

Finite Element Model of a Superconducting Generator for Aircraft Application Coupled to an External Electrical Circuit

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Abstract

High temperature superconductor (HTS) material are strong candidates for the development of future electrical machines due to their high energy density at low AC losses resulting in greater electrical efficiency for lighter and compacter designs than traditional machines. The features are particularly appealing for transports. The present work focuses on the electromagnetic modelling of a superconducting synchronous generator for aeronautic applications with a particular interest in the coupling between Finite Element Model (FEM) and external electrical circuits. The FEM implements different formulations of the Maxwell equations, namely **H-A**, **T-A** and the classic **A-V** to find the best suited combination FEM - electrical circuit for computation load reduction (time and memory). The external circuit simulates the generator coupled with a rectifier and DC bus. The electrical power obtained in the DC bus is evaluated, which must satisfy the demand of the load.

Details of the HTS Synchronous Generator

The present work deals with the use of compact and light superconducting (SC) generators for aircraft applications.

Table I. Electromagnetic characteristics of the generator design.

Parameters	Value
Power (P)	10 [MW]
Speed rotational (n_s)	10000 [rpm]
Frequency of rotation, (f_{rot})	166.667 [1/s]
Mechanical speed, (ω_m)	1047.2 [rad/s]
Torque	10 [kNm]
Number of pole pairs	5
Electrical frequency, (f_e)	833.33 [Hz]
Electrical speed, (ω_e)	5236 [rad/s]
Current density in stator (J_{stator})	1.5E7 [A/m ²]
Number of slots	12
Winding factor (k_w)	0.966
Concentrated winding	
DC-link Voltage	3 [kV]

