

# Effects of Steel Tapes on Internal Pressure in Mass Impregnated HVDC Cables

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## Abstract

Thin steel tapes providing radial mechanical support is a vital component in mass impregnated non-draining (MIND) HVDC cables. When the insulation volume increases with temperature during operation, the tapes work against the expansion and make sure that the cable is not permanently deformed by repeated heat cycles. It is believed that the application of steel tapes also compresses the insulation, increasing the internal pressure building up when the cable is loaded. The oil impregnant has a much higher thermal expansion coefficient than the paper, which can cause both radial flow of oil when heating and cavity formation – and thereby the risk of dielectric breakdown – when cooling. Steel tapes are important in this regard, as they may enhance these effects by reducing the insulation volume. Through measurements of internal pressure and thermal expansion as a function of temperature, this work confirms that there is a significant difference in pressure behavior in cables with the steel tapes in place and when they are removed. Measured pressures range from some 0.3 bar below atmospheric at 20 °C, to approximately 8 bar at 46 °C. The experimental results are compared to available literature, and a new mathematical model that calculates the pressure at the insulation/sheath interface.

## 1. Introduction

### 1.1 Background

Even though the general design of mass impregnated non-draining (MIND) cables is old, this technology is still highly relevant for the longest subsea connections for transmission of large quantities of power. This is highlighted by the planned NSN project [1], which will set a new record for longest subsea power transmission by using a MIND cable.

Dielectric failures occurring in the cooling phase of load cycling during type tests of MIND cables have been reported [2]. A consequence of this is the strict operational requirements imposed on the installations. Improving this situation, by e.g. increasing the current rating or permitting rapid load changes, requires a better understanding of the behavior of the insulation system during load variations, as explained in [3].

### 1.2 Problem description and scope of work

During manufacturing of MIND cables, layers of paper are wound onto the conductor before everything is submerged in a tank filled with mineral oil at an elevated temperature. The temperature is slowly lowered to around 50 °C, where the impregnation process virtually stops [3]. At this point the cable is taken out, and the lead sheath is applied. Now a finite amount of oil has filled most of the pores and gaps in the paper layer. To quantify the total oil volume, the *impregnation level*  $q$  will be used, which is the ratio of oil to total insulation volume. When the cable is cooled further, the mineral oil contracts substantially more than the paper, and the result is that cavities are formed in butt gaps - and possibly between paper layers - in the insulation [4]. It is presumed that the cavities will not be filled until the insulation again reaches the volume it had when the impregnation ended, which will hereby be referred to as the *cavity-free temperature*  $T_0$ . Relating this to cable operation, it is believed that the formation of excessively large cavities between the paper layers during cooling is a precursor for the so-called *cavity-induced breakdowns* observed during type tests [4]. It is suggested that by applying steel tapes outside the lead and polyethylene (PE) sheaths with a certain tension, the available volume for the insulation may be somewhat reduced. This will effectively lower  $T_0$ , meaning that the cavities will disappear at temperatures somewhere below 50 °C.

As the cable is loaded, the insulation heats up from the inside, and when the cavity-free temperature is exceeded a pressure gradient will start to build. Due to the mechanical strength of the outer layers, and in particular the steel tapes providing radial support, the pressure will presumably increase quite fast.

Having a cavity-free insulation with high internal pressure at a relatively low temperature is clearly beneficial from a dielectric strength point of view [5], so if this assumption holds it may explain some of the success of the design. On the other hand, if the pressure builds up from the inside, oil may be transported radially outwards. When cooling, the same driving force is not present to push the oil back, leading to a redistribution of both oil and cavities. This may generate larger, more dangerous, cavities in the period after load turn-off.

The goal of the present work is to assess the hypothesis that  $T_0$  is lowered by the addition of steel tapes, and that a positive internal pressure will not build up before this temperature is exceeded. This is done experimentally, by measuring internal pressure and thermal expansion on real MIND cable samples as a function of temperature. The measurements will be compared to a new model of the pressure at the insulation/sheath interface.

## 2. Literature review

Despite the maturity of the MIND cable design, little is found in the literature regarding insulation pressure build-up and the effects of steel tapes. Some efforts have been made to model internal pressure, but published measurements about this phenomenon are lacking.

An exception is the study by Ross [6] concerning pressure influence on moisture migration. The cables considered were for 10 kV applications, but the design is similar, with mass impregnated paper surrounded by a lead sheath and additional armoring. Relatively long samples (about 83 m) were used, and pressure was measured just beneath the sheath at three different positions along the objects. During load cycling, pressures ranging from 0.1 to 8.0 bar absolute were reported.

