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Coupled FEM-Circuit analysis for interconnected High Temperature Superconducting machines and components

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Motivation

- Development of models:
  - Existing advanced formulations of Maxwell equations: **H-A** and **T-A** mixed with homogeneous technique ⇒ *practical for machine models* [1]
  - Modeling of SC components interacting with simple external circuit / components
  - Next step: from component to system ⇒ FEM - Circuit coupling [2]

- Supporting:
  - Development light and compact power components for transportation based on High Temperature Superconductor (HTS) components [3]

- Responding to:
  - Growing interest in the aircraft industries (two axes): 1) liquid hydrogen fuel, 2) more electric aircraft (MEA) ⇒ Hydrogen as coolant for SC components [4]

Fig. 1: Hybrid hydrogen aircraft from airbus (https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe)

[1]: Y. Yang, et al, *IEEE Trans on App. Sup.*, 2020, doi: 10.1109/TASC.2020.3005503.
[2]:Z. Wang et al.,*IEEE Trans. on App. Sup.*, 2017, doi: 10.1109/TASC.2017.2653807.
[3]: K. S. Haran et al, Supercond. Sci. Technol. 30 (2017) 123002 (41pp)
[4]: Airbus website, ACEND project, March 2021: https://www.airbus.com/en/newsroom/press-releases/2021-03-airbus-to-boost-cold-technology-testing-as-part-of-its

DC power chain

- ❑ <u>Power chain:</u>
  - Generation (HTSG, 10 MW) - cold
  - Conversion (power electronics) - warm/cold
  - distribution (HTSC) - cold
  - Load (HTSM, 2.5 MW) - cold

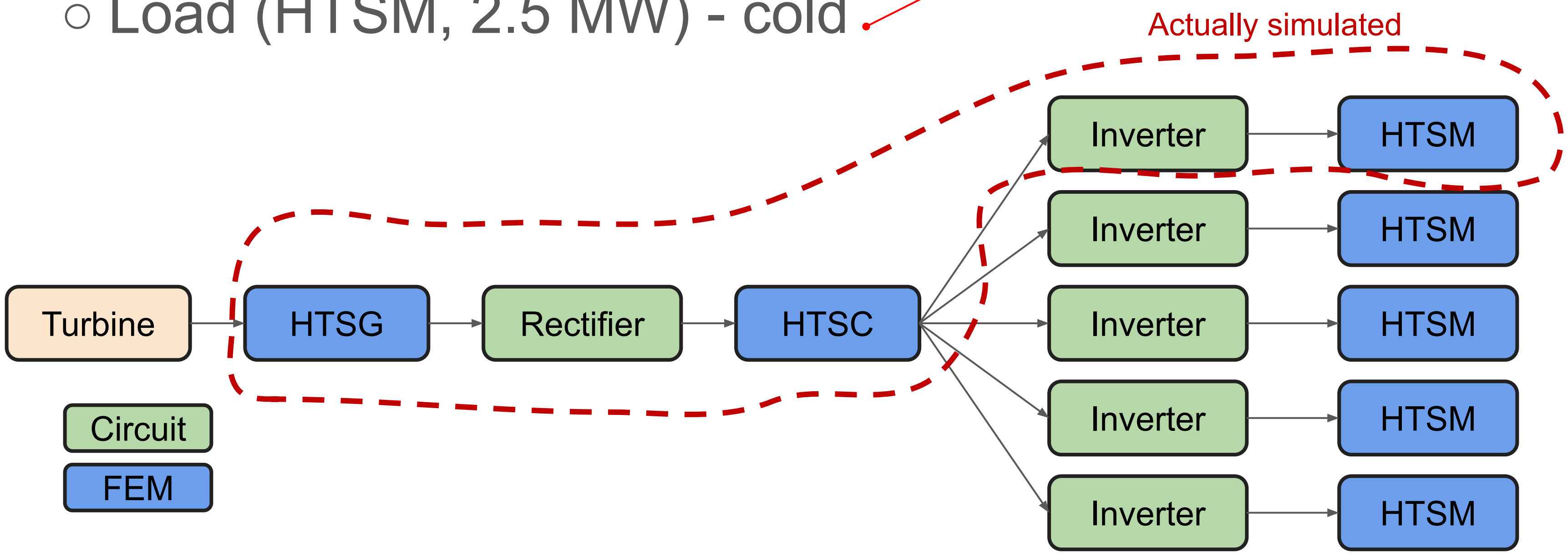


Fig. 2: Power chain from turbine to load: G for generator, C for cable and M for motor.

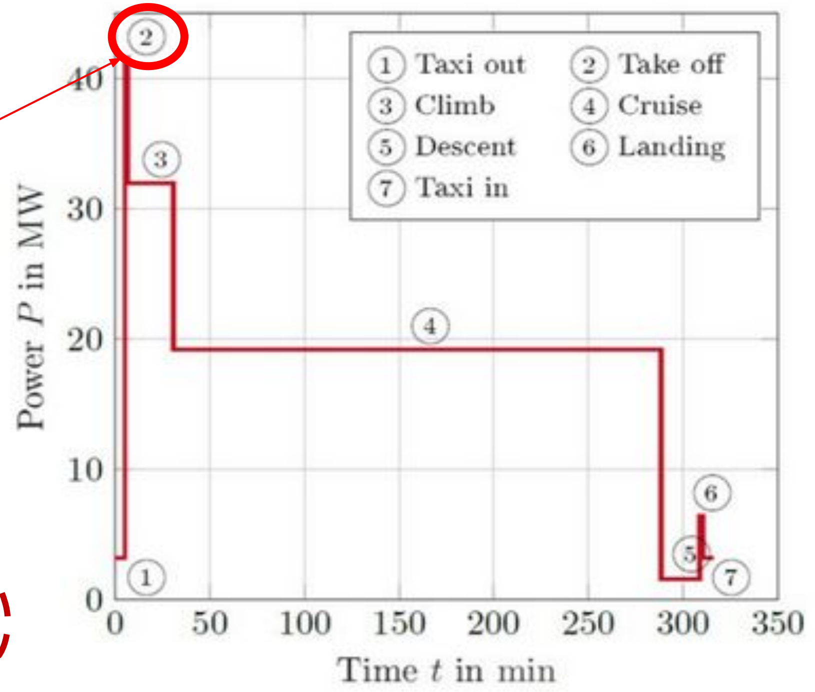


Fig. 3: Power demand. Interest in transient: Take off (2) wit maximum peak of demand [5]

[5]: M. Boll et al, Supercond. Sci. Technol. 33 (2020) 044014 (14pp)

