Structure of Paper–Oil Insulation for Mass-Impregnated HVDC Cables

Link to the final, published version
https://ieeexplore.ieee.org/document/9009943

Citation
Gunnar Håkonseth, Knut Magne Furuheim, and Erling Ildstad, "Structure of Paper–Oil Insulation for Mass-Impregnated HVDC Cables," *2019 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Richland, Washington, USA, 2019.

Digital Object Identifier (DOI)
10.1109/CEIDP47102.2019.9009943

Structure of Paper–Oil Insulation for Mass-Impregnated HVDC Cables

G. Håkonseth*
Nexans Norway AS
PO Box 42
NO-1751 Halden, Norway

K.M. Furuheim
Nexans Norway AS
PO Box 42
NO-1751 Halden, Norway

E. Ildstad
Dept. of Electric Power Engineering
Norwegian University of Science
and Technology (NTNU)
NO-7491 Trondheim, Norway

*Also with Dept. of Electric Power Engineering, NTNU.

Abstract- **The electrical insulation in mass-impregnated high voltage direct current (HVDC) cables consists of many layers of paper tapes that are wound helically around the conductor and subsequently impregnated in oil. The oil fills the interstices between the fibers in the paper, as well as the larger gaps ("butt gaps") between the revolutions of the helices. In order to assess the electric field in such insulation, the insulation needs to be modeled either as a homogeneous material, or as a composite of several materials. One approach is to model the butt gaps as oil and the rest as a homogeneous material, without paying special attention to the interfaces between the butt gaps and the rest of the insulation. In this work, scanning electron microscopy (SEM) has been used to assess whether or not such an approach is appropriate. The results show that the internal structures in the impregnated paper tapes are much smaller than the paper-free butt gaps. Moreover, the internal structures contain paper–oil interfaces that are comparable to the interfaces between the butt gaps and the rest of the insulation. This justifies the mentioned approach.**

I. INTRODUCTION

Mass-impregnated cables are widely used for high voltage direct current (HVDC) interconnectors [1], [2]. In order to understand breakdown mechanisms and improve the design of such cables, it is important to know the electric field in the different parts of the insulation. The electric field distribution is determined by the applied voltage and the electric properties of the different parts of the insulation. Therefore, it is necessary to have a model that describes which part of the insulation has which electrical properties.

In this work, the terms "thickness" and "thick" are used only about dimensions parallel to the radial direction of the cable. The terms "width" and "wide" are mainly used for other dimensions.

The electrical insulation of mass-impregnated cables is made of additive-free kraft paper that is cut into tapes, approximately 10^{-4} m thick and approximately 10^{-2} m wide, and wound helically around the conductor. The winding is done neither edge to edge nor with any overlap, but with an approximately 10^{-3} m wide gap between the windings. These gaps are called "butt gaps", and they accommodate relative movement of the individual paper tapes during bending of the cable. Each layer of paper windings is staggered with respect to the underlying layer, so that the placement of butt gaps of two consecutive layers do not coincide with each other. This means that the butt gap thickness equals the paper thickness, while the butt gap width is determined by the lay length, radial position, and paper tape width. The lay direction is periodically changed, so for some of the layers, the lay direction is not the same as for the layer underneath. At those places, butt gaps will cross each other and cause a gap of double thickness at the crossings [1], [3].

The internal structure of the paper tapes is fibrous and irregular. The paper fibers are collapsed and fibrillated from the pulp refinement process. Therefore, the paper contains a network of channels in between the fibers.

The surface of paper is rough and irregular, so that the surfaces of the paper tapes of two adjacent layers are in contact with each other only at discrete spots. This leaves some space between the paper surfaces, except for at the contacting spots [4]. Such spaces will hereafter be called "surface gaps".

After the paper is wound around the conductor, the cable is impregnated under vacuum with a high-viscosity, oil-based compound (hereafter called "oil"). During impregnation, the oil fills the butt gaps, the channel network inside the paper tapes, and the surface gaps [1], [3]. In addition, it is likely that the oil wets the paper fibers also at the contacting spots, hindering direct contact between the paper tapes. This adds to the surface space.

A sketch of the insulation is shown in Fig. 1.

