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Co-Simulation of Transient Effects in Superconducting Accelerator Magnets

ABSTRACT

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Numerical modeling of complex physical systems involving several coupled physical domains, so called multi-domain and multi-physics systems, poses considerable challenges w.r.t. consistency of the formulation and selection of a suitable representation. The landscape is further complicated in case these phenomena occur at a wide range of temporal (multi-rate) and spatial (multi-scale) scales. Resolving all in one scale may result in unacceptable computational time.

Modern high-energy particle accelerators demand high magnetic fields in order to steer the trajectory of charged particles traveling at nearly the speed of light. Superconducting magnets fulfill this requirement and are one of the main components of particle accelerators. In circular accelerators, the particles travel in opposite directions and are accelerated over multiple turns (a circular accelerator is also called a storage ring). Once the particles reach the desired energy, while bunched together as a beam, they are made to collide. As a first approximation, the center-of-mass energy of a particle is proportional to the circumference of the accelerator and the magnetic field of the bending magnets. The larger the beam energy during collisions, the deeper we can probe the fundamental constituents of the colliding particles. Analysis of the resulting particle showers created during a collision provides insights into the structure of matter, as well as the forces governing it.

In order to reach the superconducting state, magnets are operated at very low temperatures (1.9 K). Since heat capacity is low at cryogenic temperatures, magnets are prone to quench due to a local energy deposition (coupling losses in the superconducting cable, beam losses, cryogenic malfunction, mechanical movement, etc.). A quench is a transition from the superconducting to the normal conducting state. The simulation of quench initiation, propagation, and subsequent protective measures represents a challenge in terms of the number of coupled physical domains, their highly nonlinear behavior, their geometric scales, and their vastly varying time constants. On top of that, a magnet is a part of a larger electrical circuits with dedicated monitoring and protection equipment as well as a controlled current source providing desired current profile.

Simulation of such a multi-domain, multi-physics, multi-rate, and multi-scale coupled system in a single tool may not be feasible and/or demand considerable computational resources. The equations representing the model would need to be discretized at a large scale. On top of that, various physical phenomena may require custom discretization. In addition, the time integration would need to deal with various transients by choosing the time step capable of reproducing the fastest time constant in the system. And, depending on the studied operational scenario, the physical phenomena are represented with different models in particular phases. In fact, depending on the desired model fidelity, there is a need for switching the models from the available collection thereof. Since the coupled problem is non-tractable in a monolithic sense, we employ the divide and conquer philosophy. Following this approach the coupled problem is subdivided into smaller parts which are solved independently, though they are allowed to exchange information at discrete points in time. These considerations, resulted in formulation of the following two research theses:

1. it is possible, by employing the port-Hamiltonian formalism, to develop a consistent mathematical formulation of magneto-thermal phenomena occurring in the superconducting accelerator magnets and circuits, which will be used to analyze cooperative simulations of these systems;

2. it is possible to develop an architecture, algorithms, and data structures in order to automatically perform hierarchical cooperative simulations of superconducting accelerator magnets, circuits, and controllers in order to solve the formulation given in (1).

The thesis is organized into 5 chapters discussing theoretical derivations of energy-based models as well as design, implementation, and application of hierarchical co-simulation framework. In addition, the thesis contains 4 appendices introducing fundamental concepts employed in the thesis.

Energy-Based Modelling

Recent development in port-based modeling techniques, in particular the port-Hamiltonian framework originating from control theory, made it possible to model complex multi-domain and multi-physics phenomena represented by means of both ordinary and partial differential equations in a generic and consistent way. The port-Hamiltonian models capture in an elegant way the internal energy flow, storage, dissipation as well as interaction through lumped, distributed, and boundary ports. In the thesis, we employ the port-Hamiltonian formalism to characterize the coupling between the electromagnetic and thermodynamic systems in a superconducting magnet along with an accompanying electrical circuit. In addition, we employ bond graph modeling to graphically represent the energy flow in the considered systems. These methods allow to study the model consistency as well as the computational causality.

In the thesis we derived a bond graph representation and the corresponding port-Hamiltonian model of a superconducting circuit. The circuit is composed of a superconducting magnet and elements used for powering and protection. The superconducting magnet model consists of electromagnetic and thermal domains originating from, respectively, the Maxwell equations and the laws of thermodynamics. Thus, the superconducting magnet is represented as a distributed-parameter model for which differential forms are employed. The superconducting circuit model is represented as a lumped-parameter network by means of the Modified Nodal Analysis (MNA).