FEM-Circuit model

- Cosimulation: transient FEM - electrical circuit model using COMSOL Multiphysics and Simulink
- Case study (Fig. 4): superconducting (SC) generators, rectifier, filter, SC cable, inverter, filter and SC motors (1 out of 4, we used 1 power converter for this case study)
- Machine model for generator and motor: SC ironless rotor - conventional stator [6]
- Machines and cable modeled with homogeneous **T-A**, with Kim's relation $J_c(\mathbf{B})$

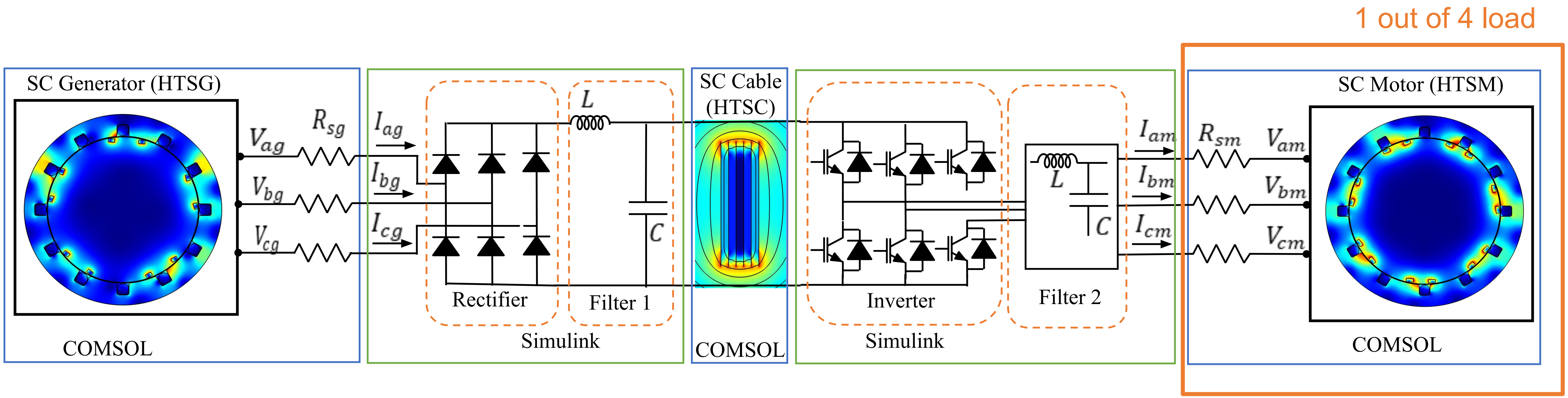


Fig. 4: Diagram of the coupled FEM-Circuit using COMSOL and Simulink.

[6]: M. Corduan et al, *IEEE Trans on App. Sup.*, 2020, doi: 10.1109/TASC.2019.2963396.

HTS rotating machines (HTSG and HTSM)

❑ Hybrid machines cooled by liquid hydrogen at 25 K:

- Ironless rotor: REBCO racetrack coils (I_c of tape at peak perpendicular field)
- Stator: basic COMSOL model (magnetic core to lock the flux)

Similar geometry on purpose

Tabla I: Characteristics of SC machines

Parameters	Generator	Motor
Maximum power	10 MW	2.5 MW
Rotor mechanical speed	10,000 rpm	4,500 rpm
Torque	10 kNm	5.31 kNm
Electrical frequency, f_e	833.33 Hz	525 Hz
Current density in stator	15 A/m^2	6.7 A/m^2
Number of pairs of pole	5	7
Number of slots	12	
Stator winding resistance	1.22 mΩ	1.31 mΩ
Rotor operating temperature (hydrogen coolant)	25 K	
Number of HTS tapes per coil on the rotor	160	180
Transport current for each HTS tape / I_c[7]	500 A / 1224 A	530 A / 1224 A

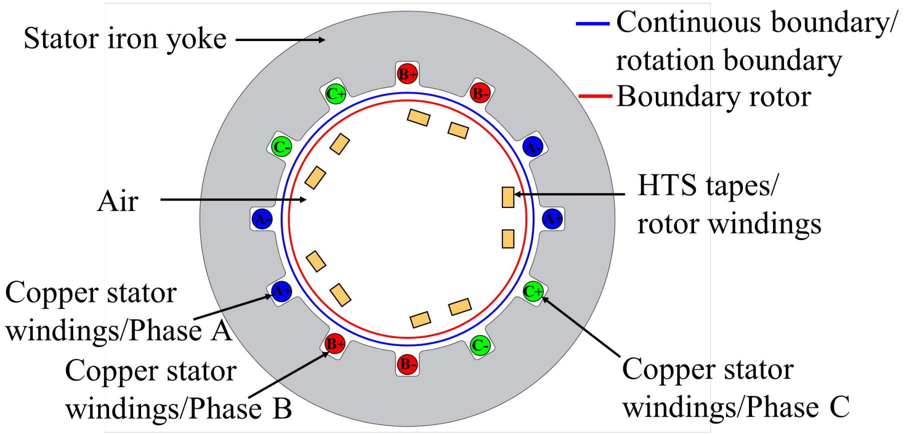


Fig. 5: Geometric model of generator.

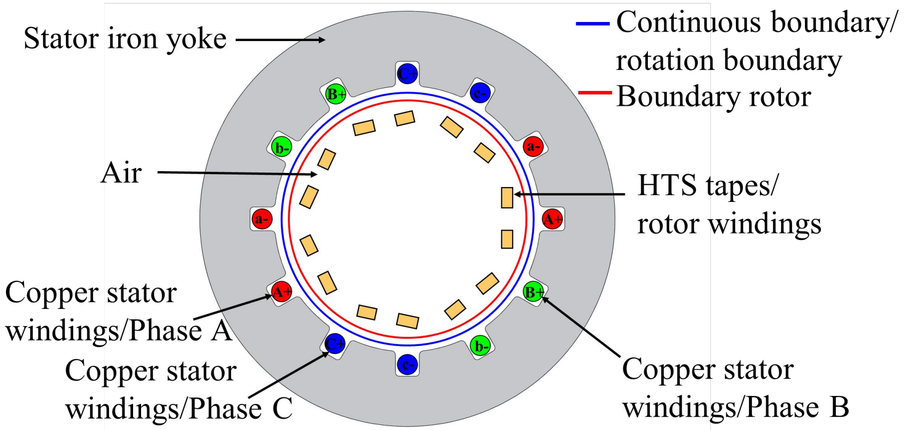


Fig. 6: Geometric model of motor.

