Radial Flow Paths for Oil in Mass Impregnated HVDC Subsea Cables

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Abstract

During temperature cycling the radial flow of oil, which is caused by differences in thermal expansion between the oil and paper, may lead to cavity formation in mass impregnated HVDC cables. Partial discharge activity in these voids is an important failure mechanism in this type of cable, but the governing processes are not fully established.

This paper contributes to flow modeling through a literature survey and a comparison between two alternative flow patterns in the insulation. Only one detailed model of radial flow in this kind of insulation has been found in the literature. The model, which is based on porous media flow in a homogeneous insulation with constant porosity, and its suitability as a starting point for further modeling is reviewed.

Two possible flow paths, radially outwards through the paper or between paper tapes from one layer to the next, have been considered. Based on previously unpublished experimental results, the flow resistance *R* of the two alternatives has been estimated. This quantity is found to be of the same order of magnitude in both cases, meaning that there probably will be flow both through and between the paper tapes.

1. Introduction

Despite having been used for over 50 years, mass impregnated HVDC cables are still the only viable alternative for long sea crossings at the highest voltages [1]. Several new projects using this design are under development, and long-range subsea cables will become increasingly important in the years to come [2].

The insulation consists of tapes of high density Kraft paper wound around the conductor with a certain tension, producing what is called the *plateau pressure* between the paper layers. Then the cable is dried under vacuum and impregnated by a high viscosity mineral-oil based compound (hereby referred to as the oil). After impregnation, the cable is slowly cooled before a lead sheath casing is extruded onto it for water protection. Mechanical strength is added in the form of steel bands, armouring and exterior sheathing.

All physical processes governing the dielectric strength of the insulation are not fully understood. Failures during the cooling phase of the load cycling part of type tests have been reported [3], showing a reduction in dielectric strength of as much as 50% in some cases. This is thought to be connected with the formation, growth and redistribution of cavities in the oil [4].

The insulation is assumed to be fully impregnated, i.e. without cavities, at around 50°C when the lead sheath is applied. Reducing the temperature means that the oil will contract, and at a certain point its volume will be insufficient to fill all the available space, resulting in the formation of cavities. Thus there will always be cavities present if the temperature is below this point. The oil has an expansion coefficient around 10 times that of paper, so the paper expansion can be neglected [5]. However, the mechanical force exerted by the steel bands, and possibly the hydrostatic pressure at the seabed, will probably compress the cable somewhat, and thus reduce the temperature at which the insulation is fully impregnated. Radial flow may result from load variations which, due to ohmic losses in the conductor, create temperature gradients in the insulation with corresponding thermal expansion or contraction. If cavities are present, thermal expansion of the oil will fill these before any radial flow can occur [5].

To increase our understanding of the important parameters in the design and operation of such cables, it is necessary to gain a proper insight into the flow of oil in the insulation during load variations. Knowing the pressure and temperature distributions during different load conditions are prerequisites for discussing void formations. This work is part of an ongoing research project that aims at developing a physical model which, together with experimental verification on full scale cable samples, can be used for this purpose.

Two different contributions to the task will be presented in this paper. Previous modeling efforts and other relevant literature have been reviewed and will be discussed in Section 3. The published models, such as [6] and [5], have treated the insulation as a homogeneous material, disregarding the structure with layered papers and butt gaps. A brief description of the cable design is thus included in Section 2 for convenience. In the second part of the paper, presented in Section 4 and 5, the validity of the macroscopic approach will be discussed on the basis of previous measurements and some new calculations.

2. Cable geometry

The insulation consists of paper tapes, typically 20-25 mm wide, which are wound in a helical pattern around the conductor, with one tape making up one layer. The pitch is slightly longer than the tape width, leaving a butt gap distance of 1.5-2.0 mm to the previous turn. A number of tapes, usually 13-16, are put on simultaneously, and in the same direction, with a staggering of around 30% from one layer to the next to avoid direct contact between the butt gaps. Then another 13-16 layers are applied, but with the helices propagating in the opposite direction to avoid torsion. Fig. 1 shows an example of a mass impregnated HVDC cable insulation, with one layer of outer carbon black paper present to highlight the helical pattern and the butt gaps.