A complete model for the radial flow and pressure effects in a MIND HVDC cable was derived by Szabo et al. [7]. While the governing equations for the insulation itself are well established, the representation of the steel tapes is somewhat lacking. It is based on empirical experience, and seems to include the elasticity of the tapes. However, it is only valid for one specific cable, and not easily extended to other specifications.

In their discussion of transient temperatures and pressures in oil-filled cables [8], Matthews and Malburg include both the elastic and thermal deformations of the sheath, which in this case is made up of corrugated aluminum. The sheath elasticity is included through the increased interior volume it creates when strained by the pressure build-up. It should be noted that this investigation considers cables where the conductor contains an oil-filled duct connected to pressurized reservoirs at both sides. Along with the less viscous oil used, this sets the situation a bit apart from that seen in MIND cables. The pressure calculations especially, are differing.

A recent series of papers by Huang and Pilgrim suggests a new current rating methodology for MIND HVDC cables, based on thermo-mechanical stress analysis. An elaborate analytical model is presented in [9] using a multiphysics approach, where the authors introduce Tresca's maximum shear stress criterion as a failure criterion for the cable sheath. To simplify the calculations, two special cases are considered, for low and high temperatures respectively, the thermal and mechanical effects of the paper are disregarded, and

cavities in the insulation are not included. A more general approach is taken in [10], where a FEM model is presented that solves the same problem. An important distinction compared to the situation covered in the present work, is that the cables considered do not have steel tapes outside the sheath. This makes a direct comparison difficult, but it is assumed that the approach presented in [9] and [10] could be extended to also include this aspect. None of the three models considered include any experimental verification.

## 3. Experimental setup and results

Several experiments carried out on objects from one real-life MIND HVDC cable type will be presented in this section. A method for determining  $T_0$  and  $q$  is described, along with long-term measurements of internal pressure as a function of temperature. All tests were carried out in a heat cabinet, to achieve isothermal conditions. No current was applied to the cable samples.

### 3.1 Thermal expansion of oil

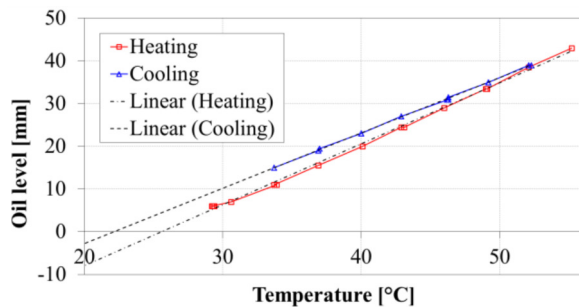
The cavity-free temperature and impregnation level of the insulation are vital parameters when calculating the internal volume change, and hence the pressure build-up. Some uncertainty surrounds the values of  $T_0$  and  $q$ , which becomes even more pronounced when examining the literature. Values of  $q$  are ranging from 0.30 [7] to 0.37 [11] and 0.4 [3], while [12] uses the range between 0.2 and 0.5. The cavity-free temperature seems to attract less attention, although it is mentioned in [13] and [14]. In [3] a source suggests a numerical value of around 50-55°C, but this is the actual end-of-impregnation temperature, before the application of the lead sheath and steel tapes. As another extreme, the cables are considered fully impregnated at 5 °C in [7].

An experiment was carried out by sealing one end of a 35-cm long cable sample and heating it vertically in an oven, while measuring the volume of oil expanding out from the other end. The accuracy was increased by mounting a thin polycarbonate tube to the open end, for the oil to flow into, as pictured in Fig. 1.



**Fig. 1** - Test object for measuring impregnation level and cavity-free temperature. The height of the oil column was measured as a function of temperature, and the objects were kept around 24 hours at each temperature.

Plotting the measured pairs of  $T$  and  $\Delta V$ , as shown in Fig. 2, it is evident that the assumption of linear expansion holds. Fitting the results to a linear model, the impregnation level can be found from the slope and the cavity-free temperature from the intersection with the x-axis. The values obtained from this experiment varied somewhat between the test cycles, with  $q = 0.49 - 0.55$  and  $T_0 = 22 - 25$  °C.



**Fig. 2** - Oil level as a function of temperature in the range  $T = [30, 55]$  °C. The linear extrapolation crosses the x-axis at the cavity-free temperature.

Another way to determine these parameters is to measure the internal pressure while heating samples sealed in both ends to a uniform temperature, as described in the next section. The cavity-free temperature presumably corresponds to the point where the pressure rises to above atmospheric levels, while determining the impregnation level will require a model of volumetric thermal expansion.