[7]: Robinson Research Institute, "Critical current characterisation of Fujikura FYSC 2G HTS superconducting wire", https://figshare.com/articles/dataset/Critical_current_characterisation_of_Fujikura_2G_HTS_superconducting_wire/3759321?backTo=/collections/A_high_temperature_superconducting_HTS_wire_critical_current_database/2861821

Cosimulation: COMSOL - Simulink

- Cosimulation tool: Simulink LiveLink™ module, sequentially coupling COMSOL Multiphysics® with Simulink®

- Setting up the cosimulation:

COMSOL side

1. Create a COMSOL model
2. Generation of a cosimulation file in FMU format

Simulink side

3. Build a Simulink circuit including a “COMSOL Cosimulation” block
4. Run Simulink

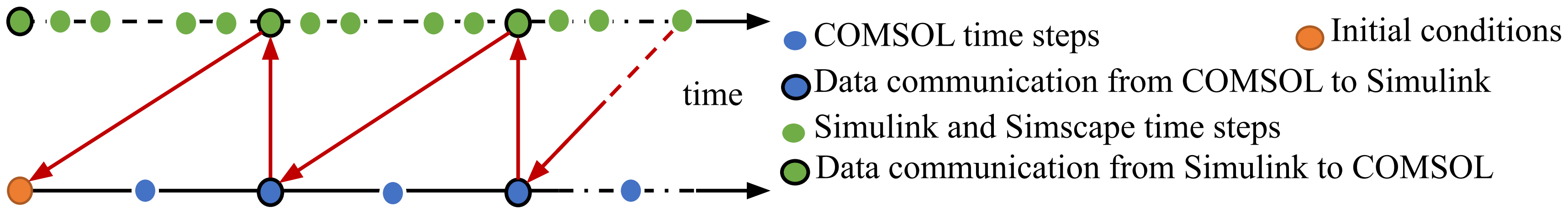


Fig. 7: Exchange process between COMSOL and Simulink.

Case studies: steady state case for now

- Step-by-step approach

- The original case study was split in 4 sub-cases:

  1. SC Generator - DC circuit
  2. DC circuit - SC motor
  3. SC Generator - DC circuit - SC motor
  4. SC Generator - Circuit - SC cable

- Rotor current ramped up from 0 to rated current

- Characteristics of the circuit components:
  - Generator resistances, R_{sg} = 1.22 mΩ
  - Motor resistances, R_{sm} = 1.31 mΩ
  - RLC filter (rectifier): r = 0.08 Ω, L = 0.05 mH, C = 100 μF
  - 3-phase LC filter (inverter): L = 0.5 mH, C = 0.132 μF

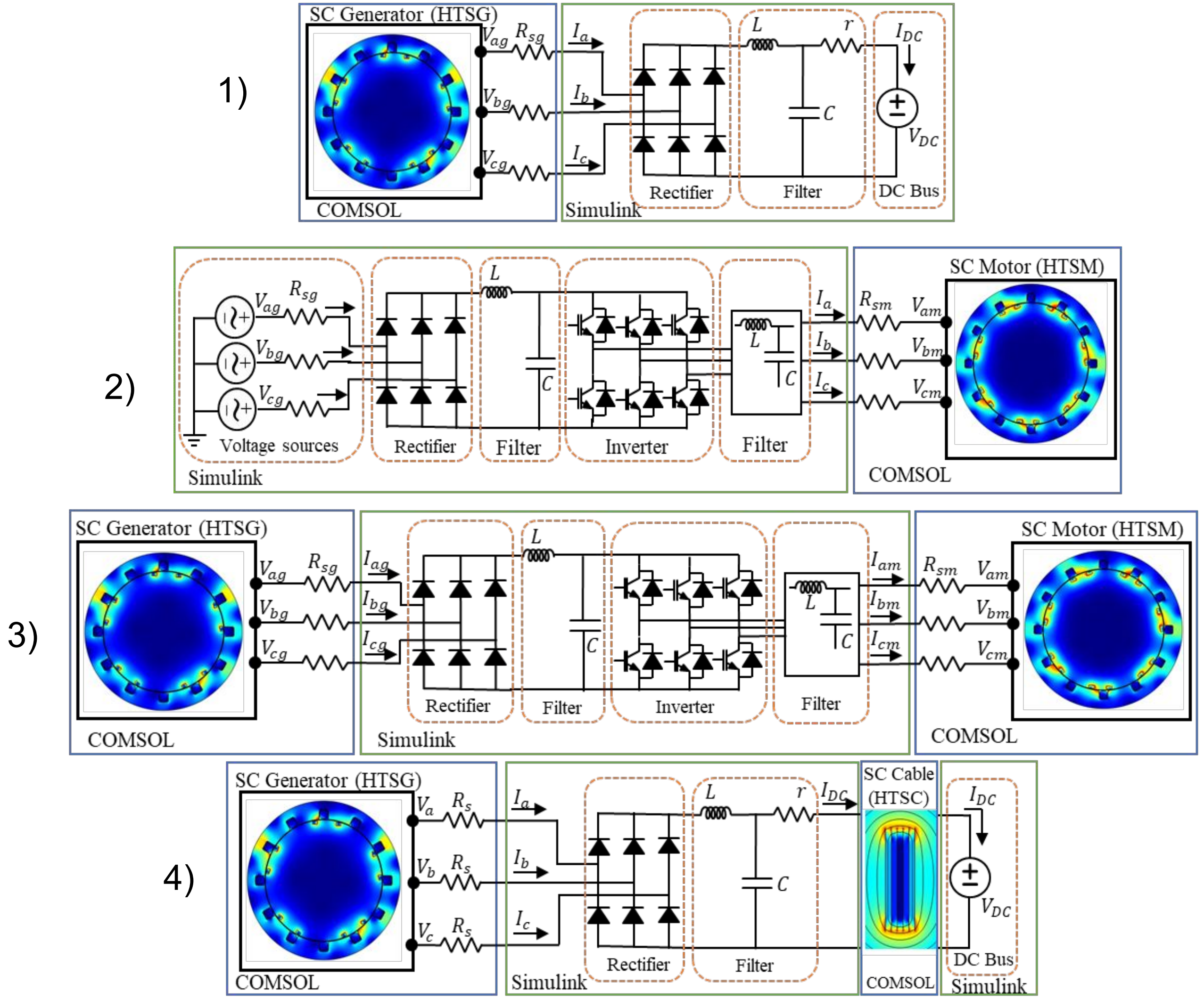


Fig. 8: Four sub-case studies: 1) SC Generator - DC circuit, 2) DC circuit - SC motor, 3) SC Generator - DC circuit - SC motor, and 4) SC Generator- DC circuit- SC cable

Case 1: SC generator - DC circuit

- Infinite DC bus modeled by a constant ideal voltage source at 3 kV
- Rectifier: power diodes; r_{on} = 0.107 mΩ, 1/r_{off} = 10 nS y V_f = 0.8 V.

