Transforming and changing

Fundamental research in UHVDC converter transformers

JOACHIM SCHIESSLING, OLOF HJORTSTAM, MATS BERGLUND – The converter transformer that connects the converter valve to the AC network is a key component of a UHVDC converter station. In order to design cost-effective and robust DC electrical insulation for this transformer, it is essential to obtain a deep understanding of the material itself as well as the physical processes that occur in the insulation under DC stress.

The main purpose of the converter transformer in an HVDC converter station is to transform the AC voltages from the AC network to the AC side of the converter valve. The electrical insulation of a converter transformer differs from that of a regular power transformer since it has to withstand combined AC and DC stress. Where the material parameter determining the AC field distribution is the permittivity, the DC field distribution is determined by the resistivity. Pressboard and oil differ by a factor of 2 in permittivity and by a factor of 100 in resistivity – thus more solid insulation is required for a converter transformer.

One major feature of DC behavior in the insulation material is that the governing parameter is not constant. Oil resistivity changes with applied electric stress, temperature, period of energization, moisture content, etc. Also, ion migration in DC fields leads to space charges at insulation interfaces that influence the electric field distribution significantly.

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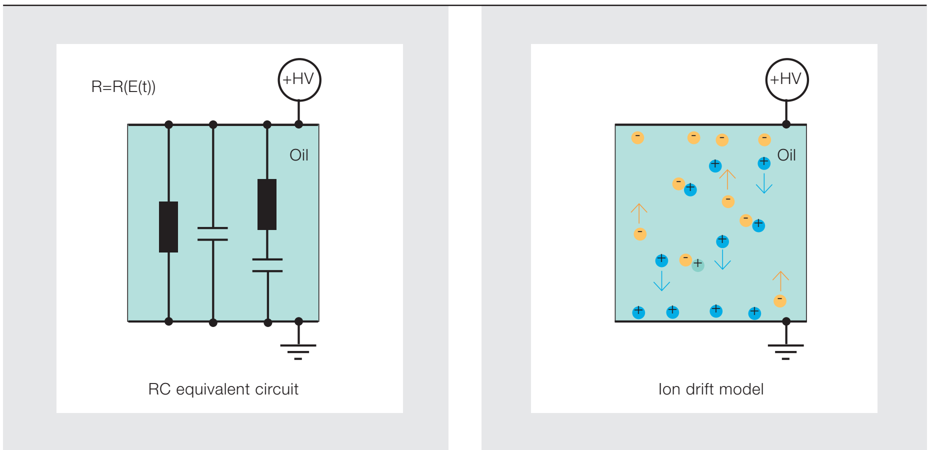
In order to design cost-effective and robust DC insulation, a deeper understanding of the physical processes under DC stress as well as material knowledge is vital. Typically, electrical insulation is designed using simplified calculations based on an equivalent RC circuit → 3. However, this cannot cover aspects such as space charge accumulation and the complex resistivity behavior of transformer oil.

In the 1980s, the ASEA Research Center in Västerås investigated the DC properties of electrical insulation and developed a model that took ion generation and ion drift into account. The model was experimentally verified and implemented in a simulation tool. Thanks to this knowledge, unique technical solutions have been developed.

Nonlinear behavior of insulation liquids makes it difficult to use traditional resistive models to predict the electrical field distribution.

3 Two simulation methods for DC insulation systems



3a RC equivalent circuit **3b Ion drift model**

4 The equations for the time-dependent ionic density in liquid insulation. These three-dimensional calculations require significant computer power to achieve good accuracy.

The Ion-drift model

Continuity equations for concentration of positive (p) and negative (n) ions:

$$\frac{\partial p}{\partial t} + \nabla \cdot \left(\mu_p \overline{E} p - D_p \nabla p\right) = S$$

$$\frac{\partial n}{\partial t} - \nabla \cdot \left(\mu_n \overline{E} n - D_n \nabla n\right) = S$$

with μ_n, μ_p, D_n and D_p being the electrical mobility and diffusion constants for positive and negative ions.

Source term including generation and recombination of ions:

$$S = K_D^0 c F(E) - K_R p n$$

with F(E) providing the Onsager field dependent contribution to the ion generation rate.

Poisson's equation including space charges (p-n):

$$\nabla \cdot (\varepsilon_o \varepsilon_r \overline{E}) = q(p - n)$$

with ε_o and ε_r being the dielectric constant and the relative dielectric constant.