The magnetoquasistatic energy-based formulation considers resistive as well as inductive voltage evolution during the transient effects in a superconducting magnet. The resistive voltage becomes non-zero only after quench initiation. The inductive voltage reflects changes of the magnetic field and includes the eddy currents in copper wedges, cable eddy currents as well as the persistent magnetization. The persistent magnetization is composed of a reversible and irreversible contributions. The reversible contribution, although lower than the reversible one, affects the internal energy and provides a link to the thermal domain. This allows to account for the magneto-caloric effect. The remainder of the energy is stored in the magnetic system. The thermal domain is driven also by the irreversible contribution from inductive and resistive phenomena. We also consider heat conduction in the thermal domain given by the Fourier law.

The obtained bond graph model reflects consecutive stages of energy conversion in both physical domains along with their reversible and irreversible interaction. The model is driven by a lumped port with either flow-in or effort-in computational causality. Furthermore, the Stokes-Dirac structures for the magnetic and thermal domains introduce boundary port enabling interaction with environment. The bond graph model not only provides a graphical representation of energy flow in a superconducting magnet, but also provides relevant insights on the computational causality and numerical implications of selection of an excitation mode (either current- or voltage-driven).

The port-Hamiltonian model followed a reverse path of aggregating consecutive Dirac structures (making up together again a Dirac structure). The resulting reversible input-state-output representation captures dynamic effects occurring in a superconducting magnets. First of all, the model facilitates analysis of the energy variation which serves as a valuable check of the consistency of the model. Furthermore, the model reveals a lumped and boundary ports for interaction and control of the dynamics of a magnet.

Cooperative Simulations

Similarly to the development in the energy-based modelling, the advances in cooperative simulation, in particular the application of the waveform relaxation algorithm to field/circuit coupling along with the use of pre-conditioners for field models allowed to achieve satisfactory convergence rates and accurate results. This method is particularly suited to approach multi-rate and multi-scale problems such as the simulation of a superconducting magnet and circuit. In this thesis, an architecture, data structures, and algorithms for automatic handling of hierarchical co-simulation are presented. The resulting framework supports four main co-simulation algorithms (one-way coupling, weak coupling, strong coupling, and waveform relaxation). Furthermore, the evolution of a transient in a co-simulation scenario may call for the adjustment of the model fidelity in order to accurately reproduce a given phenomenon. This is achieved by switching models and coupling algorithms during the co-simulation execution.

The coupled problem is composed of three domains, namely the distributed field model along with the lumped electrical and controller models. The field model comprises coupled magnetoquasistatic and thermodynamic systems. In addition, the mechanical response due to electrodynamic forces and temperature differences is relevant for the analysis of the magnet behavior. These distributed multi-physical systems are governed by nonlinear equations with highly nonlinear material properties. Furthermore, the transient effects span over a wide range of temporal and spatial scales. To tackle these challenges the STEAM co-simulation framework has been developed. The architecture of the framework provides several features: (i) an inheritance structure to accommodate each simulation tool; (ii) algorithms implementing four co-simulation schemes; (iii) data structures and algorithms for signal exchange.

The Model-Based System Engineering (MBSE) approach was followed in the development of the framework [1]. This approach introduces a set of characteristics of high-fidelity models (obtained by means of thorough validation and verification) such as modularity, consistency, and availability of interfaces. Furthermore, MBSE provides a syntax and a set of diagrams based on the SySML language in order to represent system architecture along with relevant relationships between main components.

The capabilities of the framework as well as the properties of the co-simulation schemes were illustrated with several relevant applications of transient effects in superconducting accelerator magnets. Firstly, we consider various models to demonstrate that the proposed architecture supports multi-domain problems. Secondly, we study different co-simulation schemes. These applications are based on lumped variables, which are exchanged between the tools in order to tackle the multi-physics, multi-rate, and multi-scale behavior. We also present first attempts to include distributed variables and extend the framework to support distributed ports. The developed energy-based models support the analysis of the performance of the co-simulation scenarios.