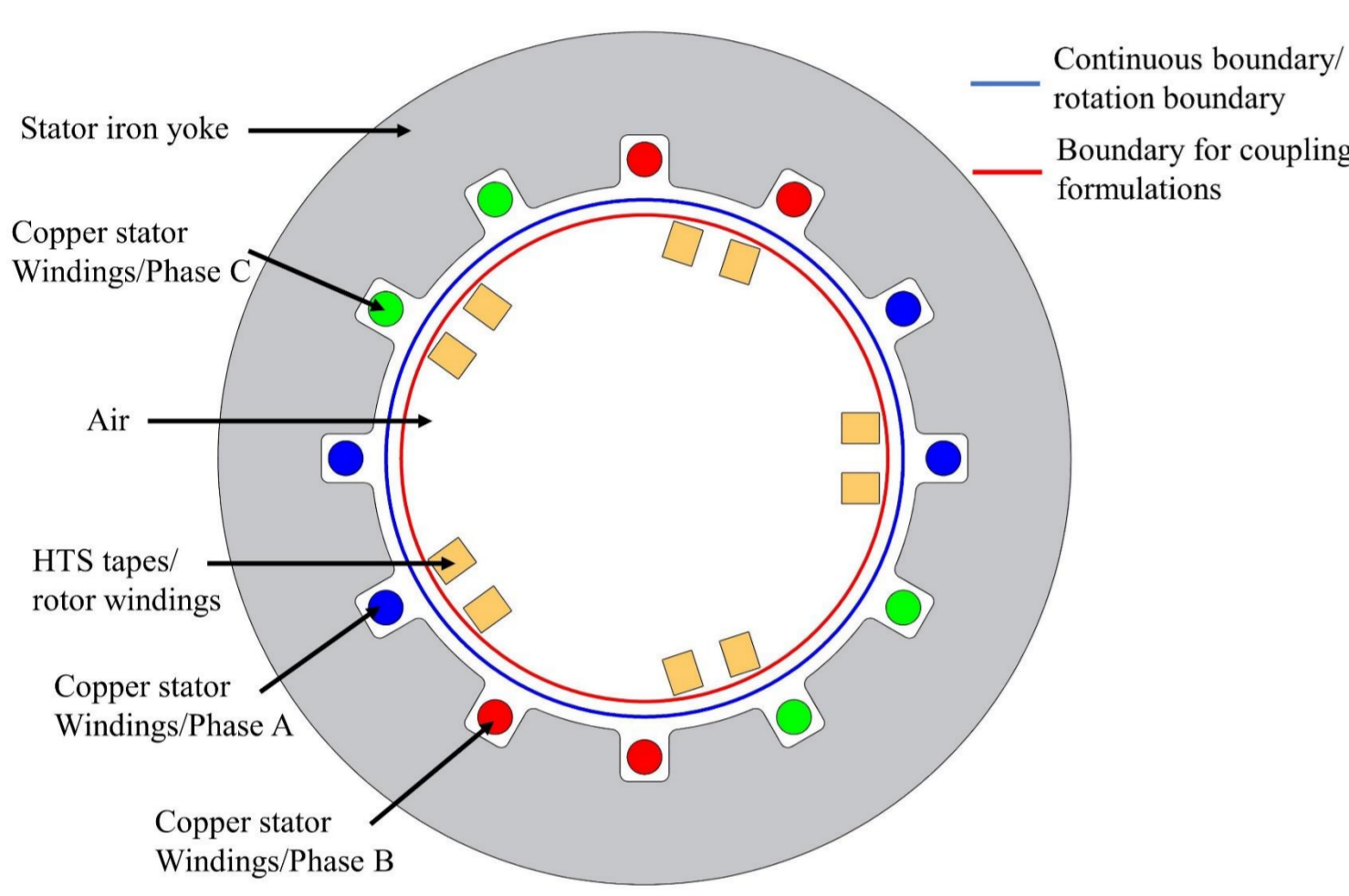


Fig. 1. Generator for aircraft application: SC rotor and conventional stator.

Fig. 1 shows the conceptual design of a 10 MW 5-pole generator with a maximum speed of 10,000 rpm and an approximate torque of 10 kNm.

Cosimulation: Coupling FEM and External Circuit

The coupling between the Finite Element software COMSOL Multiphysics and Simulink is being implemented.

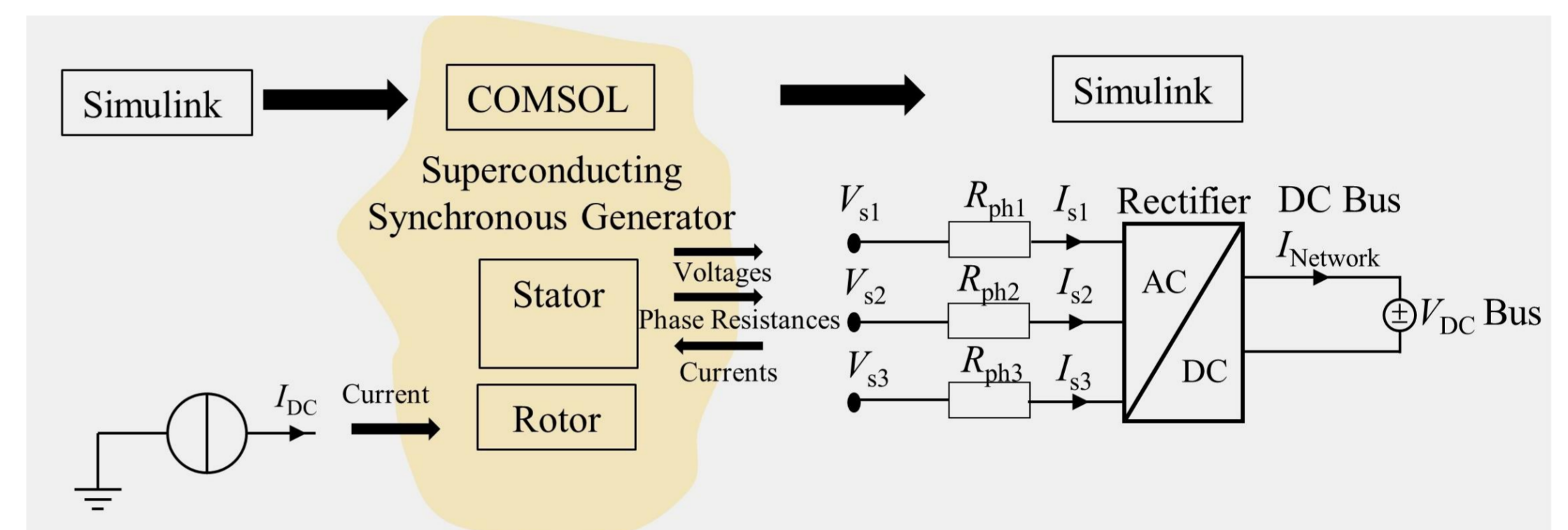


Fig. 2. Conceptual diagram of the coupling configuration COMSOL-Simulink.