### 3.2 Internal pressure – setup

The goal of this experiment is two-fold. First, the pressure beneath the lead sheath should be determined as a function of temperature. The secondary objective is to examine the differences between objects with and without steel tapes, to see how it affects the pressure behavior and  $T_0$ .

Based on experiences from the experiment described in Section 3.1, the test objects were sealed in both ends using stainless steel caps. They were fastened to the sheath and armoring using an epoxy containing aluminum oxide particles, which gives it similar thermal expansion properties as metals. Analog manometers with a range between -1.0 and 1.5 bar relative were applied through brass connectors soldered to the lead sheath, in a similar manner to what is described in [6]. Two manometers were applied to each object, at the same distance from the ends. The objects were placed inside a heat cabinet for uniform heating, and a standard thermocouple was used to measure the temperature on the cable surface. A picture of the setup is shown in Fig. 3.

To ease the calculation of the internal volume as a function of temperature, and thereby the model comparison, it was chosen to heat the objects from the outside to a uniform temperature. However, this meant that the size of the heat cabinet limited the length of the

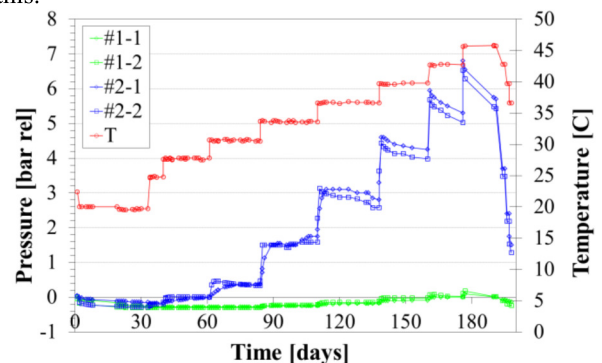
test objects to 1 meter. It is possible that the measurements were influenced by some end effects due to this fact, and that the recording of the pressure amplitude was somewhat affected.



**Fig. 3** – The two test objects with manometers attached, inside the heat cabinet. The sample with steel tapes is seen to the left, and the one without to the right.

### 3.3 Internal pressure – results

The test objects were first kept at 20°C until the internal pressure stabilized, i.e. both sensors showed the same, constant value. Somewhat surprisingly, it took almost one month to reach a state of equilibrium. A similar behavior was observed also when increasing the temperature, albeit the time constant decreased to some degree. After the pressure had stabilized, the temperature was increased in steps of 3 or 5 °C up to 46 °C. The pressure was allowed to settle to some extent at each temperature before increasing to the next level, as shown in Fig. 3. It should be noted that the manometers on the sample with steel tapes were changed during the period at  $T = 34$  °C, when the range of the original ones were exceeded. The results shown in Fig. 4 are adjusted for a short pressure drop experienced in connection with this.



**Fig. 4** - Internal pressure measured between insulation and lead sheath at various temperatures. Results are shown for 2 test objects, one without (#1) and one with (#2) steel tapes. Each test object has 2 pressure gauges. The measured temperature is shown in red.

Examining the measurements displayed in Fig. 4, several interesting aspects require some comment. First, the two manometers of each test objects are in reasonable agreement. The reason for including several pressure gauges was to ensure trustworthy results, which is indicated by this fact.

Second, the difference in internal pressure build-up between the object with and without steel tapes is striking. Whereas the pressure inside the object with steel tapes exceeds atmospheric between 28 and 31°C - and increase quite dramatically beyond that point - a sub-atmospheric pressure is measured inside the object without steel tapes up to  $T = 43^\circ\text{C}$ . This supports the claims from [3], that without the steel tapes there would be cavities present in the insulation up temperatures approaching the maximum allowable operating conditions of the cable.

Another point connected to this is the marked break in the curve after the internal pressure exceeds ambient conditions. As mentioned in the introduction, this is as expected when  $T > T_0$ . The break in the curve appears between 28 and 31°C, which can be compared to the value of 22 to 25°C from Section 3.1.

The third observation is the time-dependent pressure behavior. After increasing abruptly when the temperature is stepped up, the pressure seems to decrease rather slowly, but also quite significantly. The problem then, is to decide which pressure value to consider for each temperature. This is very important for a model of internal volume changes, and will also affect predictions from a boundary pressure model such as the one described in the next section. Since the period immediately after temperature changes, e.g. load turn-offs, is thought to be the most important, the maximum pressure for each  $T$  will be used the following.