- The controller/circuit coupling is an application of a weak coupling and waveform relaxation scheme to a problem composed of two ordinary differential equations [2]. Properties of the waveform-relaxation algorithm's convergence, i.e., the minimum and maximum number of iterations, are studied.
- The 1D field/circuit coupling considers a 1D nonlinear thermal model characterized in terms of a partial differential equation coupled to an electrical circuit. This application aims at carrying out a comparison of weak coupling and waveform relaxation schemes.
- With field/circuit coupling we present an analysis of waveform relaxation scheme and two equivalent circuital representations of field models [3]. Several concepts for the convergence improvement and computational time reduction are also discussed.
- Eventually, we consider coupling of distributed magneto-thermal and mechanical models by means of mesh-based interpolation [4]. The goal of this study is to introduce distributed ports to the STEAM framework.

Hierarchical Co-Simulation

Nominal operation of a superconducting circuit is composed of a cycle that follows the operation of a particle accelerator, namely there is the ramp-up of the current (following the increase of the beam energy), the steady-state operation at the nominal current (period when collisions are taking place), and the current ramp-down (in case the beam quality has deteriorated below certain value and the beam has to be dumped). In case no faults occur, such a cycle is being repeated during the machine operation. For an analysis of such a scenario the controller/circuit coupling algorithm is sufficient to obtain meaningful results capturing the controller and circuit behavior. In some scenarios only a monolithic circuit model is sufficient [5]. In this case a lumped element model composed of inductors, capacitors, and resistors is sufficient to reproduce the transient behavior of a magnet.

However, in case of a malfunction of one of the subsystems, due to the complexity of an accelerator circuit, there is a large amount of failure scenarios that could take place. One of the more frequent events is a quench for which the operation of protection systems is governed by a dedicated sequence of steps. To consistently study quench initiation, propagation, and protection several models of a superconducting magnet shall be employed. As it was already mentioned, during the nominal operation of a circuit a lumped element circuital representation of a magnet is sufficient. In order to reproduce the resistance growth following a quench, at least a 1D thermal model has to be introduced. The growing resistance coupled to the electrical circuit model results in an increase of the resistive voltage. The evolution of the resistive voltage is monitored by a model of a quench detection system which, in case the voltage exceeds a detection threshold, triggers magnet and circuit protection systems. At this stage it is important to estimate the peak temperature and the maximum voltage to ground. Therefore, 2D finite element magneto-thermal models are introduced. This requires the application of the field/circuit coupling algorithm. The algorithm is executed as long as the current flowing through the magnet is above certain value. Afterwards, the study is continued until the circuit current is discharged (which could be different from the magnet current). Eventually, the mechanical response of the magnet's structure to the variation of the electrodynamic forces and temperature differences shall be studied.

In this context, an added value of the equivalent circuital representation of field models for the field/circuit coupling is that it can be used for several purposes: (i) the controller/circuit coupling (pre-conditioner with differential inductance only); (ii) the 1D field/circuit coupling (with additional time-varying resistance); and (iii) the 2D field/circuit coupling (with additional compensation elements). As a result, the circuit topology can be kept intact and can accommodate several coupling schemes.

Depending on the state of the superconducting magnet operation it can be represented by one out of a hierarchy of available models (hierarchy can be determined by model accuracy, complexity, etc.). Selected models, representing a particular state of the operation, are coupled by means of a coupling algorithm. Once a state is executed it can transition to another one (switching of states). In order to obtain consistent results it is necessary to switch models and coupling algorithms. Furthermore, to ensure the continuity of solutions and avoid inconsistencies, the switching should be automated and take place during the co-simulation run-time. Since physical domains can be introduced on demand we need to consider the so-called hierarchical co-simulation.

Conclusion

The goal of this work was to develop a consistent representation of multi-domain, multi-physics, multi-rate, and multi-scale phenomena occurring in superconducting accelerator magnets. On the modeling side, the multi-domain and multi-physics challenge was captured by employing the energy-based modeling framework. On the algorithm side, the multi-scale and multi-rate behavior is harnessed by means of the co-simulation technique that allows to combine dedicated models of selected phenomena (e.g., fast vs. slow dynamics, 1D vs. 2D discretization). The port-Hamiltonian representation can provide a relevant perspective on the coupling process.