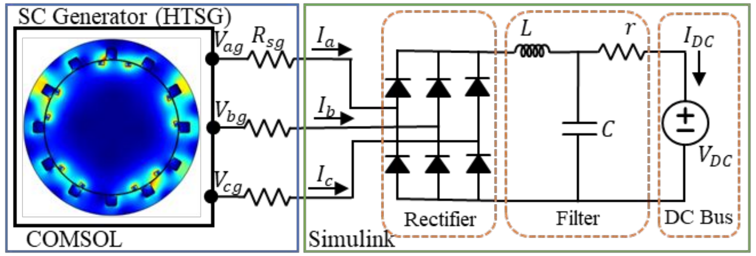


Fig. 9: Circuit: SC Generator - DC Bus.

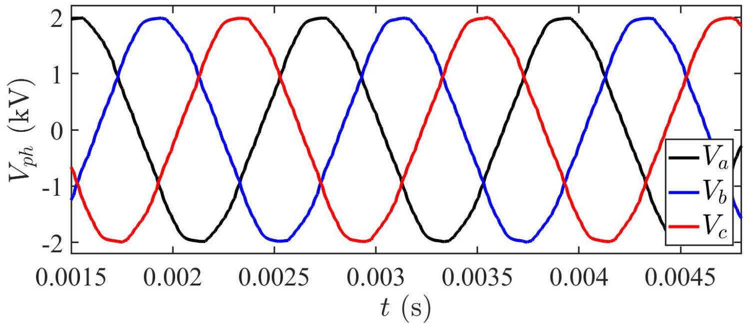


Fig. 10: Generator output voltages

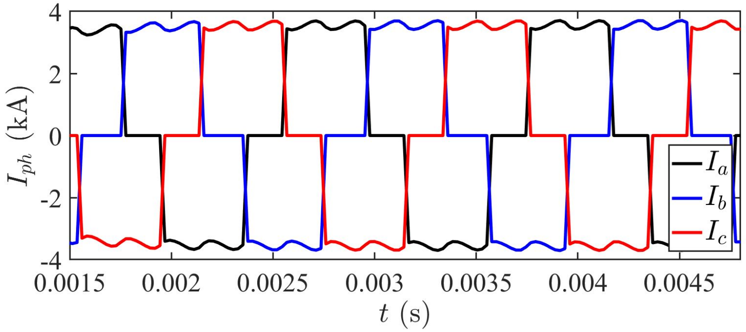


Fig. 11: Generator output currents

Tabla II. Co-simulation time parameters SC generator - DC bus circuit

Cosimulation FEM-Electric Circuit (for 4 electrical cycles)	
Cosimulation time	6 h 30 min 24 s
Time step in FEM	1/100/f_e = 1.2 E-5 s
Communication step	2/100/f_e = 2.4 E-5 s
Stop time	4.8 E-3 s

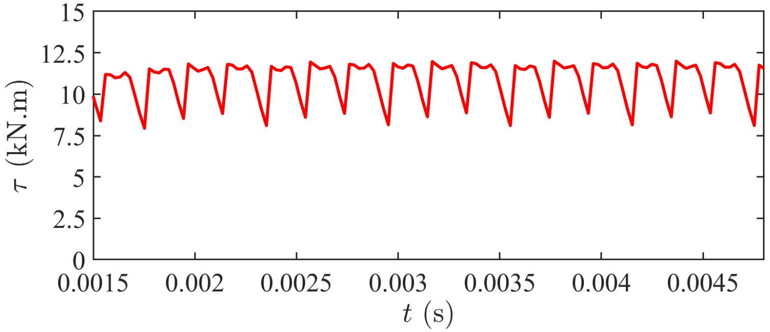


Fig. 12: Generator electromagnetic torque

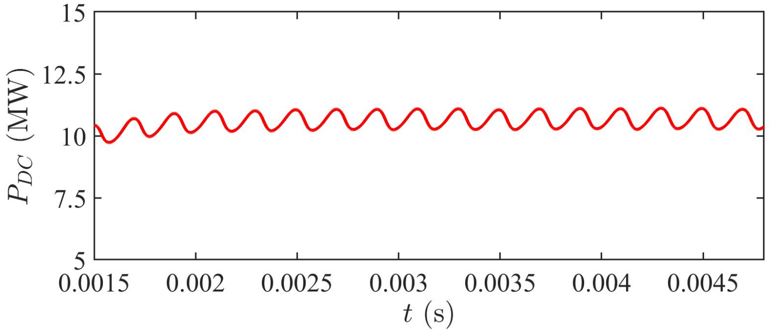


Fig. 13: Power supplied to the DC bus

Case 2: DC circuit - SC motor

- AC voltage source, maximum voltage 2 kV, f_e = 833.33 Hz, phase of 120º
- Inverter: Pulse Width Modulation (PWM)

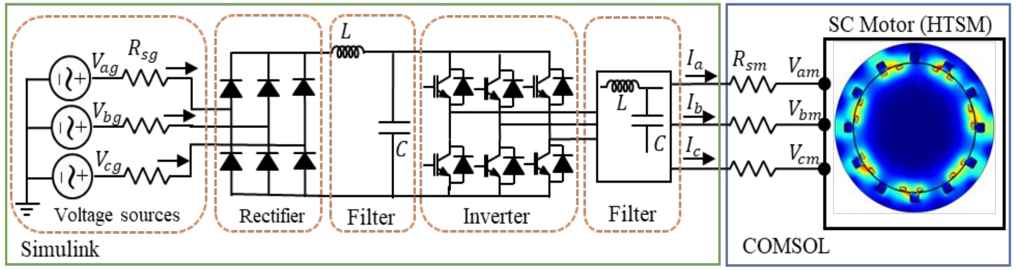


Fig. 14: Circuit: DC Circuit - SC motor.