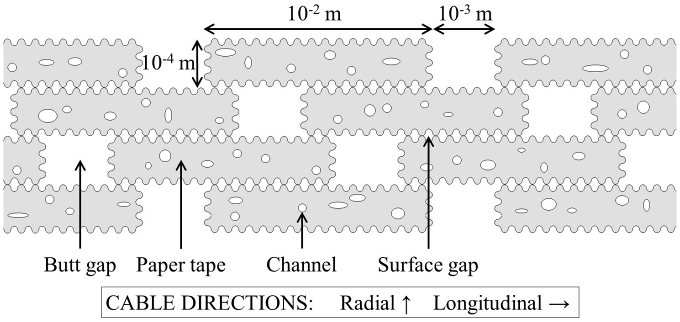

Fig. 1. Sketch of four layers of cable insulation. Cross-sections of rough and fibrous paper tapes are shown. Note that real paper surfaces are not as regular as shown here. The sketch is not to scale. Approximate lengths are indicated.

In various studies [5]–[7] of the electric field distribution in mass-impregnated cables, the main approach has been to regard the insulation as homogeneous. Such “one-material models” may take temperature gradients and cylindrical geometries into account, and this causes the electric field to be inhomogeneous.

In other studies [8]–[10], some of the heterogeneity of mass-impregnated insulation has been accounted for. The insulation has been modeled as a two-material composite, with the one material being *impregnated paper* and the other material being *oil*. The impregnated paper is considered a homogeneous material whose electrical properties are given by the combined action of the paper fibers and the oil in the channel network. This means that the internal structure of the paper is neglected. The butt gaps are modeled as oil—also this in itself considered a homogeneous material. In addition, the surface gaps may be modeled as a narrow oil gap between tapes of impregnated paper. Alternatively, these gaps may be neglected and thus be considered as part of the impregnated paper. In other words, this kind of models consist of oil gaps distributed in elsewise homogeneous impregnated paper, with each oil gap in itself being homogeneous. A consequence of this is that any interface between an oil gap and impregnated paper is modeled merely as an abrupt change of electrical properties. The neighborhood around the interface is not considered specially, i.e. it is considered no transition zone between the two materials. Such models will hereafter be called “semi-homogeneous models”.

A condition for semi-homogeneous models to be sound is that the widths of the channels, whose shapes are neglected, are considerably smaller than the oil gaps. Further, interfaces and their neighborhoods play a large role in charge transport and electric field distributions [7], [11]. It is therefore important to justify that the neighborhoods of the interfaces between the impregnated paper and the oil gaps are not considered specially.

In this work, scanning electron microscopy (SEM) images that show examples of paper structure are presented. Channel sizes are compared with the paper and butt gap thickness. Additionally, the presence of interfaces is discussed. In this way, it is assessed whether or not semi-homogeneous models can be justified.

II. METHOD

HVDC cable insulation paper without oil was used for surface and cross-section analysis. The nominal paper thickness was 90 µm.

Paper surfaces were examined by SEM without any other preparation than sputter coating of gold to make the specimens conductive. The microscope was operated in secondary electron mode.

Specimens for examining cross-sections were prepared in the following way: Pieces of paper were impregnated with epoxy in casting molds. The epoxy was subsequently cured in the molds to fixate the paper fibers. The epoxy casts containing the paper were cut and polished to achieve smooth cross-sections. The specimens were made conductive by coating them with a thin layer of carbon. The microscope was operated in back-scattered electrons mode to distinguish between the paper fibers and the epoxy that surrounded the fibers.

III. RESULTS

SEM images (micrographs) of paper surfaces are shown in Figs. 2 and 3, while SEM images of paper cross-sections are seen in Figs. 4 through 7. In Fig. 4, the angle of view is parallel to the cross direction[1] (CD). In Figs. 5 through 7, the angle of view is parallel to the machine direction[2] (MD). Since the fibers mainly are oriented more along MD than towards CD, they generally appear longer or wider when the angle of view is along CD than along MD. This can be seen by comparing Figs. 4 and 5.

In the surface images (Figs. 2 and 3), the largest fiber width is approximately 40 µm. In the cross-section images (Figs. 4 through 7), it appears that the fibers generally are wider than they are thick. This can be due to the fiber orientation and angle of view. It can also be a result of the collapsing and compression of the fibers during production of the paper.

The cross-section images (Figs. 4 through 7) show regions with various densities of fibers. They also show various channel thicknesses. The largest apparent channel thickness shown here is 14 µm (Fig. 6).

