Excerpt from the Proceedings of the 2011 COMSOL Conference in Stuttgart

Heat Transfer in High-Voltage Surge Arresters

Oliver Fritz*[,1], Marlene Ljuslinder[2] and Bernhard Doser[2]
[1]ABB Switzerland Ltd, Corporate Research, [2]ABB Switzerland Ltd, High Voltage Products
*Corresponding author: Segelhofstrasse 1K, CH-5405 Baden-Dättwil, oliver.fritz@ch.abb.com

Abstract: We present results of the use of COMSOL Multiphysics for the design optimization of gas-insulated high-voltage surge arresters. By solving the equations for electric conduction and heat dissipation in non-linear media and for heat-transport through conduction and convection, we achieve meaningful results and can compare them to specially designed equivalent measurements. We model the important materials by fitting measured power-loss and impedance data with analytic functions. The good agreement between simulations and measurements make design optimizations based on computations a valid option for the further development of high-voltage surge-arresters.

Keywords: high voltage equipment, heat transfer, varistor, nonlinear impedance, design optimization.

1. Introduction

Surge arresters are part of the protective equipment in an electric network, their core part is a piece or stack of so called varistor material that becomes quickly conductive in the event of an overvoltage (to be precise, of a high electric field) while being basically non-conductive in the nominal case. For high-voltage applications, the varistor part is usually enclosed in a pressurized SF_6 casing and therefore the need for thermal management calculations is given. Basis for the simulations reported in this paper is the model AZ14 by ABB, a commercially available high-voltage gas-insulated metal-oxide surge arrester that has been in successful operation for several years.

Improved material manufacturing and the requirement of smaller footprint make the redesign of high-voltage surge arresters a regular task. Before newly designed equipment can be offered to customers, type-tests according to standards must be passed. In order to virtually prepare for such tests, coupled studies and simulations of the electrical and thermal behavior are an important development step.

COMSOL Multiphysics has since several years been one of our methods of choice for coupled simulations of electric and thermal processes, especially when proprietary information in the form of field- and temperature-dependent material properties had to be used. In the present case, it was additionally important to minimize the number of manual steps between importing a two-dimensional CAD design drawing and simulating the full test scenarios.

2. Design, Geometry and Meshing

Basis for the simulated geometry was a two-dimensional CAD drawing of the AZ32. The drawing was already slightly “cleaned” of parts that would not influence the simulations significantly (details of drilled holes, screws, etc.). Then, the geometry was imported into COMSOL with the CAD import module, using dxf as exchange format. A further cleaning step followed with the removal of sharp edges or other small-scale features.
The finally used model consists of four different types of material domains, namely, aluminum, epoxy insulation, varistor material, and SF_6 gas. A view of the full geometry is given in Figure 1.

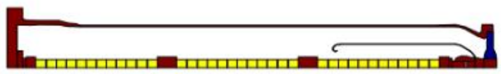

Figure 1. Material domains of the simulated arrester: Varistor material is shown in yellow, aluminum in red, epoxy insulation in blue, and SF_6 gas in white. Note that we simulate an upright arrester in two-dimensional rotational symmetry; the flat position shown above is only used to fit the figure. So, the bottom line is the symmetry or z axis, rising from left to right. The top central end including the field grading hood (thin red curved structure) are connected to high voltage, the bottom plate (left) and the outer insulation are on ground potential. The varistor column is divided into three sections of twelve blocks each in the used AZ32 design. These blocks were characterized with dedicated measurements as explained in the text.

The mesh creation had as most important goal to keep the total number of cells below 100’000 while respecting all necessary conditions for stable flow simulations. These requirements could be fulfilled with minor manual intervention in the automatic mesh generation process: The order in which the domains were meshed and certain size settings had to be adjusted manually.