## 4. Model development

### 4.1 Cable geometry and model assumptions

The stranded conductor is surrounded by around 200 layers of Kraft paper tapes, typically 0.1 mm thick and 2-3 cm wide. At the inner and outer boundaries of the insulation, layers of semiconducting tape are added. A lead sheath is applied outside the insulation, before a PE layer, and the steel tapes. Two layers of tape are commonly used, each around 0.4 mm thick, with a tape width of around 4.5 cm. Finally, outer armoring is added, in the form of longitudinal steel tapes or wires surrounded by a bitumen compound and a thin outer serving. The latter part is important mainly for the laying of the cable. A more thorough description of the cable geometry can be found in e.g. [13].

Some assumptions have been made to ease the model calculations. The most important are that only the insulation oil is expanding, and that the only thing withstanding the expansion is the steel tapes. These simplifications can be justified by the much higher thermal expansion coefficient [14] and elastic modulus, of the oil and steel respectively, compared to the other materials involved.

### 4.2 Thin-walled pressure vessel

The pressure build-up in the cable insulation is mainly due to the forces set up in the steel tapes when they are strained by the expanding interior. Within their elastic

domain, the steel tapes can be regarded as springs according to Hooke's law. It is natural to apply the known equations for thin-walled cylindrical pressure vessels as a vantage point for a simple model of the pressure build-up, as the situations are so similar. The requirement for using this approach is that the wall thickness  $t$  is less than a tenth of the radius  $r$ , which is the case for these cables. A thorough deduction of these equations can be found in textbooks such as [15], so only the main result will be presented here. For a cylindrical cable, the internal pressure is given as a function of internal volume change by

$$P(\Delta V) = \frac{2tE}{r[5-4\nu]} \frac{\Delta V}{V}. \quad (1)$$

Here,  $E$  is the elastic modulus and  $\nu$  is Poisson's ratio for the steel tapes. The form is comparable to the corresponding equation in [7], and can thus be directly substituted as a boundary condition in a complete model of internal pressure effects.

### 4.3 New pressure model

However, it is possible to improve upon the simple model presented above, by including phenomena known to affect the pressure build-up. First, the steel tapes do not form a solid cylindrical wall, as they are wound on in two layers with a pitch slightly larger than the tape width. This is considered by modifying the wall thickness with a factor  $\phi$  accounting for the gaps between the tapes.

Second, and perhaps more important, is the compressibility of the mineral oil, which acts as the pressurizing medium. To describe this property, the bulk modulus  $K$  can be used, which is the ratio of volumetric stress to volumetric strain. When the stress is represented by oil the pressure, the bulk modulus is given by  $K = P / (\Delta V / V)$ . Incorporating these changes in (1) produces a new version of the pressure model as

$$P(\Delta V) = \left( \frac{2tEK\phi}{rK[5-4\nu] + 2tE\phi} \right) \frac{\Delta V}{V}. \quad (2)$$

Compared to the first model, it is clear that both modifications will lower the predicted internal pressure. Further modifications are also possible, e.g. the tension already set up in the steel tapes at application could be included, but this is not done here. Incorporating this element would presumably increase the models pressure level estimates.

To assess the model predictions, the volume change must be calculated. It is not within the scope of this work to develop a model for this quantity, so a simple linear thermal expansion model will be used, on the form

$$\Delta V = \begin{cases} 0 & \text{for } T \leq T_0 \\ q\alpha_r\Delta TV & \text{for } T > T_0. \end{cases} \quad (3)$$

Here,  $q$  and  $T_0$  are the impregnation level and cavity-free temperature described above, and  $\alpha_r$  is the thermal

expansion coefficient. As discussed in Section 4.1, only oil expansion is considered, suggesting a break in the volume change curve when the temperature exceeds  $T_0$ .

Fig. 5 shows the maximum measured pressure as a function of temperature, along with values computed using (2). The break in the curve is very pronounced, and reproduced by the model by using  $T_0 = 31^\circ\text{C}$ . As discussed further in Section 4.4, the predicted pressure is strongly dependent on the input, and the example given below is found using  $q = 0.3$  and values in the lower range for the remaining parameters.

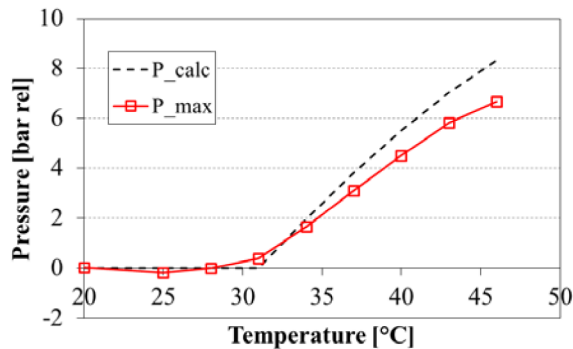


Fig. 5 - Maximum measured pressure and pressure computed from (2) and (3) as a function of temperature, for the object with steel tapes in place.

