Design and Optimization of Cable Accessories using COMSOL Multiphysics

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Abstract: This **paper demonstrates the overall process of modeling and optimization involved in the design of a cable joint by Lovink Enertech B.V with the aid of the COMSOL Multiphysics user software and its relevant packages. It involves electrostatic and thermal calculation at steady state and magnetostatic and mechanical estimations at transient cases.**

I. INTRODUCTION

CABLE joints are important and critical components of High Voltage/Medium Voltage cable systems that necessitate extreme care in their design and installation in order to facilitate a smooth connection between two cable ends which in turn reduces the chances of failures. However, design and optimization implies repetitive testing through trial and error which proves to be an expensive process as we move to higher power levels. However, Comsol Multiphysics provides a virtual workspace that simulates the problem domain close to reality by enabling the coupling between different physics phenomena.

This paper is organized to first introduce the geometry of the problem space and the materials used. The next sections that follow demonstrate step by step the design procedure involved in electrostatic and thermal simulations of the joint in steady state. And the last section describes the mechanical estimations made for transient cases followed by a short conclusion.

II. TEST STANDARDS

There are several electrical Test standards that specify the Requirements of High Voltage assets such as cable joints. The designer of cable joints makes sure that it is compliant with the relevant test standards available. One such international standard is the HD, for EU nations. HD 629.1 S2-2006 titled 'Test requirements for accessories for use on power cables for rated voltage from 3.6/6(7) kV up to 20.8/36(42) kV and cables with impregnated paper insulation' is taken as a reference for this paper and all the simulations that follow check the compliance of the joint design with the relevant norms. Additional reference is made to the IEC 60287 test standard for thermal simulations.

III. GEOMETRY AND MATERIALS

A. Geometry

The cable joint used in the simulation is a 12/20kV (U_o=U) silicone-filled straight joint for polymeric cables is as shown in figure 1. The commercial product name of which is Lovisil M-series® [1]. In the simulations performed, a XLPE cable of 185mm^2 cross-section with a current rating of 550A in air and 460A in buried soil (1m deep) is modelled [2]. The other relevant geometry specifications that were involved in the simulations are listed in Table I. The drawings used for simulations are drawn using the CAD tool, SOLIDWORKS, and imported into Comsol using the CAD kernel.

TABLE I. GEOMETRY SPECIFICATIONS

Cable dimensions:	
Size (mm^2)	185
Diameter (mm)	15.9
Thickness of Insulation (mm)	5.5
Thickness of conductive screen (mm)	1
Thickness of HDPE (mm)	2.5
Current Rating:	
Continuous current rating in Air (A)	550
Continuous current rating of buried cable (A)	460

Fig. 1. Example of a generic straight cable joint from Lovink

The joint is modelled to be under 1m deep soil of type 'peat', which has the worst thermal behavior in the various classes of soils. Figure 2 shows the geometry that was used in COMSOL Multiphysics. The domain above the soil domain represents air. This is an essential requirement for modelling heat fluxes in thermal simulations. The model is solved utilizing the axis symmetry available in the joint geometry, as this helps reduce the required computation time.
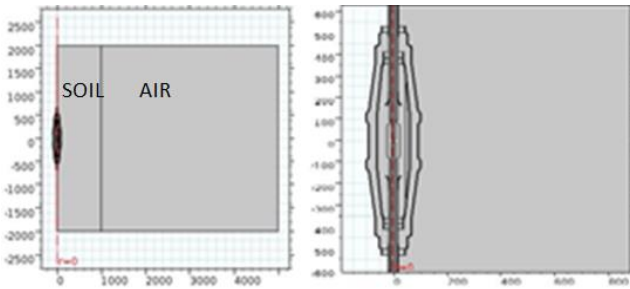

Fig. 2. COMSOL geometry of the problem space

B. Materials

The cable conductors are assigned the properties of Aluminum 3003 H-18 available under the in-built materials in Comsol. The polymeric cable insulation is XLPE with a dielectric constant of 2.5 and the joint casing is made of ABS (Acrylonitrile Butadiene Styrene) which is a hard plastic with good mechanical strength. The thermal conductivity of soil is taken to be 0.53W/m.K [3]. The liquid silicon material (Lovisil) inside the joint has 2.73 as its dielectric constant.

