Coupled FEM–Circuit analysis of interconnected High Temperature Superconducting machines and components

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Abstract—**The present work focuses on the co-simulation of two HTS superconducting machines interconnected through a superconducting DC line made of a HTS DC cable and power electronics. The HTS rotating machines and the cable are modeled with the homogeneous T-A formulation of the Maxwell equations using Finite Element (FE) method in COMSOL Multiphysics whereas the remaining electrical components are simulated via lumped-parameter circuitry in Simulink. These components are a rectifier at the output of the generator with its associated RLC filter connected via the HTS cable to an inverter and its LC filter at the input of the motor. The challenges related to co-simulation for simulating interconnected HTS devices and the best settings to balance accuracy and computation time are studied in the context of the simulation of complex superconducting systems as found in future More Electric Aircrafts (MEA).**

Keywords—co-simulation, DC link, Superconducting devices, homogeneous **T-A** *formulation.*

I. INTRODUCTION

The present work deals with the co-simulation of compact and light superconducting (SC) generators and motors connected by a SC cable in the DC electrical network of future More Electric Aircrafts [1]. The electromagnetic behavior of such devices is in part dictated by their design including the choice of materials and in part by the nature of their connections with the electrical system. The latter is ensured by power converters. Here, co-simulation is employed to simulate the detail electromagnetic response of the HTS machines as well as the SC cable using a FE solver coupled
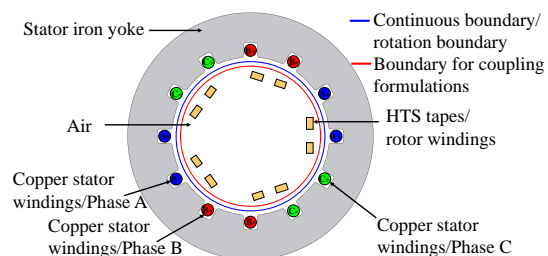

Fig. 1. Geometric model of the generator. The motor has a similar layout.

to a DC circuit simulated in Matlab/Simulink. The **T-A** formulation combined with homogenization technique is used for its fast computation time at a fair accuracy. The challenges and the best settings for coupling the FE models (FEM) and the lumped-parameter electrical circuit model are studied to provide the optimum range of co-simulation parameters minimizing the overall computation time accounting for the different regimes experienced by the aircraft generators [2].

II. DESCRIPTION OF HTS ROTATING MACHINES

Fig. 1 shows the conceptual design of the 5-pole generator with a maximum speed of 10,000 rpm. The motor represents here an equivalent model of several motors in parallel as a preliminary study involving only two interconnected machines in co-simulation. Both machines, in the 10 MW range, are composed of a superconducting iron-less rotor and a conventional stator benefiting from the high energy density offered by HTS wires. The rotor coils are wound with insulated commercial REBCO tapes cooled by liquid hydrogen at 25 K. The machine stators hold a three-phase Cu winding surrounded by ferromagnetic laminated material to lock the
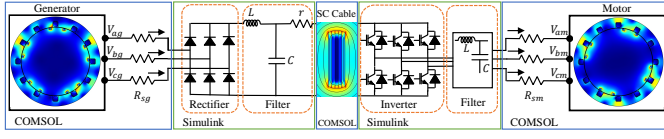
Fig. 2. Conceptual circuit diagram of the coupled FEM-Circuit using COMSOL and Simulink.

(a) B

(b) J_{sc}/J_c

Fig. 3. **T**-**A** results for the generator alone: (a) magnetic flux density B, (b) normalized current density J_{sc}/J_c.

Fig. 4. Electromagnetic torque of the generator in co-simulation and FEM only.

magnetic flux still allowing a lighter design but avoiding a large fringe field. Even though the machines are very similar, some distinctive features have been purposely chosen to test out the co-simulation settings.