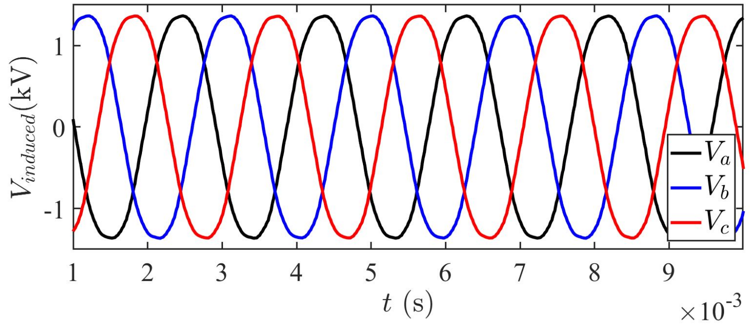


Fig. 15: Motor input voltages

Tabla III. Co-simulation time parameters DC circuit - SC Motor

Co-simulation FEM-Electric Circuit	
Co-simulation time	9 h 45 min 5 s
Time step in FEM	$1/100/f_e$ = 1.905 E-5 s
Communication step	$2/100/f_e$ = 3.81 E-5 s
Stop time	0.01 s

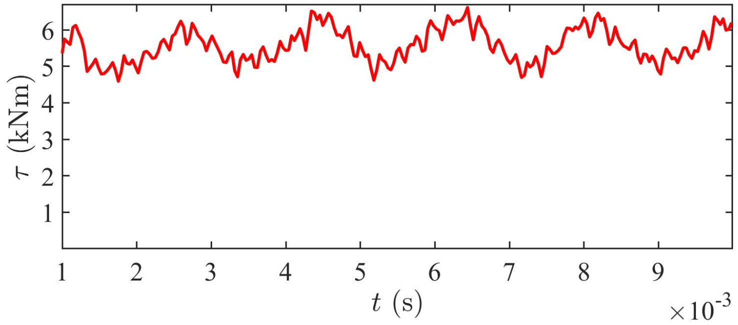


Fig. 17: Motor electromagnetic torque

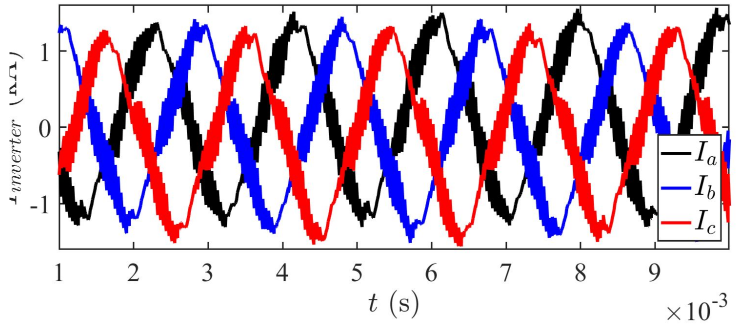


Fig. 16: Inverter input currents

Case 3: SC Generator - Circuit - SC Motor

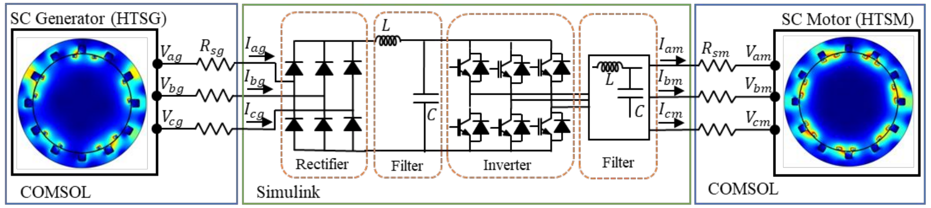


Fig. 18: Circuit: SC Generator - DC Circuit - SC motor.

Tabla IV. Parameters of the co-simulation: SC Generator-Circuit- SC Motor

	No. internal steps per 1 cycle/electric (FEM)	Time step in FEM (s)	Communication Step(s)	No. Electric cycles	No. of rev	Stop time	Cosimulation time
Generator	80	1.5E-5	3E-5	5 .83	1.16	0.007s	14 h 14 min 16s
Motor	100	1.905E-5	3.81E-5	3.67	0.525		