IV. ELECTROSTATIC SIMULATION

The A.C voltage (dry) test specification on HD629 states that the cable joints should be tested at $2.5U_o$ for 15mins with no breakdown. However the initial conditions for the electrostatic simulation, which is the static voltage is taken to be U_o instead of $2.5U_o$ because the system behaves linearly and the field plots obtained can be scaled using the factor of 2.5 instead.

The electrostatic module in Comsol solves the Gauss' law for electric fields using the scalar electric potential as the dependent value [4], given by the equations;

$$-\nabla.(\varepsilon_0\varepsilon_r\nabla V) = \rho$$

Where,

$D = \varepsilon_o\varepsilon_r E$

And $E = -\nabla V$

The electric fields in a cable joint is confined to the central region between the two field control ends. The field control device, which in this case is a stress cone made of semiconducting material (specially tailored for HV equipment) guides the electric field in such a way that the tangential component of electric field is restricted below the dielectric strength of the insulation material. Figure 3 illustrates the field control with and without stress cone.
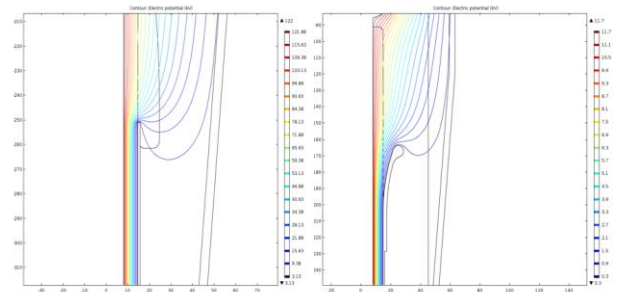

Fig. 3. Plot of potential lines without field control (left) and with field control (right).

Electrostatic simulations are the most important among all in the design of joints. They help to verify the robustness of the design electrically. The normal electric field plot obtained by Comsol is shown in figure 4. The plot of the tangential electric field along the cable surface in shown in figure 5. These values determine the electrical stress inside the joint and through these results it is possible to verify the design dimensions.
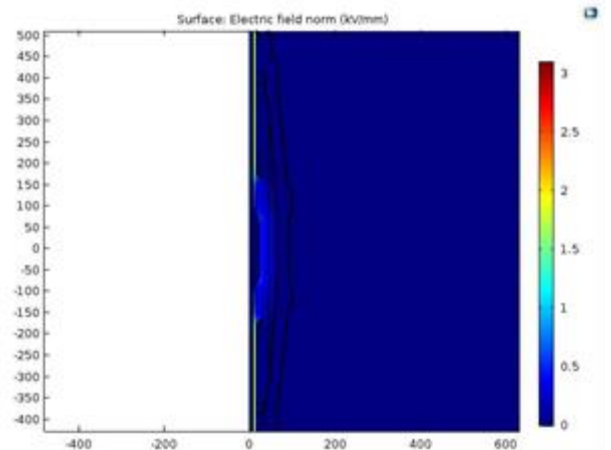

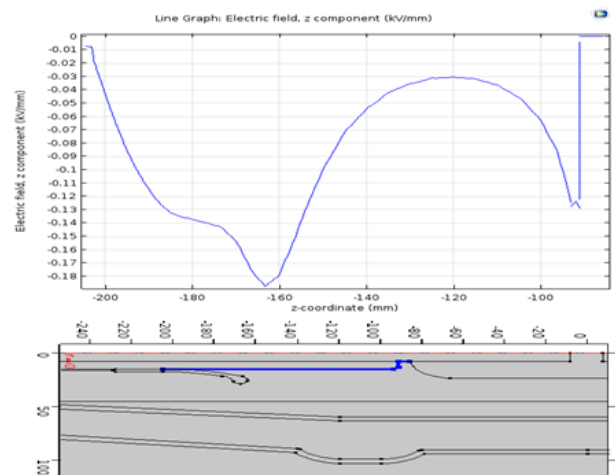Fig. 4. Plot for normal component of electric field