IV. DISCUSSION

The SEM images indicate that when impregnated with oil, paper contains large areas of fiber–oil interfaces. It is very likely that there are interfaces also on a smaller scale than what is visible in these images. When impregnated paper is considered a homogeneous material in a semi-homogeneous model as explained in Section I, it is implied that contributions from the interfaces in the bulk of the impregnated paper are incorporated in the electrical properties of that material. These interfaces are not essentially different from the interfaces between the tapes and the oil-filled butt gaps. Neither are they different from interfaces between the paper surfaces and the oil-filled surface gaps. Consequently, interfaces between impregnated paper and oil do not need to be treated separately in such models; they can simply be considered part of the impregnated paper.

Cross-section images hide much of the three-dimensional structure of the paper. A quantitative study of channel sizes based on SEM would require numerous images to be analyzed. Still, in the few images examined here, the observed channel thicknesses vary considerably. The thickest channel section measured on the present cross-section images was

---

[1] *Cross direction* is the direction in the paper plane perpendicular to the machine direction [12]. (See footnote 2.)

[2] *Machine direction* is the direction in a paper parallel to the direction of travel through the paper making machine [12]. It is the same as the circumferential direction of a paper roll and the longitudinal direction of the paper tapes. Since the lay length of the paper tapes around the cable is short, the machine direction roughly corresponds to the circumferential direction in the cable.

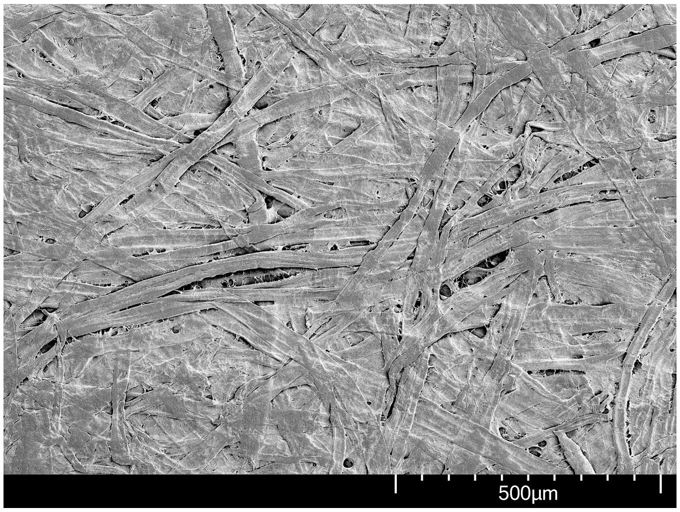

Fig. 2. SEM image of cable paper surface. Secondary electrons mode.

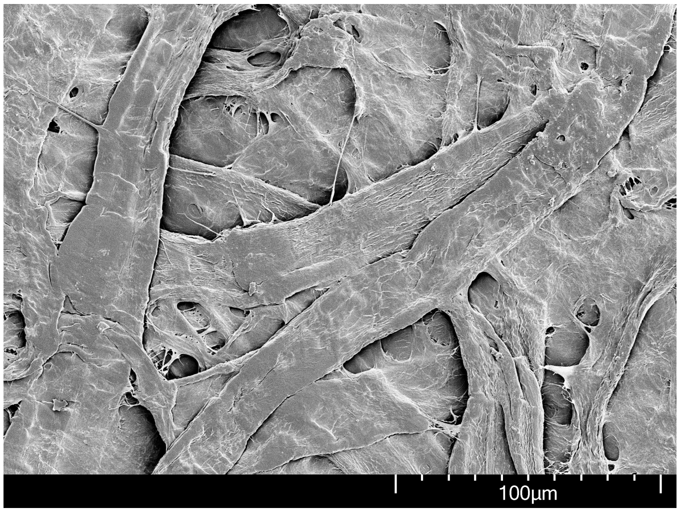

Fig. 3. SEM image of cable paper surface. Secondary electrons mode.