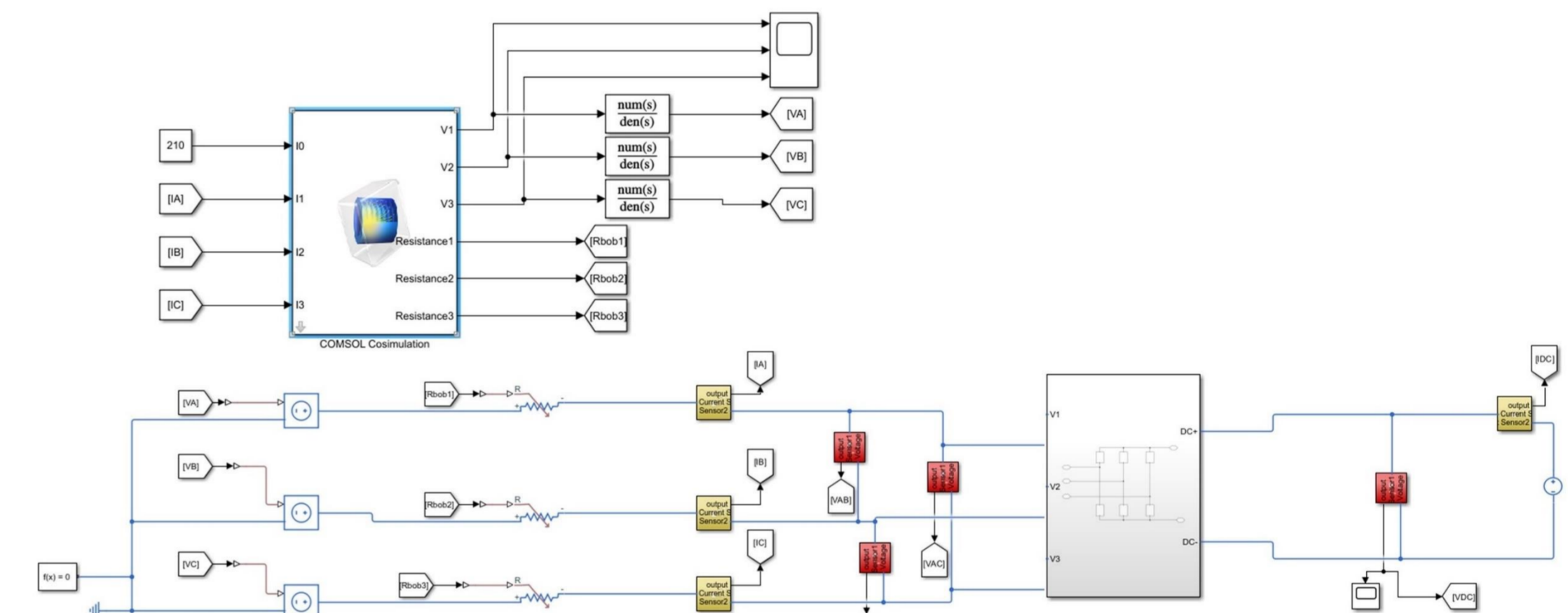


Fig. 3. Generator-rectifier-DC bus coupling model diagram in Simulink.

Formulation of Maxwell Equations

A. H-A formulation

H is solved in the superconductor domain (ρ given by the power law and $\mu = \mu_0$). **A** is solved in the non-superconducting region including the iron core ($\mu = \mu(H)$).

- The governing equations for the **H** and **A** formulations are
- The power law

$$\nabla \times (\rho \nabla \times \mathbf{H}) = -\mu_0 \frac{\partial \mathbf{H}}{\partial t}$$

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = \mathbf{J}$$

$$\rho_{HTS} = \frac{E_c}{J_c} \left| \frac{\mathbf{J}}{J_c} \right|^{n-1}$$

The two equations are coupled at the boundary of the domains ($\partial\Omega_{H-A}$) as shown by their weak form

$$\int_{\Omega_H} \rho \nabla \times \mathbf{H} \cdot \nabla \times \mathbf{H}^* d\Omega_H + \int_{\Omega_H} \mu_0 \partial_t \mathbf{H} \cdot \mathbf{H}^* = \int_{\partial\Omega_{H-A}} (-\partial_t \mathbf{A} \times \hat{\mathbf{n}}_H) \cdot \mathbf{H}^* d\partial\Omega_{H-A}$$

$$\int_{\Omega_A} \frac{1}{\mu} \nabla \times \mathbf{A} \cdot \nabla \times \mathbf{A}^* d\Omega_A - \int_{\Omega_A} \mathbf{J} \cdot \mathbf{A}^* d\Omega_A = \int_{\partial\Omega_{H-A}} (\mathbf{H} \times \hat{\mathbf{n}}_A) \cdot \mathbf{A}^* d\partial\Omega_{H-A}$$

Homogenization technique is used where J_c is scaled by a ratio of the surface of the superconductor layer (δ) to the surface of a tape (Δ), that is $\lambda = \frac{\delta}{\Delta}$.