Fig. 5. Plot for tangential component of electric field

V. THERMAL SIMULATION

The conditions for heat transfer are obtained from the standards IEC 60287-3-1-Section on 'operating conditions' [5]. It prescribes the operating conditions such as thermal conductivity of the surrounding soil media, the ambient atmospheric temperatures and surface temperatures for soil; all grouped based on the region.

Further, the IEC standards 60840(2004) prescribes a limit for the maximum conductor temperature under normal operation based on the insulation material of the cable. And for a XLPE cable the maximum operating temperature is set at 90ºC. Hence, this would serve as a benchmark to the results of the simulations. The thermal simulations account for the heating due to the eddy currents and skin effect at AC conditions. The heat transfer physics interface solves for temperature using the differential form of Fourier's law with electromagnetic heat dissipation as the heat source. The equation for heat flow for a pure conductive domain is described by the equation;

$$\rho C_p \frac{\partial T}{\partial t} = -\nabla.q + Q$$

Where,

ρ is the density in kg/m^3

C_p is the heat capacity at constant pressure in J/Kg.K

T is the temperature in K

Q is the heat source in W/m^3

$q = -k\nabla T$ is the heat flux due to conduction in W/m^2

Figure 6 shows the temperature plot obtained by the Comsol simulation. The conductor maximum temperature is 81.7 ºC, and this confirms that it abides by the prescribed IEC standards.
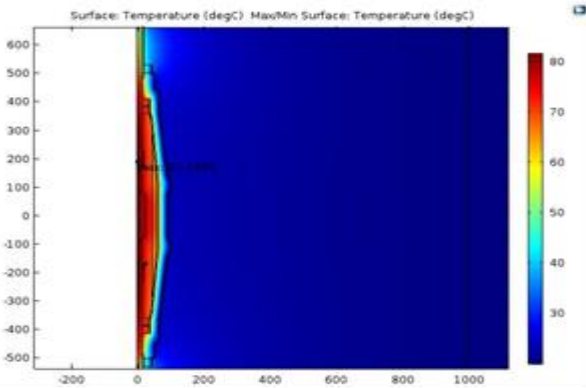

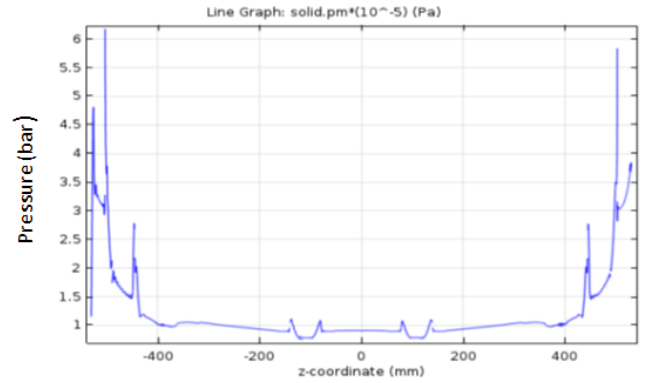Fig. 6.   Temperature plot

Fig. 7.   Steady state pressure over the joint outer casing

Further simulations are performed using a combination of joule heating and thermal expansion Multiphysics interface to simulate the pressures and thermal expansion due to the heat generated during operation. The thermal expansion in the module is solved based on the temperature gradients through the equation;

$$\varepsilon_{th} = \alpha(T - T_{ref})$$

It is essential to define the thermal expansion coefficient of the constituent materials in this case, in order to obtain accurate results. Frequency study at 50Hz is performed to obtain the steady state temperature, expansion and pressure. Figure 7 gives the plot for pressure over the joint casing.

The thermal expansion of the various parts of the joint that are of interest from the design perspective are listed on Table II.