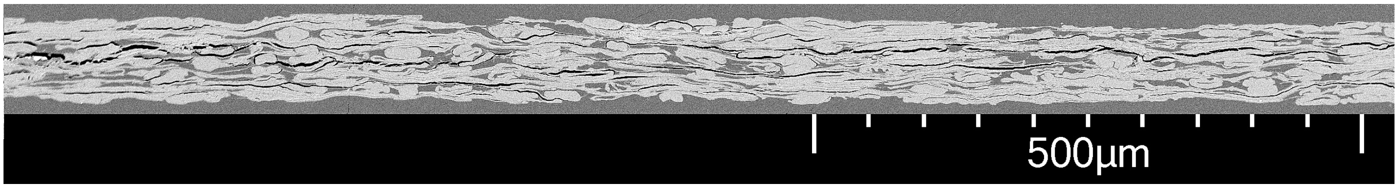

Fig. 4. SEM image of cable paper cross-section. Angle of view: Cross direction. SEM mode: Back-scattered electrons. White areas: Roughness due to specimen preparation. Light grey areas: Paper fibers. Dark grey areas: Epoxy for fixating the paper fibers. Black areas: Cracks in the specimen.

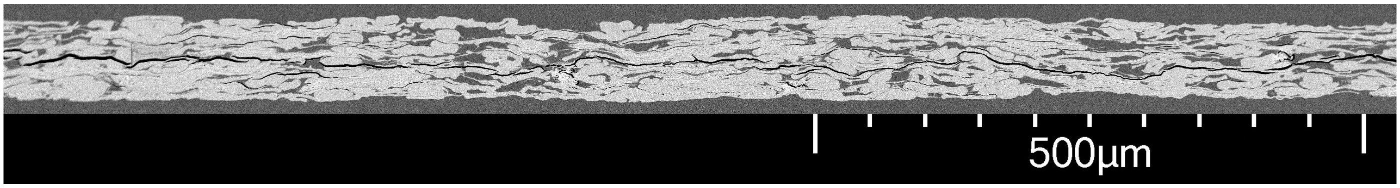

Fig. 5. SEM image of cable paper cross-section. Angle of view: Machine direction. SEM mode and colors as in Fig. 4.

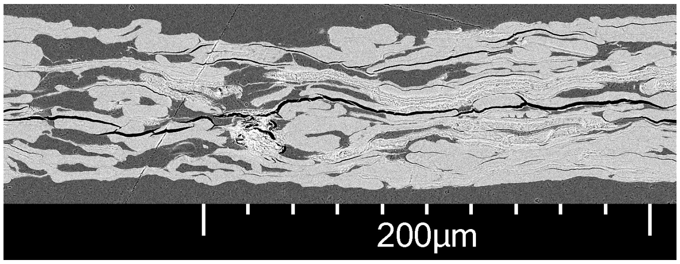

Fig. 6. SEM image of cable paper cross-section, zoomed in on a region corresponding to 400–700 µm to the right of the left edge of Fig. 5. Angle of view: Machine direction. SEM mode and colors as in Fig. 4.

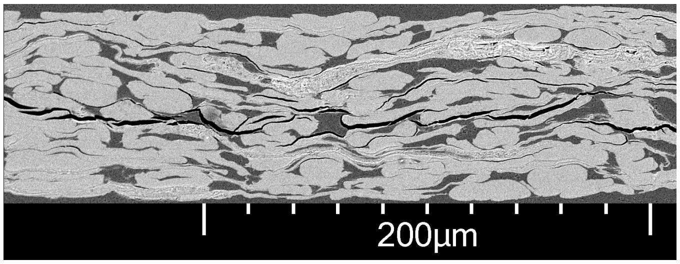

Fig. 7. SEM image of cable paper cross-section. Angle of view: Machine direction. SEM mode and colors as in Fig. 4.

15 % of the paper thickness at that point (left part of Fig. 6). This is considerably smaller than the typical paper thickness or butt gap thickness. However, this channel section was situated directly above several other thick channels sections, causing the total channel volume to be larger than the total fiber volume in this region of the paper. When impregnated with oil, regions like this contain more oil than paper fiber. Nevertheless, such oil-rich regions contain considerable areas of fiber–oil interfaces. This makes such regions substantially different from butt gaps, despite the abundance of oil. Further, it seems that such regions are less common than regions with higher density of fibers. Moreover, the widths of such regions seem to be around 0.1 mm, which is much smaller than the typical butt gap size of 1–4 mm [1]. In sum, the presence of oil-rich regions within impregnated paper does not appreciably discredit semi-homogeneous models.

As mentioned in Section I, a surface gap can be modeled as a narrow oil gap , i.e. a thin film of oil, between smooth tapes of impregnated paper. Another option is to consider such gaps as part of the impregnated paper. Sizes and shapes of typical surface gaps should be studied in more detail in order to decide which of the two options is the most appropriate. This is not done in the present study.