#### 4.4 Parameter sensitivity analysis

It should be noted that the predictions made by this model will depend strongly on the input, both the material and geometric parameters and the volume change. The former of these can be measured, or are available from the cable manufacturer, while the latter requires a model of its own.

Clearly, the value of  $P$  calculated by (2) will be dominated by  $\Delta V/V$ , but it will also be sensitive to perturbations in the other input parameters, such as  $t$ ,  $E$ ,  $K$ ,  $\phi$ ,  $\nu$  and  $r$ . On one side, these can be obtained from literature, or from the cable manufacturer, but measurements show that such values should not always be taken for granted. As an example, the elastic modulus of steel tapes taken from a MIND cable that has been in operation was measured to 172 GPa. The standard tabulated value for this type of steel is between 190 and 200 GPa. Similar discrepancies can be present for the other parameters as well, and while they may be small on their own, the accumulated effect may be significant.

By examining slight variations on some of these parameters, it can be shown that a wide range of pressure values can be predicted, depending on how the input is chosen. As an example, the pressure predicted at  $T = 46^\circ\text{C}$  can be varied from 8.3 to 17.6 bar, by adjusting the parameters mentioned above within reasonable boundaries. The most influential parameter is undoubtedly  $q$ , with the lowest suggested value of 0.3 producing results closest to the measured pressure.

This highlights two major points regarding this problem. First, experimental verification is paramount. Second, if experiments are not an option, careful consideration has to be put into the choice of input parameters.

## 5. Discussion and suggestions for further work

### 5.1 Comparing model and measurements

This paper does not deal with main difficulties in modelling the pressure behavior inside mass-impregnated HVDC cables, but rather considers the pressure at the outermost part of the insulation. Experimental verification is thus easier, but the model is still strongly dependent on a calculation of the internal volume change. As shown in Section 3.3, the pressure decreases slowly with time at a given temperature. This complicates the prediction of  $\Delta V/V$ , and undermines the simple thermal expansion approach outlined in (3).

A comparison between the measured pressure in the object with steel tapes and the pressure computed from (2) and (3) has been included in Fig. 5 anyway. This is done both to assess the current model, and to highlight the importance of experimental verification. As discussed in the previous section, small perturbations on the input parameters can have a major impact on the output. Hence, a large range of computed pressures can be achieved by only just tweaking a combination of parameters, making it difficult to trust model-only predictions.

There seems to be reasonable agreement between model and measurements in Fig. 5, but the uncertainty surrounding parameter values and internal volume computation should be emphasized. Especially the calculation of internal volume change influences the calculated pressure amplitude. This is highlighted by the fact that the comparison presented in Fig. 5 suggests that  $q \approx 0.30$ , which is significantly lower than the value found in Section 3.1. It is believed that more accurate measurements, and a better understanding of the time-dependent pressure effects, are necessary to appropriately assess the performance of the model described in Section 4.

### 5.2 Suggestions for future work

Considering the overall situation, both the problem at hand and the available literature, it is evident that there is a lack of reliable measurements. Pressure effects must be measured in order to truly be able to assess the situations that can lead to cavity-induced breakdowns. If possible, the pressure should be measured at several radial positions, while the cable is loaded to achieve a temperature gradient at various surrounding conditions. Such experiments would also serve to assess the different suggested models available.

## 6. Conclusion

The most important contributions from this work are summarized as follows:

- Measurements of pressure inside short samples, taken from one real MIND HVDC cable type, have demonstrated a pronounced difference between objects with and without steel tapes providing radial mechanical compression.
- The cavity-free temperature of the cables is strongly affected by the application of the steel tapes, and has been measured to around 30 °C with steel tapes compared to 43°C without.
- The maximum measured pressure was almost 8 bar, at a uniform temperature of 46 °C.
- A mathematical model of the pressure at the outer boundary of the insulation, arising from the straining of the steel tapes, has been proposed. Model predictions fit the measured pressure reasonably well when using an impregnation level of  $q = 0.3$ .
- The results seems to verify the claims [3] that application of steel tapes compresses the impregnated insulation and makes radial flow and cavity redistribution possible.

## 7. Acknowledgements

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