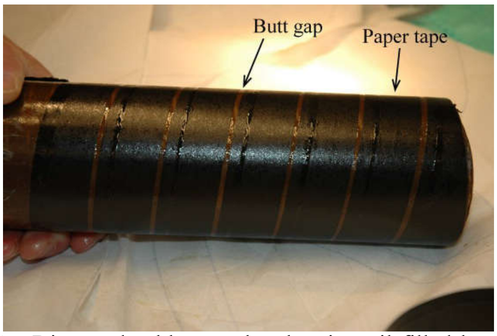

Fig. 1 - Dissected cable sample, showing oil filled butt gaps between carbon black paper wound outside the paper tapes.

The paper itself is porous, allowing radial flow of oil, in addition to around 10% of the insulation volume being comprised by the helical butt gap channels. A 30% staggering means that the shortest distance between two butt gap channels, without passing through paper, is around 5 mm in the small slit between adjacent paper tapes. Due to the plateau pressure this slit becomes very narrow, but the surface roughness of the paper may still facilitate flow of oil at the interface.
The slit between the layers is one of two alternative flow paths which will be considered in this paper, the other being radially outwards through the layers. A sketch of a cross section of the insulation is shown in Fig. 2, with the conductor at the bottom and the two flow patterns indicated.

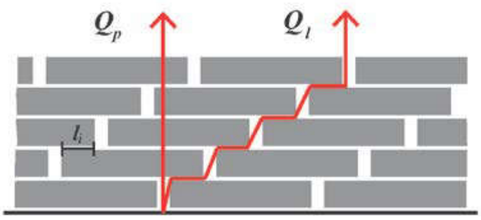

Fig. 2- Two possible paths of flow through the insulation.

3. Literature review

Few actual models have been found that treats radial flow of oil in cables, even though it is assumed to be connected with cavity formation. The cavity formation process is in turn widely considered to be of great importance for the dielectric strength of the insulation during load turn-offs. Some experiments concerning material properties are available, and the effect of different plateau pressures is briefly treated in [3].

3.1. Modeling of pressure during load variations

The only detailed model published, is the one by Szabo et al. [6]. Based on Darcy's law, which describes flow through a porous medium (in this case the paper), and the conservation of heat and mass, the model is used to calculate the pressure distribution due to flow of oil over the insulation for different load conditions. The solution of the heat equation is decoupled from the rest, and the result is used to update density, viscosity, pressure, and radial velocity in an iterative procedure for each time step. To simplify the calculations only one spatial dimension is assumed, as well as a constant porosity including both butt gaps and the paper pores. With a fixed temperature at the outer surface of the cable the model predicts a pressure drop near the conductor at load turn-off, which may facilitate cavity growth or formation.
However, the model has some limitations in its current form. An assumption in the implementation is that the cable is fully impregnated at a temperature of 20°C, which is probably too low, as mentioned in the introduction. Thus the presented results must be treated with some care, but it seems the model could easily be changed to accommodate a higher temperature limit for pressure increase. Two-phase flow situations, i.e. the actual presence of cavities, are not considered. As pointed out by the authors, the penetrability of stranded conductors should also be included for increased accuracy. Finally, it should be mentioned that the pressure dynamics in the insulation model is determined by the flow resistance of the paper matrix and a fixed outer pressure only. It would be reasonable to assume that other factors contribute to this in real life, such as the plateau pressure between paper layers and the elasticity of the paper, outer casing, steel bands and armouring.
Another model is mentioned in [5], but neither the physical foundation or the actual implementation is presented. It is seemingly based on the same assumptions as in the model described above, and produces similar results with a fixed outer temperature.
None of the papers report on any experimental verification of the models, making it difficult to evaluate how well they describe a real cable. Pressure measurements at the outer lead sheath during load cycling are however found in a study treating mass impregnated cables for lower voltages [7]. The results agree quite well with the model predictions, but cannot be used for anything other than to indicate that the models are relevant.

3.2. Experimentally determined flow rates

The steady state flow rate of T2015 type oil through paper layers has been investigated at SINTEF Energy Research during a previous HVDC subsea cable project. These unpublished experimental results have been made available for this study. Two experimental set-ups were used, one for measuring perpendicular flow through the layers, and one for flow longitudinally between them. The perpendicular setup consisted of 20 layers Munksjø 90 µm paper, with an area of 21.9 cm². In the longitudinal test cell, a stack of 270 papers, 4.0 cm wide and 6.1 cm long, were weighed down to produce a certain plateau pressure. Parameters such as temperature T, driving pressure ΔP, plateau pressure P_p and paper type were varied in the experiments.

