A novel method to simulate coupled 3D FEM with circuit applied to SIC-SFCL

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***Abstract*—High Temperature Superconducting (HTS) devices are taking an important role in electrical power systems. The Finite Element Method (FEM) often simulates the device in itself, and some simplified models are applied to represent the equipment in electric grid studies, sometimes neglecting its physics. In this scenario, the development of models that can simulate the equipment integrated with the grid may be useful. Due to it, this paper presents a coupling method to link the superconducting devices modelled by 3D FEM to the power electrical system. This model enables an electromagnetic transient analysis. Moreover, by the FEM model, the critical current density of the tape can be examined in the transient period. A saturated iron-core superconducting fault current limiter (SIC-SFCL) will be modeled and connected to the power electrical grid as a study case. The simulation results are compared with experimental data to validate the model.**

Keywords*—*Superconducting Fault Current Limiter, Coupling Method, T-A formulation, Coated Conductors

I. T-A FORMULATION

In [1] the authors developed the procedures to simulate a 3D superconducting system using the T-A formulation. Figure 1 summarizes the idea of this formulation, where the T-formulation calculates the current density in superconductor domains and enforces this current in the A-V-formulation as a source. On the other hand, the A-formulation computes the magnetic field everywhere and applies it in the T-formulation.

Equations (1) and (2) represent the T-A formulation [1], [2]:

$$\nabla \times (\rho \times \mathbf{T}) = -\frac{\partial(\mathbf{B})}{\partial t}, \tag{1}$$

$$\nabla \times (\frac{1}{\mu} \nabla \times \mathbf{A}) = \mathbf{J_{HTS}} + \mathbf{J_e} + \mathbf{J_i}, \tag{2}$$

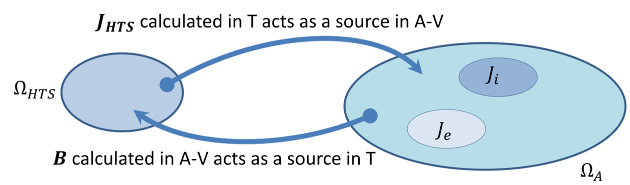

Fig. 1. T-A formulation idea

where $\mathbf{T}$ is the current vector potential, $\mathbf{A}$ is the magnetic vector potential, ρ is the electrical resistivity, μ is the magnetic permeability, $\mathbf{J_{HTS}}$ is the current density through the superconductor, $\mathbf{J_e}$ is the applied current density (a source term) that does not need to be calculated because is otherwise known, and $\mathbf{J_i}$ is the induced current.

II. COUPLING METHOD

The idea of the coupling method is calculated by FEM model the electrical parameters of the HTS device and input them as a voltage drop in the lumped electrical circuit. On the other hand, on the power electric system side, the current throw the HTS device is calculated and enforced to the HTS device by a Dirichlet's boundary condition. The procedure is summarized in figure 2. The box on the right represents the electrical power system, and the box on the left side represents the superconducting device modeled in T-A formulation. The block in the center schematizes an iterative procedure where the FEM model is linked to the power electrical grid.

The superconducting device is seen by the power system as a voltage drop V_{HTS}, which is obtained from the FEM model as follows:

$$V_{HTS} = -\int_{c_{HTS}} \mathbf{E} \cdot \mathbf{dl} - \int_{c_{HTS}} \frac{\partial \mathbf{A}}{\partial t} \cdot \mathbf{dl}, \tag{3}$$

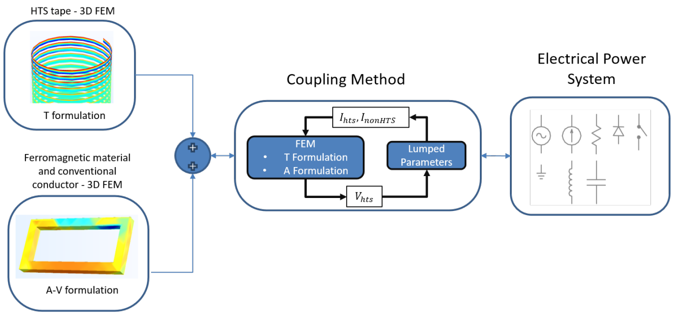

Fig. 2. Coupling method schematic of the 3D FEM model to the lumped parameter circuit.