III. RECALL OF HOMOGENEOUS **T**-**A** FORMULATION

The current vector potential **T** is computed over the superconductor domain only, whereas the **A** potential is solved in the complementary domain [3], according to:

$$\nabla \times \rho_{sc} \nabla \times \mathbf{T} = -\partial_t \mathbf{B} \tag{1}$$

$$\nabla \times \mu^{-1} \nabla \times \mathbf{A} = \mathbf{J} \tag{2}$$

with $\mu = \mu_0$ for the air and the superconductor and $\mu = \mu(H)$ for the ferromagnetic material. **T** is related to the current density in the SC tape via $\mathbf{J} = \nabla \times \mathbf{T}$ and the magnetic flux density **B** is given by $\mathbf{B} = \nabla \times \mathbf{A}$. For the rotating HTS machines, it should be noted that a local coordinate system is introduced to impose properly the boundary conditions on **T** and to compute accordingly **J** [4]. The resistivity of the superconductor, ρ_{sc}, is given by the power law taking into account the impact of the magnitude and direction of the magnetic flux density on the critical current density.

IV. CO-SIMULATION: FEM-CIRCUIT

The coupling between the software COMSOL Multiphysics (FE) and Simulink (circuit) is carried out using the Function Model Unit interface (FMU) built in Java. The overall time stepping is controlled by Simulink independently of the COMSOL's settings. Fig. 2 illustrates the full coupled model showing a HTS generator (COMSOL), a rectifier with its associated RLC filter (Simulink), a SC cable made of a stack of 6 REBCO tapes operated in DC at 3.3kA/3kV (COMSOL), an inverter with its LC filter (Simulink) and finally a HTS motor (COMSOL). The rectifier is made of 6 power diodes modeled with a single slope. The inverter is a 6-pulse 3-phase converter using IGBT controlled via Pulse Width Modulation (PWM).

V. RESULTS

At this stage, the generator, motor and SC cable have been simulated separately at a nominal power of 10 MW. Fig. 3 shows the magnetic flux density and current density distribution in one of the HTS generator coils. For a preliminary co-simulation study, the COMSOL FEM of the HTS generator was coupled to simulink with a simpler circuit involving the rectifier, the RLC filter and a DC bus simulated as an ideal voltage source at 3 kV. Fig. 4 shows the electromagnetic torque of the HTS generator. Two cases, with co-simulation and FEM alone, are compared. In co-simulation, the ripples arise from
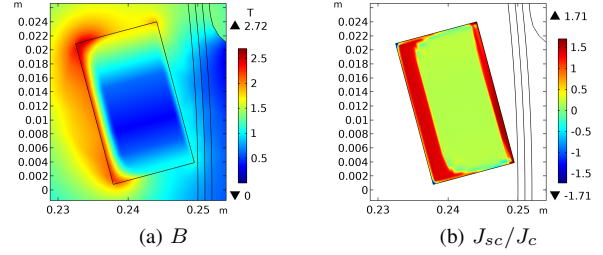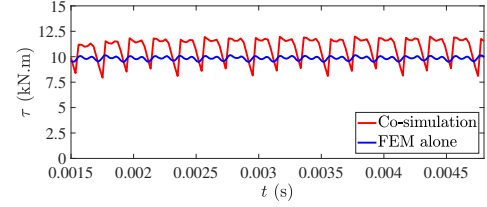
the connection to the rectifier which is not the case when the FEM is not coupled to the circuit. The next step is the connection of the motor to the inverter to finally interconnect the generator and the motor through the full circuit including the SC cable. One of the main challenge is to find the optimum communication time between the COMSOL and Simulink models taking into account the optimal time steps of each individual model.

VI. CONCLUSION

A coupled FEM-Circuit is being developed to simulate the electromagnetic behavior of a DC system made of HTS components and power converters for aircraft application. The idea is to provide a roadmap to develop complex system models taking into account HTS devices connected to or part of electrical networks. A first co-simulation was carried out on the generator and all the HTS devices have been simulated in COMSOL. The next step is the coupling of the motor FEM with its inverter and the subsequent co-simulation of the full DC system.

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