In the calculations presented in the next section, the measured perpendicular and longitudinal flow rate, Q_p and Q_l respectively, obtained at $T = 50°\mathrm{C}$ with $P_p = 2$ bar are chosen as an example. To compare the two flow patterns, the *flow resistance* $R = \Delta P \,/\, Q$ will be used, which describes the driving pressure needed to achieve a certain flow. The measured resistances were $R_{p,m} =$ 66.7 bar $(\mathrm{g/h})^{-1}$ and $R_{l,m} =$ 0.21 bar $(\mathrm{g/h})^{-1}$ for perpendicular and longitudinal flow respectively.

4. Flow path calculations

The foundation for the calculation presented here is the experimental results discussed in Section 3.2.

Using the measured flow resistances $R_{p,m}$ and $R_{l,m}$, it will be argued which of the two alternative flow patterns shown in Fig. 1 is dominating, i.e. what is the path of least resistance. If purely radial flow through a porous medium is the most significant mechanism, it could mean that the paper laying is not really important for the pressure distribution and that the modeling approach of [6] is viable. However, if the oil flows more easily between the papers from one butt gap to another, it could mean that more careful geometrical considerations must be taken in the modeling process. It is also possible that the type of flow pattern present will affect the local pressure distribution and thus the cavity formation.

A model cable with an inner and outer insulation radius of 20 mm and 40 mm respectively, is used in the calculations. With 90 µm thick paper tapes, the number of layers becomes $n = 222$. Following the modeling argument that will be given in Section 4.2, there is 37 longitudinal channels per meter cable length, which will be the length scale for the comparison. To convert the flow units from mass to volume, an oil density of 909 kg/m³ is used [6]. In the following, it is assumed that the flow resistance in the butt gaps can be neglected.

4.1 Perpendicular flow

To obtain a relevant figure for the radial flow resistance, the results from the laboratory cell must be adapted to the cable geometry. A scaling with the number of layers encountered and the area of flow must be performed. As the butt gaps make up around 10% of the insulation volume, only about $n \approx 200$ layers of paper are encountered when moving in a straight line between the conductor and the lead sheath. The area of flow in a cable sample is a cylinder shell, $A = 2\pi r w$, and in the example an average radius of $\bar{r} = 3$ cm and a width of $w = 1$ m are used. Combining these assumptions with the values given above and converting to SI units, the scaling is given by

$$R_{p,c} = \left(\frac{n^c}{n^m} \cdot \frac{A^m}{A^c} \right) \cdot R_{p,m} \approx 2.53 \cdot 10^{15} \text{ Pa (m}^3\text{/s)}^{-1}. \quad (1)$$

Here the superscript *m* denotes measured values, while *c* is used for parameters related to the model cable.

4.2 Longitudinal flow

A simple model for flow outwards between paper layers consists of flow between concentric cylinder shells with a width of around l_i = 5 mm in n layers. The real-life situation with continuous helical butt gap channels is thus approximated by a number of equally spaced cylindrical channels connected by the slits described in Section 2. The radius of each shell increases with the paper thickness, but for simplicity an average radius $\bar{r}$ is used for all of them. Again neglecting the flow resistance in the butt gaps, this flow can be equated with that between two sheets of paper with length $L = nl_i$ and width $W = 2\pi\bar{r}$. The approach is shown in Fig. 3.

In this simplification, a number of cone-shaped channels propagate outwards along the whole length of the cable, approximately 37 per meter if using 25 mm wide paper tapes and a butt gap width of 2 mm.

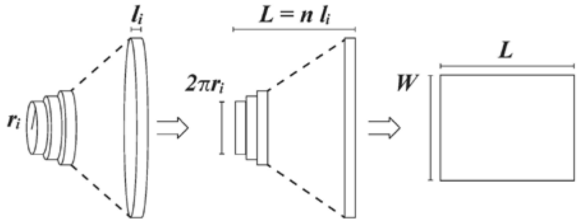

Fig. 3 - Modeling of longitudinal flow outwards through the insulation.