TABLE II.   THERMAL EXPANSION AT STEADY STATE

Section of the Joint	Thermal expansion in mm
At inner casing	0.78
At outer casing	1.12
cable entry point	1.92

VI. SHORT CIRCUIT SIMULATION

The objective of the short-circuit simulations is to simulate the magnitude of Lorentz forces that will act on the conductor. HD-628-V1.1996 and IEC 60840(2004) [6] [7] are used as the reference standards to calculate the current capacity at short-circuit and its corresponding maximum temperatures. The maximum current for cables with aluminum conductors can be calculated from the expression;

$$I^2 t = 2.19 * 10^4 * S^2 * \ln(\frac{\theta_{sc} + 228}{\theta_t + 228})$$

Where,

S is the cross sectional area in mm2

θ_{sc} is the permissible temperature after short circuit in Celsius

θ_t is the initial temperature in Celsius

t is the duration of short circuit in seconds

and I is the maximum rated short circuit current

The simulations are done for a short-circuit current of 26.3kA (or peak-to-peak current of 52.6kA) for 1s. The waveform used for the simulation in comsol is generated using the equation;

$$I_{sc} = I_m \sin(\omega t) + e^{-t/\tau}$$

Where,

I_m is the maximum rated short-circuit current of the conductor

ω is the angular frequency at 50Hz and

τ is the circuit time constant

The 'Electromechanics' interface in Comsol is used to model the Lorentz forces and magnetic flux density while the 'Joule heating interface' is used to deduce the temperature of the conductor at the end of the short-circuit condition.

Magnetic fields simulations in the axisymmetric setup in 2D is quite a challenge, as it requires to solve for in-plane vector potential. It eliminates the use of the coil node to define the conductor as it assumes the current in the out-of-plane vector direction. Therefore, the external current density term is used to define the current over the conductor and connector section. However, the use of external current density does not take care of the skin effect. Which means that a part of the current in the bulk of the conductor is neutralized due to the induced eddy currents. And to compensate for this, a new control parameter is defined using the global equations and forced to the value of the required current by measuring the actual current flowing out of the domain specified. The equations for the new parameter used is given by;

$$I = I_{req} - I_{measured}$$
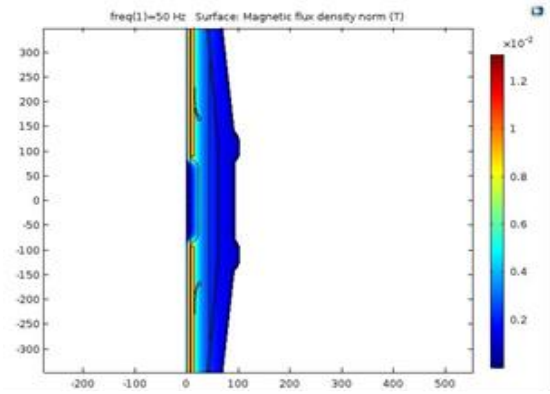$$\text{And } I_{measured} = \int J_z$$

Fig. 8. Magnetic field plot

The other complexity involved in this model is the changing cross-section of the current domain. This would mean that the current density defined along the z-axis in the connector-connector region is not constant. Therefore, this violates the current conservation law. However, the Gauge fixing for A-field enabled over the problem space compensates for this problem. The enormous degree of freedom (mathematical) available while solving for in-plane components in a certain cross-section could be limited by applying a gauge transformation. The gauge fixing enforces the relation $\nabla.A = 0$ on all the domains which solve for A, along with an additional potential variable ψ (A/m). The ψ ensures that the absolute value of the derivative of A has no actual significance but only its gradient has. This gauge transformation could be demonstrated by the following equations;

$$B = \nabla \times A$$

Using the transformation; A=A + ∇ ψ

$$B = \nabla \times (A + \nabla\psi) = \nabla \times A$$

The magnetic field physics interface solves for the magnetic fields using the Maxwell's equations with the magnetic vector potential ($\bar{A}$) as the dependent variable. The equations are briefly described below;

$$B = \nabla \times A$$

Solves for B and the Ampere Maxwell's equation;

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

Where,

$$J = \sigma E + j\omega D + J_e + \sigma(v \times B)$$

$J_{d=}j\omega D$ is the displacement current (Occurs only in quasi-static mode when E is varying with time)

$$J_c = \sigma E + J_e + \sigma(v \times B)$$

is the conduction current. It is the sum of the current induced due to electromagnetic induction (first 2 terms) and the external current.