B. T-A formulation

The current vector potential **T** is solved for the superconductor domain and the **A** potential is solved for the complementary domain.

T is related to the current density in the tape via $\mathbf{J} = \nabla \times \mathbf{T}$. From the Faraday's law, **T** is solved knowing the magnetic flux density $\mathbf{B} = \nabla \times \mathbf{A}$ as

$$\nabla \times \rho \nabla \times \mathbf{T} = -\frac{\partial \mathbf{B}}{\partial t}$$

Homogenization technique is used where the current density **J** is scaled by λ .

C. Classic A-V formulation

It combines the magnetic vector potential **A**, and the electrical scalar potential V . The governing equation

$$\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} + \sigma (\partial_t \mathbf{A} + \nabla V) = \mathbf{J}$$

$$\nabla \cdot \sigma (\partial_t \mathbf{A} + \nabla V) = 0$$

where $\sigma = 1/\rho$ is a nonlinear function of the magnetic flux density and electric field in the superconductor.

Results

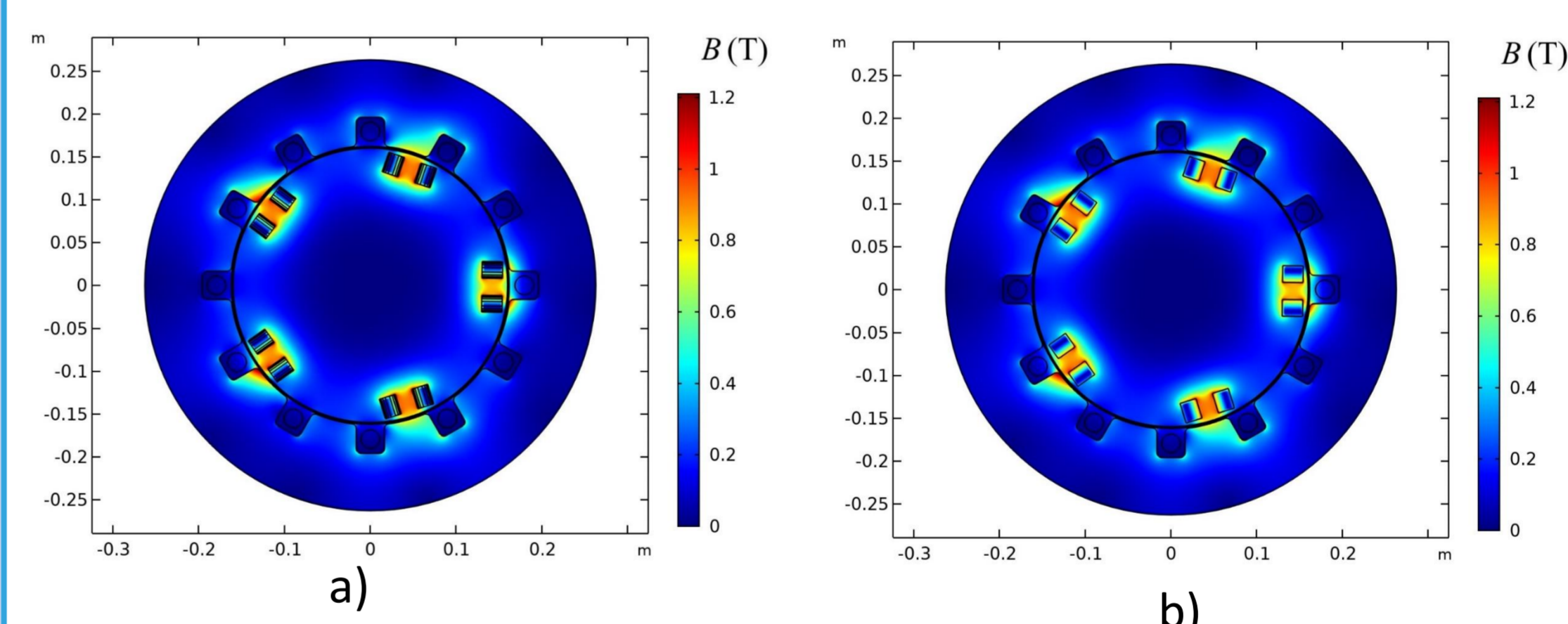


Fig. 4. Comparison of magnetic flux density distribution: a) H-A formulation and b) T-A formulation.