The cross-section images were made by impregnating the paper in epoxy, whereas paper in cables are impregnated in oil. Possible differences between epoxy and oil regarding ability to impregnate paper, as well as the swelling capacity of the paper fibers in the impregnant, may have affected the results.

The study does not take into account radial and tangential, mechanical stresses that result from the paper tapes being wound with a certain tension [13]. Such forces could potentially lead to compression of the tapes and reduction of channel sizes and surface gap thicknesses.

V. CONCLUSION

The internal structures in the paper tapes are considerably smaller than the size of a typical butt gap. Therefore, it is reasonable to model butt gaps as oil and the paper tapes as impregnated paper.

Each of the two materials oil and impregnated paper can be regarded as homogeneous. Then the electrical properties of the latter material include the effect of large areas of interfaces between paper fibers and oil channels in the bulk of the paper tapes. The interfaces between impregnated paper tapes and oil gaps are no different from the interfaces in the bulk of the paper tapes and need not be treated separately.

ACKNOWLEDGMENT

Senior Engineer Per Olav Johnsen at RISE PFI AS gave advice regarding SEM analysis of paper. He also prepared the SEM specimens, operated the SEM equipment, and made the SEM images. The original SEM images are © RISE PFI AS, Trondheim, Norway. (The SEM images are edited by the authors of this article and used with permission.)

This work is part of the project "Mass Impregnated Non-Draining HVDC Submarine Cables" led by Nexans Norway AS. The project is financially supported by The Research Council of Norway (Norges forskningsråd), Nexans Norway AS, Statnett SF, Affärsverket svenska kraftnät, and Fingrid Oyj, and has project number 256405 within the ENERGIX program of The Research Council of Norway.

REFERENCES

[1] T. Worzyk, *Submarine Power Cables: Design, Installation, Repair, Environmental Aspects*, Heidelberg: Springer-Verlag, 2009.

[2] G. Chen, M. Hao, Z. Xu, A. Vaughan, J. Cao, and H. Wang, "Review of high voltage direct current cables," *CSEE J. Power and Energy Syst.*, vol. 1, no. 2, pp. 9–21, June 2015.

[3] G. Evenset, "Cavitation as a precursor to breakdown of mass-impregnated HVDC cables," Dr. ing. dissertation, Dept. Elect. Power Eng., Norwegian Univ. Sci. and Technol., Trondheim, Norway, 1999.

[4] N. Garoff, "The Friction between Paper Surfaces," PhD dissertation, Institutionen för pappers- och massateknologi (Dept. Pulp and Paper Chemistry and Technol.), Royal Inst. Technol., Stockholm, Sweden, 2002.

[5] E. Occhini and G. Maschio, "Electrical Characteristics of Oil-Impregnated Paper as Insulation for HV DC Cables," *IEEE Transactions on Power App. Syst.*, vol. PAS-86, no. 3, pp. 312–326, Mar. 1967.

[6] B.R. Nyberg, "Electrical stress in HVDC cables under stationary and transient conditions," doctoral dissertation, Dept. Elect. Eng., The Univ. of Trondheim – The Norwegian Inst. of Technol., Trondheim, Norway, 1973.

[7] M. J. P. Jeroense, "Charges and discharges in HVDC cables: in particular in mass-impregnated HVDC cables," Delft: Delft University Press, 1997.

[8] G. Håkonseth, E. Ildstad, and K. M. Furuheim, "Local Electric Field in Mass-Impregnated HVDC Cables," in *Proceedings of the Nordic Insulation Symposium*, 2017, vol. 25.

[9] G. Håkonseth and E. Ildstad, "Steady-State Electric Field and Conductivity in Mass-Impregnated HVDC Cable Insulation," in *2018 IEEE 2nd International Conference on Dielectrics (ICD)*, 2018, pp. 1–4.

[10] G. Håkonseth and E. Ildstad, "Time-Dependent Local Electric Field in Layered Paper–Oil Insulation," in *Proc. Nordic Insul. Symp.*, Tampere, Finland, June 2019.

[11] A. K. Jonscher, *Dielectric Relaxation in Solids*. London: Chelsea Dielectrics Press Limited, 1983.

[12] *Paper, board, pulps and related terms — Vocabulary — Part 3: Paper-making terminology*, ISO 4046-3:2016.

[13] D.R. Roisum, *The mechanics of winding*. Atlanta, GA: Tappi Press, 1994.