The magnetic field plot is shown in figure 8. At normal operating conditions, the magnetic fields in a cable network are quite small in the range of mT. However, they are of interest and concern during the event of a short-circuit when the values grow to dangerously high levels due to the large current flowing through the screen and conductors.

The magnetic fields generated during the short circuit is shown in figure 9. The magnetic fields and forces simulated through Comsol Multiphysics can be checked through analytical calculation. The calculated values confirm the correctness of the simulations designed through Comsol.

$$B = \frac{\mu_0 \, I_p}{2\pi r}$$

These equations are given below;

$$F_L = BIL \, sin\theta = 1.2 * \left(\frac{26.3kA}{\sqrt{2}}\right) * l * sin90°$$
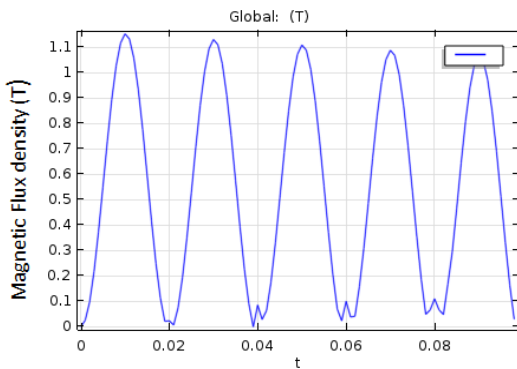$$= 22.316 N/m$$

Fig. 9.   Magnetic field variation during a short circuit

Figure 10 shows the forces on the conductor and figure 11 shows the temperature at short-circuit. The values of maximum force can be checked against the analytical calculation made above.
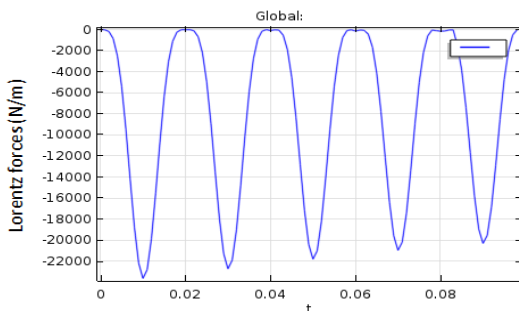
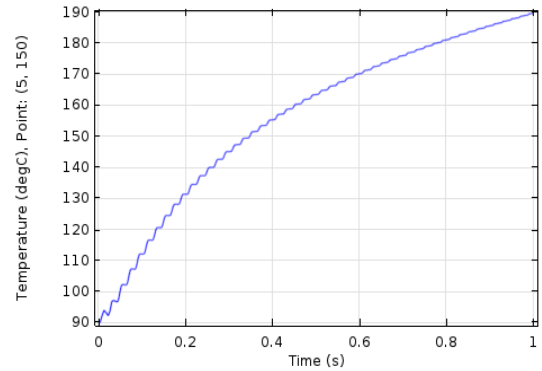Fig. 10. Lorentz forces on the conductor during short circuit

Fig. 11. Temperature at short circuit current

VII. CONCLUSION

The paper demonstrates the developmental process of a cable joint with the help of COMSOL Multiphysics. The application of the simulation software in the field of designing accessories has helped speed up the development process and reduced the need for repetitive pre-clearance tests. Crucial decisions have been able to be made based on the simulation outcomes through Comsol. There is still a scope to develop a simulation for ageing of insulation in cable joints through the heat cycle tests as defined in the IEC and HD testing standards using COMSOL Multiphysics.

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