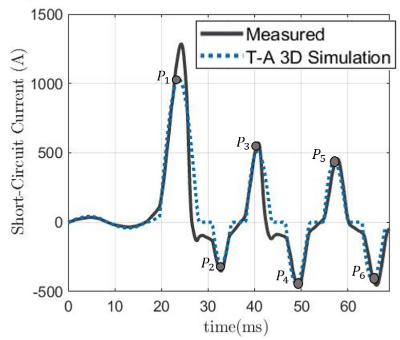

Fig. 3. Fault Current in different short-circuits types

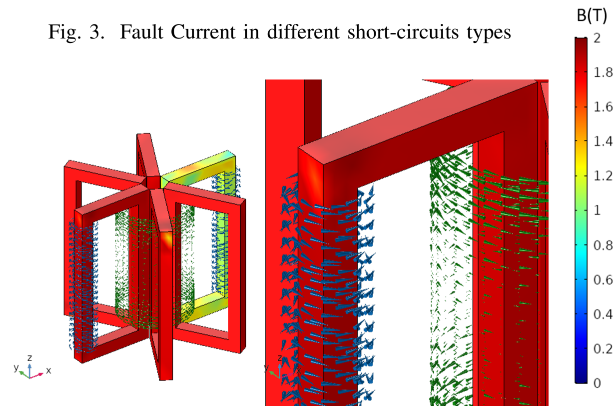

Fig. 4. Magnetic flux density and the current density (green and blue arrows) after 2 ms fault happens for different short-circuits types, at this time I_a =0.56 A, I_b =-37 A and I_c = 37 A

where c_{HTS} represents a path that connects the coil's two terminals.

III. The Studied Case: 3D Saturated Iron Core SFCL

The SIC-SFCL that was presented in [2], [3] is modeled in 3D system here. This case represents all iron-cores and phases.

The HTS voltage (V_{HTS}) is computed by the integration of the electrical field and the variation of the magnetic vector potential along the coil's path, as presented in equation 3. To validate the coupling method, results wer compared with experimental tests presented in [2], [3]. After the validation, a three-phase short-circuit is studied.

IV. Results

Figure 3 presents the ac currents of the simulated cases. Figure 3 compares the results of the single-phase short circuit and the experimental test that is explained in [3]. Comparing both experimental and simulation results, the highest error was found in p1 with 15%. In the steady-state regime the error was lower than 1%. The relative difference between these results is obtained by:

$$Error_{MS_{T-A}} = \frac{Data_{measured}(k) - Data_{T-A}(k)}{max(Data_{measured})}, \quad (4)$$

where, $Error_{MS}$ is the relative error between the measured bench test and the T-A simulation, $Data_{measured}(k)$ is the measured data at the point k, $Data_{T-A}(k)$ is the data obtained from the T-A simulation at the point k, $max(Data_{measured})$ is the maximum value of the measurements.

Figure 4 presents the magnetic flux density inside the iron-cores. In Figure 3 due to just one phase is connected to the grid, in the short-circuit only two iron-cores from phase A are completely desaturated as it is possible to see in 4.

V. Conclusions

This article proposed a new method to simulate superconducting devices considering both the superconducting and the ferromagnetic non-linearities in the 3D system coupled with the lumped electrical parameters. To validate this method, a SIC-SFCL prototype was simulated and compared with experimental tests. The simulation and the bench test agree, validating this methodology. The proposed methodology also allowed the investigation of the normalized current density and the critical current density. Then, the influence of the magnetic field over the HTS coil could be properly considered. Moreover, this transient behavior of the HTS coil calculated by the FEM is also seen by the power electrical system due to the proposed coupling method.

References

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