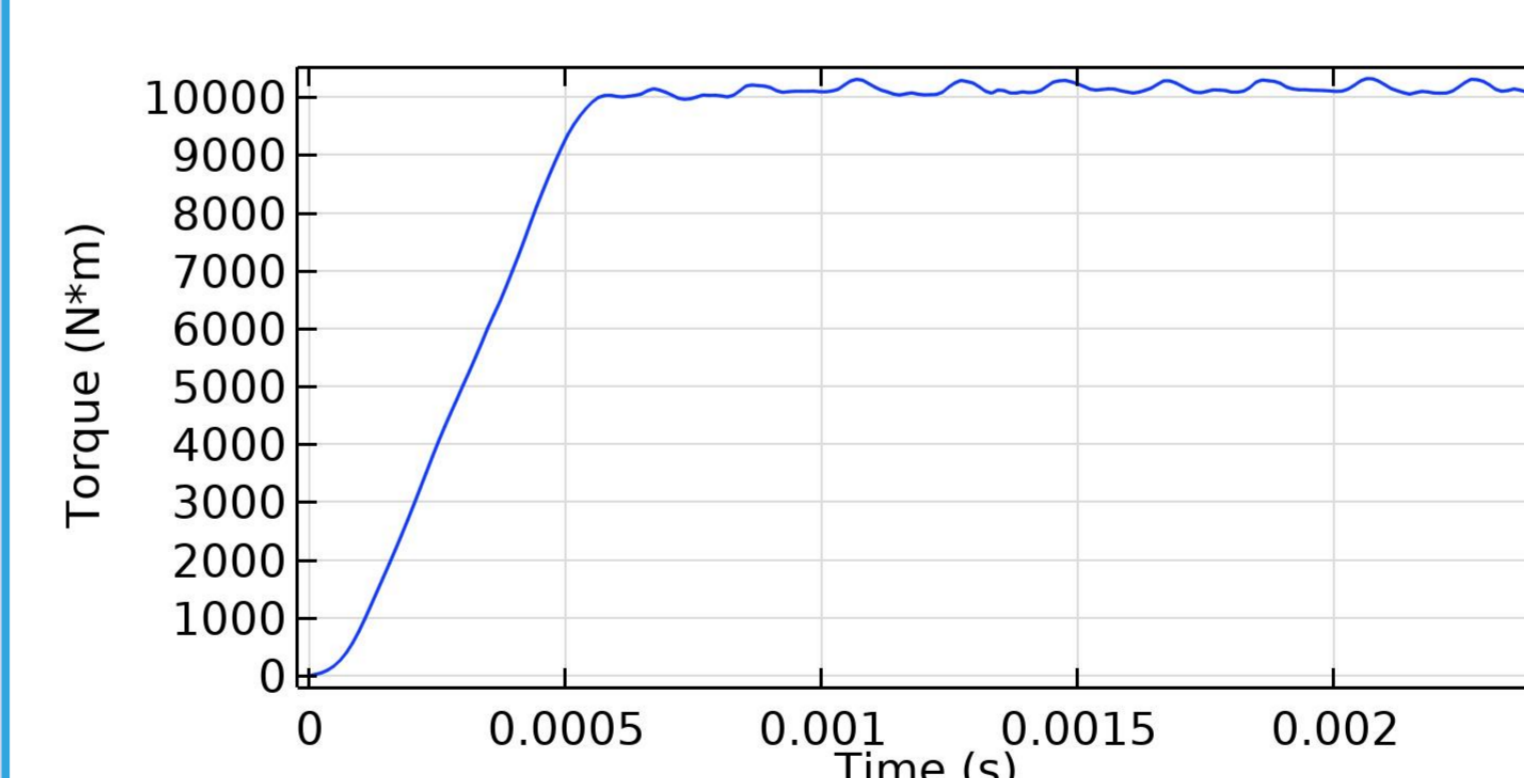


Fig. 5. Torque .