3. Material Data and Simulation Strategy

The key ingredient of a surge arrester is the varistor material. Its nonlinear, temperature and field dependent electric conductivity as well as the high dielectric constant are responsible for the desired functionality. Power loss and dielectric constant (at 50 Hz AC) of the selected varistor material were measured experimentally in house, both as functions of temperature and electric field. The measurements were performed on single blocks of varistor material; typical results are shown in Figure 2.

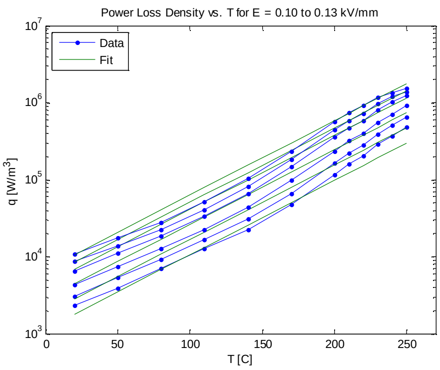

Figure 2. Measured and fitted power loss density of a single varistor block for six different values of applied electric field. The data was acquired in an oven with a controlled temperature.

The basic question to ask was how to practically feed the detailed AC property characterization of the varistor material into hour long thermal-transport simulations. Obviously, fully transient simulations of the electric currents (AC at 50 or 60 Hz) cannot be considered effective for this purpose, as the thermal and convective time-scales of the problem are orders of magnitude larger than the AC time-scale of milliseconds.

Strictly speaking, of course, a harmonic approach of AC conductivity is not correct for a medium of which the conductivity depends on the electric field. So, we had to take a way out of this fact by using a “pseudo-harmonic” approximation. We defined an artificial conductivity σ in such a way that the “harmonic” Joule heating of a material with this conductivity at a given voltage and temperature would be exactly the same as the power loss of the “real” nonlinear material as measured (and effectively averaged) over a few AC periods at the same applied voltage and temperature.

With other words, the conductivity σ of the varistor material was fitted from heat-loss experiments of a block in such a way that the same block used in a harmonic AC simulation in COMSOL would yield the same resistive Joule heating measured in the experiment given the same voltage and temperature. For that purpose, a fit function of the form

$$\sigma = \sigma_0 \exp(\beta_E E) \exp(\beta_T T) f(E - E_c)$$

was assumed. The function $f(E\text{-}E_c)$ is of order unity and takes into account deviations from a factorized exponential behavior at high electric fields above a critical field E_c. This critical field is related to the microstructure of the varistor material (see [1] and [2] for reference, e.g.). The coefficients σ_0, β_E and β_T were obtained directly from a fit to the mentioned power-loss measurements (Figure 2).

The relative permittivity ε_r of the varistor material has been determined experimentally as well. It ranges at 50 Hz from around 800 at room temperature up to 2000 at 200 °C. The measured data was fitted with a simple second-order polynomial in temperature.

The electric and thermal parameters for aluminum, SF_6 and epoxy insulation were taken from standard tables with linear temperature dependence, the values for the varistor blocks were measured in house.

The simulation strategy chosen followed closely the experimental setup of the dedicated validation measurements performed on complete arresters. In these experiments, temperatures inside the arrester and on its outer surface were measured while a voltage was applied at the top contact against ground on the bottom. While the varistor blocks – together with the whole surge arrester – heated up slowly, the voltage was adjusted every few minutes such that a given total electrical power input was kept constant. This amounted in fact to a steady reduction of the applied voltage as – through increased temperature – the varistor material became increasingly conductive.

Translated to COMSOL paradigms, this strategy was effectuated by a script that alternated between a stationary harmonic AC calculation and a transient heat conduction and convection calculation using the Joule heating in the varistor column as a source.

Normally, the total simulation time was five hours, every ten minutes the heat transfer calculation was interrupted by a re-calculation of the electric field and consequently the Joule heating sources. So, 30 steps as described above gave one full scenario; on our moderate computation infrastructure, two to three such scenarios could be simulated overnight. In experiments and simulations, total power dissipation values of 500, 1'000 and 1'500 W were chosen, these were achieved with applied rms voltages of around 200 kV with the given varistor material and arrester size.