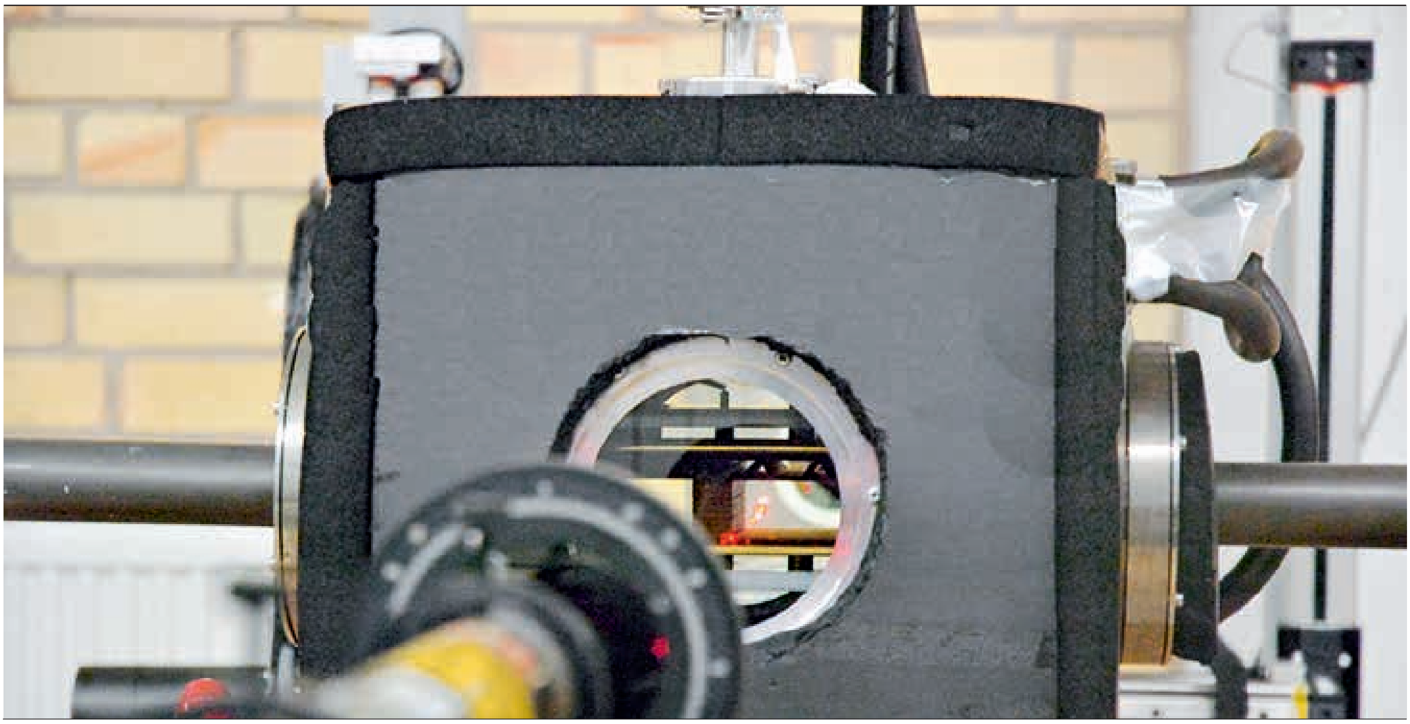
The ion drift model for oil/cellulose insulation

The resistivity of insulation liquids such as mineral oil is not an intrinsic or well-defined material property. The apparent resistivity of such a liquid is defined by the concentration of free ions and their electrical mobility. However, if a liquid is exposed to an electric field, the free ions will start to move along the direction of the field, causing ion depletion – and, thus, reduced resistivity – in certain regions. This means that the apparent resistivity depends on the "electrical stress history" of the oil.

The extremely sensitive detection system to measure the electric stress in mineral oil directly exploits the electro-optical Kerr effect.

This nonlinear behavior of insulation liquids makes it difficult to use traditional resistive models to predict the electrical field distribution in oil-based insulation systems under DC stress. An alternative to resistive models – the ion drift model – was introduced in the 1980s by ASEA researchers [1]. In the ion drift model, transport equations are used to calculate the time-dependent behavior of the ionic density in liquid

5 Experimental setup demonstrating the Kerr measurement technique



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insulation ➔ 4. Using the difference in the density of positive and negative ions, the electrical field can be calculated as a function of time for each position in the system. It is clear from ➔ 4 that solving the equations in three dimensions for many points is computationally demanding. However, modern computers in combination with improved numerical schemes make it feasible to use the ion drift model to design critical parts of the insulation system in converter transformers.

Measurement of electric fields under DC stress in transformer oil

The ion drift model had to be verified by experimental measurement. Therefore, at the ABB Corporate Research laboratory in Västerås, an extremely sensitive detection system was created to measure the electrical stress in mineral oil directly. The setup exploits the electro-optical Kerr effect, which influences the birefringence of light passing through a liquid dielectric in an electrostatic field ➔ 5. Using this technique, the direction, magnitude and time evolution of the electric fields can be resolved.

The results from the Kerr technique compare well with ion drift model predictions and deviate strongly from the electrical fields predicted from resistive models, as would be expected.

The Kerr technique and the ion drift model – first used for the Itaipu project – have become important tools in the continuous development of insulation systems for converter transformers. These tools, along with associated simulations, enabled the development of the 1,100 kV DC converter transformer prototype in a very short time. The design tools, together with a deep understanding of the phenomena involved, have significantly contributed to ABB's technical leadership when it comes to HVDC and UHVDC converter transformers.

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[1] U. Gäfvert, et al., "Electrical field distribution in transformer oil," *IEEE Transactions on Electrical Insulation,* vol. 27, no. 3, p. 647, 1992.