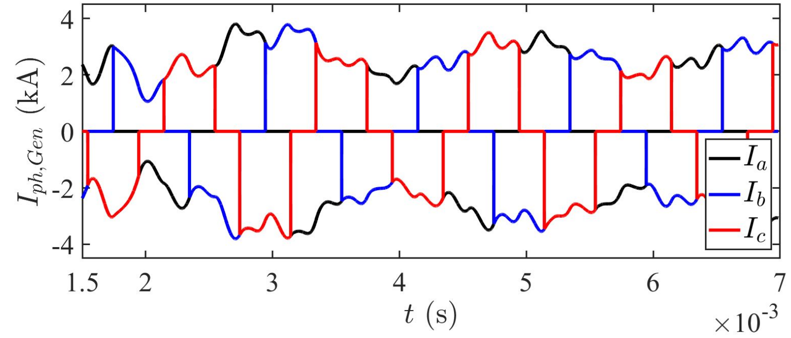


Fig. 19: Generator output currents

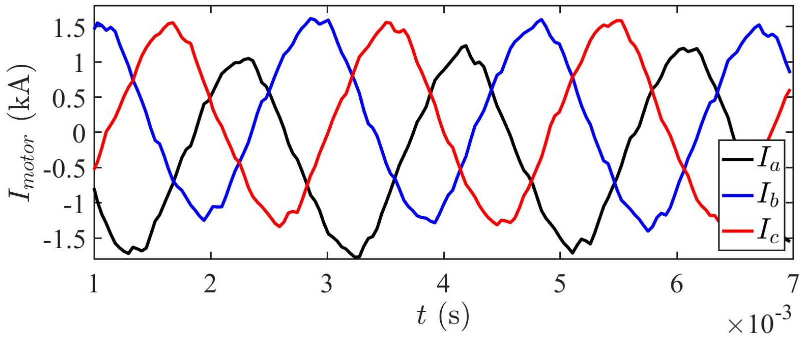


Fig. 20: Motor inputs currents

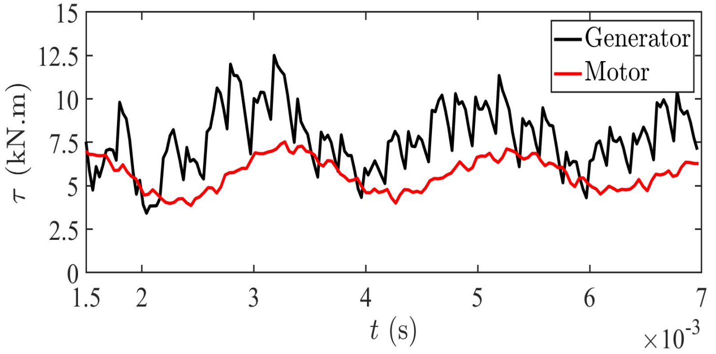


Fig. 23: Electromagnetic torque comparison

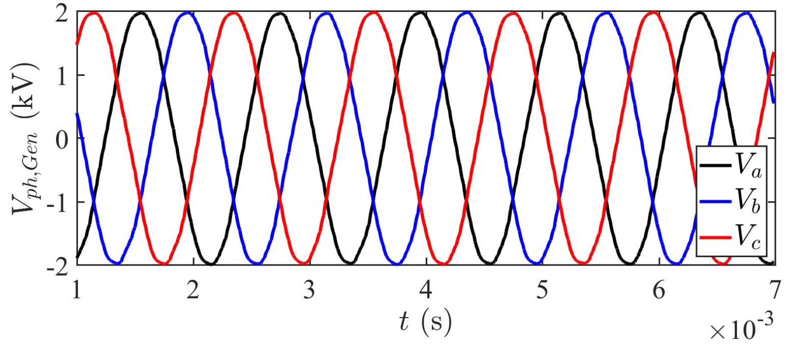


Fig. 21: Generator output voltages

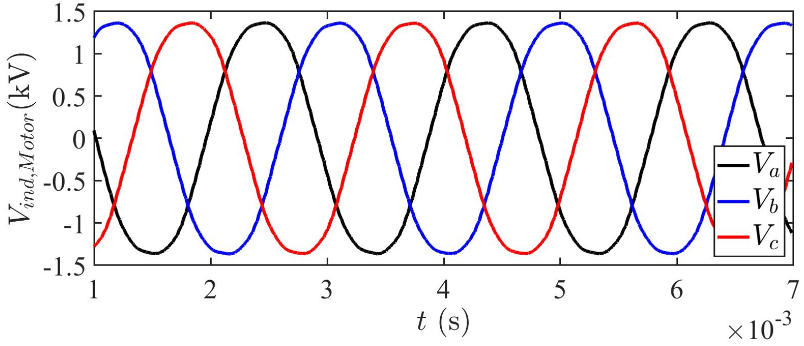


Fig. 22: Motor input voltages

Case 4: SC generator - Circuit - SC cable

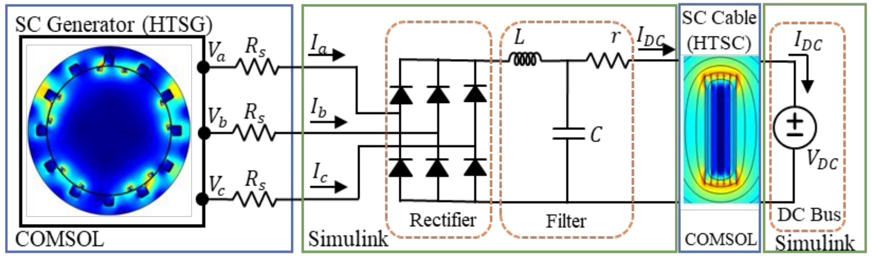


Fig. 24: Circuit: SC Generator- DC circuit- SC cable

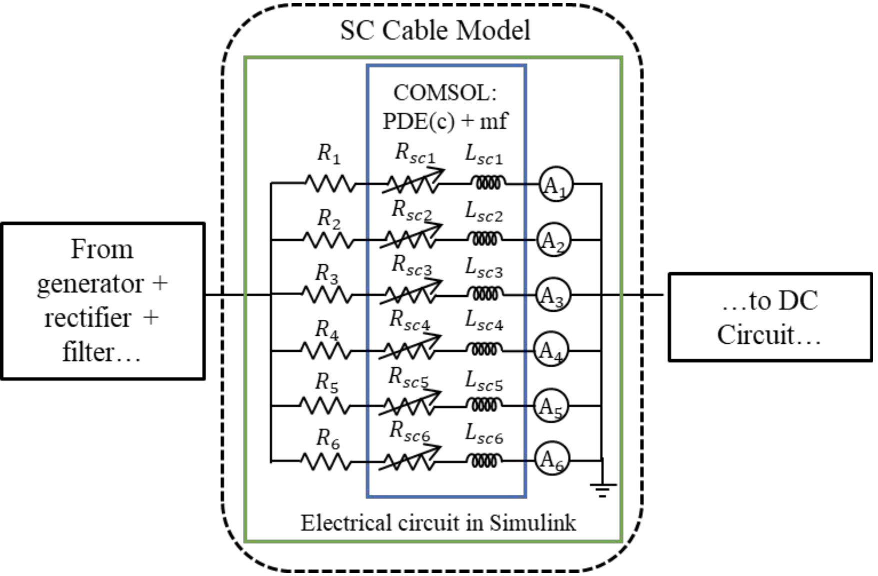


Fig. 25: Conceptual diagram of the electrical circuit (Simulink) coupling SC Generator- DC circuit- SC cable

- Redistribution of current in the cable may be not uniform from layer to layer (I_c dependency on **B** and transients)

Tabla V. Parameters of the cosimulation: SC Generator-Circuit- SC Cable

	Time step in FEM (s)	Communication Step (s)	Stop time (s)	Co-simulation time
Generator	1.5E-5	3E-5	0.0036 s	5 h 41 min 47s
Cable	1.2E-5	6E-5		

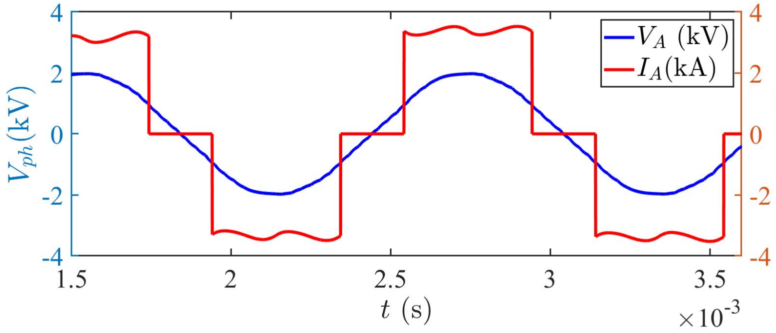


Fig. 26: Generator, voltage vs current (phase a)

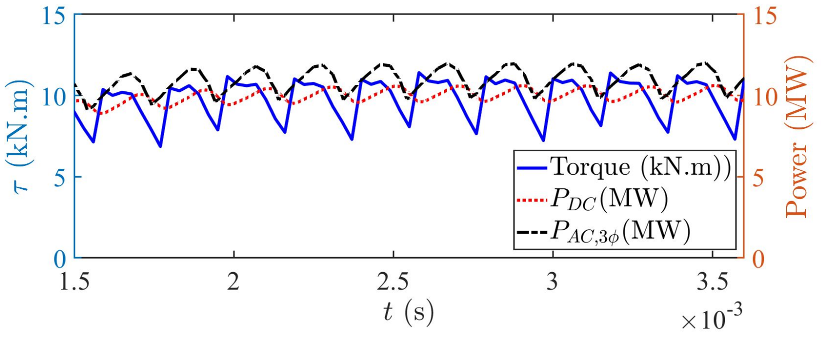


Fig. 27: Comparison of electromagnetic torque, power supplied to the DC bus and three-phase power generator.

