping Dielectric Structure at 77 K" *IEEE Transactions on applied superconductivity*, VOL. 24, NO. 5, Article Sequence Number 9002604, October 2014

[14] H. G. Cheon, D S Kwag, J. H. Choi, H. J. Kim, J. W. Cho, and S. H. Kim "A study on thickness effect of HTS cable for insulation design" Journal of Physics: *Conference Series 43 (2006) 889-892, 7th European Conference on Applied Superconductivity*, doi:10.1088/1742-6596/43/1/217

[15] R. Ross, "Evaluating methods for detecting end-of-life and non-compliance of asset populations" SCD1 *Colloquium, Trends in Technology, Materials, Testing, and Diagnostics Applied to Electric Power Systems*, pp. 1-6, Rio de Janeiro, Brazil, September 13-18, 2015

[16] R. Bartnikas, K. D. Srivastava, *Power and communication cables: Theory and Applications*, IEEE-WILEY, 2000

[17] G. Mazzanti, M. Marzinotto, *Extruded cables for high-voltage direct-current transmission: Advanced in Research and development*, IEEE-WILEY, 2013

[18] M. O. Pace, I. Sauers, D. R. James, and A. R. Ellis, "Aging of lapped tape insulated model cables at cryogenic temperature", *IEEE, Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp. 27-30, October 2002

[19] A. T. Bulinsky and J. R. Densley "High voltage insulation for power cables utilizing high temperature superconductivity," *IEEE 6th International Conference on Conduction and Breakdown in Solid Dielectrics* (ICSD), pp. 397-400, June 22-25,1998, Vasteras, Sweden

[20] O. Maruyama, T. Ohkuma, T. Masuda, M. Ohya, S. Mukoyama, M. Yagi, T. Saitoh, N. Aoki, N. Amemiya, A. Ishiyama, and N. Hayakawa "Development of REBCO HTS power cables," *Physics Procedia*, Vol. 36, pages 1153-1158, 2012

[21] G. Mazzanti "What Have We Still to Learn about the Inverse Power Model?" *IEEE Conference on Electrical Insulation and Dielectric Phenomena* (CEIDP), 16-19 Oct. 2016, Toronto, ON. Canada, pp 959-962