A further key parameter of the simulations was the heat transfer coefficient at the outer surface of the surge arrester, it was chosen between 5 and 10 W/(m^2K) which corresponds to indoor conditions with no or very little surrounding air movement. In this context it should be noted that even after five hours of simulation, a stationary state was not yet reached.

4. Typical Results

Basically, three important values were used in every scenario to validate the simulations against the measurement results. These were the electric field distribution along the symmetry axis of the varistor column, the total Joule heating within the column, and finally the development of temperature distribution in the whole arrester.

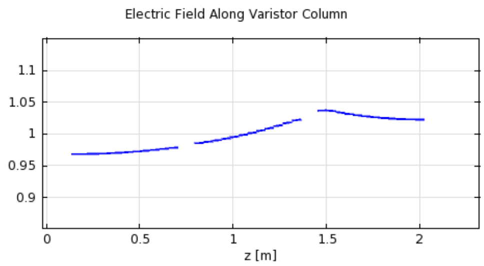

Figure 3. Normalized distortion of the electric field along the central axis of the varistor column. The highest electric field is roughly at the height of the tip of the field-grading hood.

Figure 3 shows the electric field in the center of the varistor column, normalized to the applied total voltage divided by the total length of the varistor column. The field distribution is fairly capacitive in nature; its maximum is near the tip of the field grading hood. No surprises were found in these results obtained with COMSOL's harmonic AC conduction mode.

The electric field and the temperature determine the conductivity of the varistor column and thereby the Joule heating. Using this heat source and an ideal-gas Boussinesq approximation for the driving force of the free convection in the SF_6 domain (gravitation pointing down), a thermal transport simulation was perfectly able to find out the temperature distribution in the whole arrester.

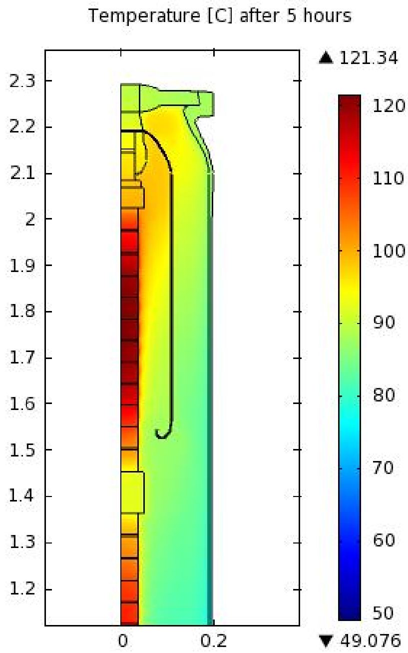

Figure 4. Temperature distribution after five hours with a constant heating power of 1'000 W. The convective distribution in the SF_6 domain can be easily seen in the top part of the arrester where the field-grading hood influences the cooling flow.

In Figure 4, we show a typical result of a full simulation scenario, the case shown used 1'000 W as constant power input, and 5 W/(m^2K) as surface heat transfer coefficient to ambient air at 20 °C. The flow velocities in the gas domain remain at an order of cm/s, the highest found temperatures are slightly above experimental observations, which is probably due to a rather conservative treatment of the boundary conditions at the top and bottom of the arrester.

5. Conclusions

We have shown results from "adequately" coupled electric and thermal simulations of large high-voltage surge arresters. We used a concept of quasi-harmonic approximation which makes particular sense in combination with the availability of precisely measured material data and a simulation strategy that ensures good control over the totally dissipated power.

We have used successfully the same mesh for electric and heat transport simulations including free convection in a basically nonviscous gas. The computational effort could be controlled with minor adjustments to standard meshing procedures and solver settings.

Given the quality of the results and the generally good agreement between the simulated scenarios and the experimental findings, we have decided to regularly use COMSOL Multiphysics simulations for supporting design decisions in surge arrester development.

6. References

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