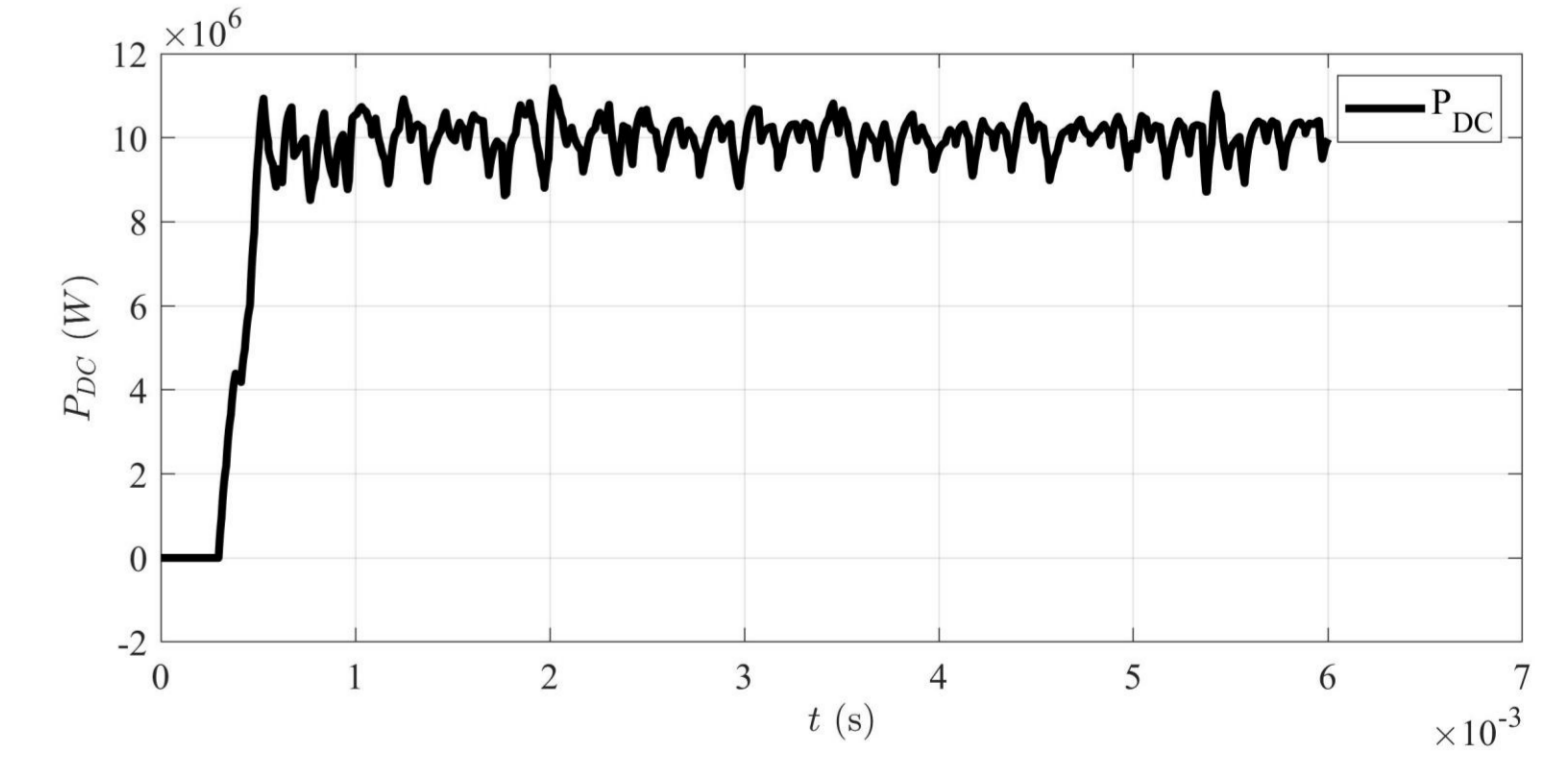


Fig. 6. Result of the co-simulation, electrical power in the DC bus.

Table II. Calculation time of formulations in FEM model.

	T-A formulation	H-A formulation
Time	49 min 53 s	7 hrs 12 min

Conclusion

- The most recent formulations of the Maxwell equations for HTS machine modeling are being compared to find the best combination to solved the coupled FEM and external electrical circuit to reduce the computation time and the resources.
- The FEM models in **H-A** and **T-A** formulation have been solved, however, the model in **A-V** formulation has convergence problems.
- The calculation speed is given by the FEM, the **T-A** homogeneous model is the most suitable in terms of computational resources as expected.
- The FEM includes the nonlinear behavior of the superconductor. It also includes all the classic features of machine simulation to get the most realistic outcomes.
- The model will be used to get some first insight on the performance of the HTS generator for aeronautic applications connected to the electrical network.