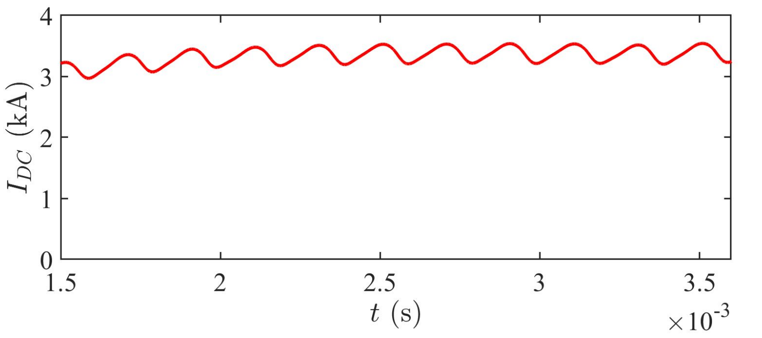


Fig. 28: I_{DC}, DC bus

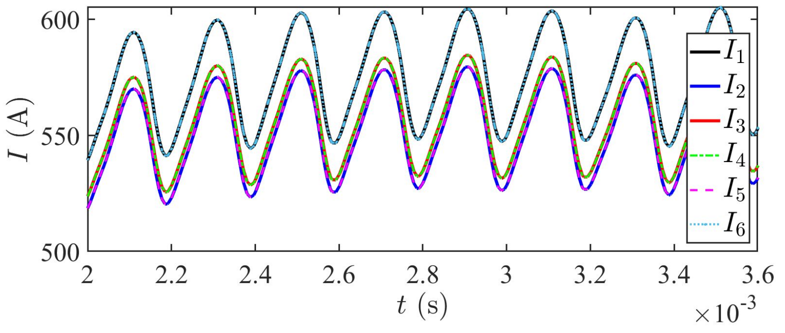


Fig. 29: Current distribution in each tape of the SC cable

Conclusions and perspectives

- A coupled FEM-Circuit is being developed to simulate the transient electromagnetic behavior of SC components for a MEA power chain
- The final step is the coupling of the SC machines and the SC cable to complete the power chain
- The goal is to provide a roadmap to study power systems considering HTS devices for performance analysis and design optimization still benefiting from the FEM capabilities

- Upcoming:
  - Initial conditions for machine models, need for a pre-estimation of machine parameters under load
  - Transient studies
  - Global reduction of computation time

- Future work:
  - MgB_2 stator for SC machines for full SC machines thinking of power electronics at cryogenics temperature [8]

[8]: H. Gui *et al.*,*IEEE Trans on P. Elect.*, 2020, doi: 10.1109/TPEL.2019.2944781.

Thank you for your attention!

Case 3: Coupling process

- ❑ Coupling HTSG 10 MW and HTSM 2.5 MW.
- ❑ Division of the electrical circuit into two subcircuits.
- ❑ Equivalent resistance (R_{Eq}) calculate:

$$R_{eq} = \frac{V_{dc}}{I_{dc}} \cdot \left(\frac{1}{4}\right)$$

- ❑ R_{Eq} represents the load of the 4 motors in parallel.
- ❑ I_{dc} and V_{dc} are DC measurements from the inverter side.
- ❑ I_{dc} ⇒ filtering process

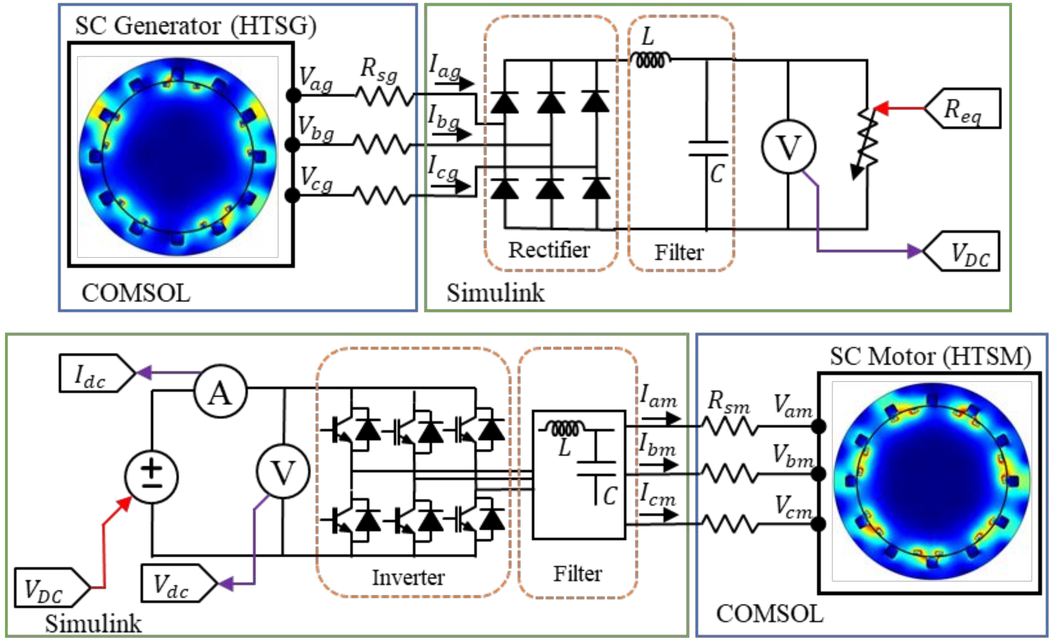
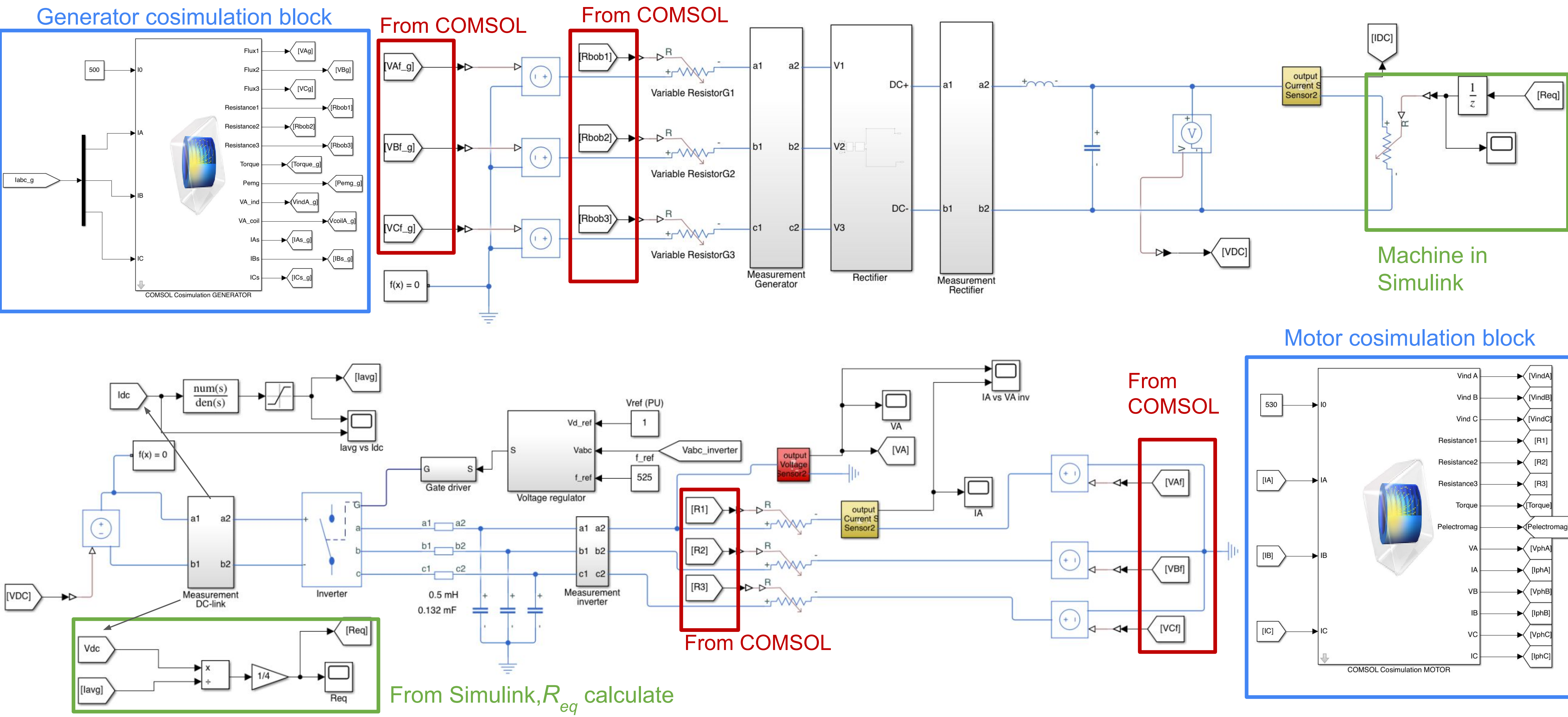