The experimentally obtained flow resistance must be adapted accordingly, adjusting for length, width and number of slits. Assuming a linear pressure distribution, $R_{l,m}$ should be multiplied by $(L^c \,/\, L^m)$ to adjust the driving pressure, and divided by $(W^c \,/\, W^m)$ to get the correct flow rate. In addition, the number of slits is reduced from 269 in the experiments to 37 for 1 m cable, as described above. Together, this scaling leads to a flow resistance of

$$R_{l,c} = \left(\frac{n^m}{n^c} \cdot \frac{L^c}{L^m} \cdot \frac{W^m}{W^c} \right) \cdot R_{l,m} \approx 1.92 \cdot 10^{15} \text{Pa (m}^3\text{/s)}^{-1}. \quad (2)$$

With reference to Fig. 2, we may also have longitudinal flow in the 18 mm slit going in the opposite direction. The flow resistance here will be $(18/5) \cdot R_{l,c}$, and when comparing with $R_{p,c}$ it will act as a parallel resistance, lowering the total $R_{l,c}$ to $1.50 \cdot 10^{15}$ Pa/(m³/s).

5. Comparison of flow patterns and discussion

Using the values obtained in the two previous sections, the ratio between perpendicular and longitudinal flow resistance becomes

$$\frac{R_{p,c}}{R_{l,c}} = \frac{2.53\cdot 10^{15}\,\text{Pa}\,(\text{m}^3/\text{s})^{-1}}{1.50\cdot 10^{15}\,\text{Pa}\,(\text{m}^3/\text{s})^{-1}} \approx 1.7. \tag{3}$$

It can be noted that the longitudinal flow resistance indeed is lower than the perpendicular one. However, these rough calculations, which are based on measured values, show that the resistance to flow is approximately equal through the paper layers and between them. There is no basis for stating that the main flow will go this way or the other, and based on the findings, neither of the suggested flow patterns should be ignored.

To decide what factors are affecting the flow resistance in each case, well-known flow equations can be used [8]. For perpendicular flow, Darcy's law for porous media is employed, taking the form

$$Q_p = \frac{-kA}{\mu}\frac{\Delta P}{L}. \tag{4}$$

Here, k is the permeability, μ is the viscosity and A and L are geometrical parameters. From the experimental data, the permeability can be found to be $k \approx 7.9\cdot 10^{-17}\,\text{m}^2$. Compared to the value used in [6], it is about 4 times smaller. This may be due to differences in the experiments, such as the type of paper used.

Longitudinally, the equation for laminar flow between parallel plates can be applied, which is given by

$$Q_l = \frac{-wh^3}{12\mu}\frac{\Delta P}{L}, \tag{5}$$

where w is the width of the channel and h is the height. As in Eq. (6), the flow rate is proportional to the pressure drop and inverse viscosity of the oil. Using the data from the experiments, an approximate average distance of $h \approx 13$ µm between the paper layers is found. This value is higher than expected, but in the right order of magnitude. The surface roughness of the papers is not considered in this approximation.

As mentioned in Section 3.2, flow measurements exist for other temperatures and different pressures. The general effect of these parameters on the ratio $R_{p,c}$ / $R_{l,c}$ is a slight decrease with both P_p and T. This is in accordance with the theory, as P_p mainly affects the longitudinal flow, increasing $R_{l,c}$. Oil viscosity decreases with temperature, which is expected to increase Q_p more than Q_l because the pores in the paper are small compared to the distance between paper layers.

Maybe the most important difference between the measurement cells and a real cable is the plateau pressure. This is expected to be both higher and more variable. According to the experimental results, it will probably lower the ratio $R_{p,c}$ / $R_{l,c}$ further.

6. Conclusion

Only one detailed attempt at modeling radial flow in mass impregnated insulation was found in the literature. Szabo et al. have developed a one-dimensional model that assumes single phase flow through a homogenous insulation. Based on physical arguments, it produces reasonable results, and may provide a good starting point for further modeling.

Two different flow patterns for radial oil transport have been investigated, perpendicularly through the insulation or between the paper tapes from one butt gap to the next. Previously unpublished measurements of oil flow through and between paper layers have been used to approximate the flow resistance R in each case. It is found that this parameter is of the same order of magnitude for both perpendicular and longitudinal flow. In a model setting, this will probably be most important in assessing local pressure conditions in connection with void formation.

7. Acknowledgements

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