Fig. 30: Conceptual diagram of coupling HTS machines (HTSG and HTSM)- DC circuit in Simulink

Case 3: Simulink model



Case 3: SC Generator - Circuit - SC Motor

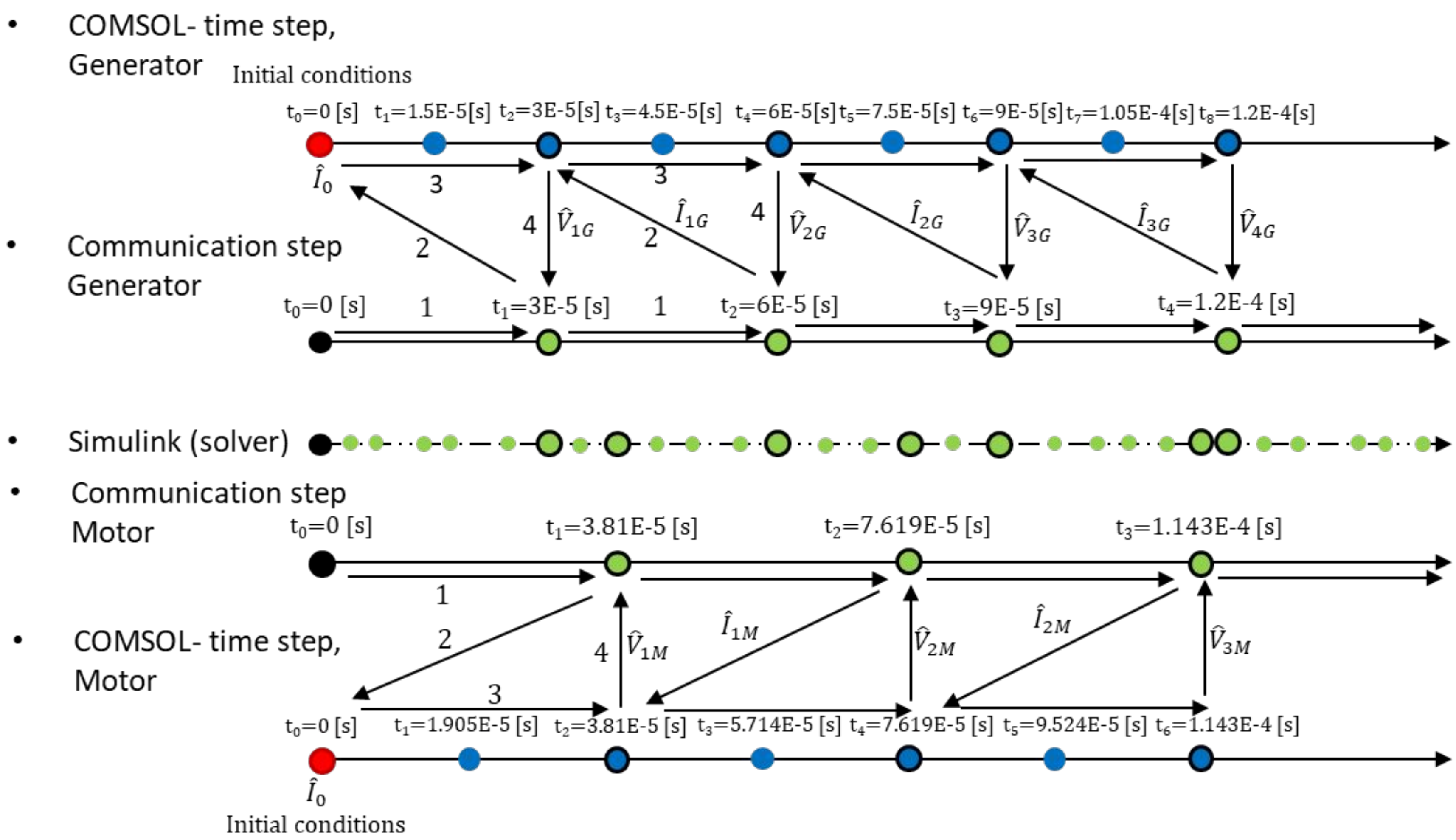


Fig. 31: Process of steps the cosimulation of the FEM models (generator and motor) with electrical circuit.