For the first time, the port-Hamiltonian formalism and bond graph modeling was applied in the field of superconducting accelerator electrical circuits modeling. In particular, we developed a distributed model of a superconducting magnet and a lumped model of a superconducting circuit. The former model consists of electromagnetic (distributed resistance after a quench, eddy currents, persistent magnetization) and thermal phenomena (heat conduction) coupled by means of the irreversible entropy creation and a common energy storage element. The common energy storage allowed to characterise the magneto-caloric effect. In addition, two distributed boundary ports along with a lumped one were identified. In fact, the variation of the internal energy of the system, i.e., power flow, is determined by the power flow through these ports. The port-Hamiltonian model provided an independent cross-check of the consistency of the existing FEM model [6]. For the superconducting circuit model we proposed application of a Kirchhoff-Dirac structure that represents the modified nodal analysis. The analysis of the underlying structure by means of the computational causality provides similar conclusions as the one obtained with the index analysis [7]. The port-based models of the electromagnetic and thermal domains as well as the electrical circuit can be further extended. In fact, the superconducting model is not yet complete and should account for fluid dynamics and mechanics. The port-Hamiltonian approach allows to extend the model due to its intrinsically modular and multi-physical nature.

In order to tackle the complexity of the multi-physics and multi-domain phenomena with multi-scale and multi-rate characteristics, the coupled problem is subdivided into subproblems. Each subproblem is represented with a dedicated numerical model solved independently. In order to restore the coupling between subproblems we employed the cooperative simulation approach with algorithms for information exchange between the subproblems. To this end, a co-simulation framework has been developed with an architecture and data structures allowing for implementation of the main four coupling algorithms (one-way coupling, weak coupling, strong coupling, waveform relaxation) along with a state machine for hierarchical scenarios. It is noteworthy that the framework is agnostic to the simulated case and can be applied to other co-simulation cases in other fields. The framework has been already employed to several relevant cases in the field of particle accelerators [8], [9], [10].

The controller/circuit coupling incorporated the weak-coupling and waveform relaxation algorithms. A model of a controller is solved with a fixed time stepping algorithm, while a network model of an electrical circuit is solved with an adaptive time stepping scheme. The digital implementation of a controller is an example of a weak coupling scheme. For the waveform relaxation we stated and proved two conditions for the minimum and maximum number of iterations. In addition, it was shown that in certain conditions, the waveform relaxation is more efficient then the weak coupling scheme.

The field/circuit coupling algorithm proved to be a suitable solution for studying complex superconducting circuits and magnets. The bond graph models were applied to study two excitation modes, namely, the current- and voltage-driven ones. The properties of both schemes were studied for a lumped and distributed setup. Due to the dependence of the differential inductance on the current (iron yoke saturation) and time derivative of current (eddy currents) we observed large number of iterations in the first time window while the transient is initialised. Therefore, two strategies for the improvement of the performance for the field/circuit coupling were identified and evaluated: (i) scaling of the differential inductance; (ii) update of the differential inductance at the beginning of each time window. Application of both strategies proved to improve the convergence rate of the coupling algorithm.

Discharge of the energy stored in the magnetic field of a superconducting magnet results in a decay of the Lorentz force and simultaneous build up of the temperature difference. The resulting stress in the superconductor may result in material degradation and, therefore, has to be studied. To this end, dedicated mechanical models are developed and applied. Since magneto-thermal and mechanical models are typically developed with different simulation suites, we developed a one-way coupling algorithm. In order to account for differences in mesh definition in both models, we employed MpCCI, an existing mesh-based interpolation environment.

The aforementioned three types of co-simulation algorithms correspond to main operational states of a superconducting circuit in both, nominal and failure conditions. Integrated analysis of the entire operational cycle involves multiple coupled models active only in particular phases. Each phase involves a subset of available models in order to represent transient effects with desired accuracy. This involves switching of models and coupling schemes and is captured by means of a hierarchical co-simulation. The co-simulation framework provides this feature by implementing a deterministic state machine. The scalability and robustness of the framework was demonstrated with a hierarchical co-simulation of a high-field quadrupole circuit [8].

Outlook

The presented work on the energy-based modelling of multi-* problems provides a foundation for the analysis magneto-thermal and electrical phenomena occurring in superconducting accelerator magnets and circuits. As such, the modelling framework can be further extended in order to approach several relevant research avenues. The estimation of the coupling strength between the subsystems representing a superconducting circuit and in general multi-physics problems is of high importance. Power is a universal quantity characterising each physical system. Therefore, the power exchanged between coupled models could be used as a metric of coupling-strength. Firstly, such a metric would provide insights into the process of heterogeneous domain decomposition and indicate whether a multi-physics model could be decomposed into submodels (weak coupling), or it should be solved in a monolithic fashion (strong coupling). Secondly, for models decomposed into smaller units, the estimation of coupling strength could guide the choice of a coupling algorithm to obtain satisfactory results in a time-efficient way. Another interesting aspect is the assignment of the computational order. In particular, this process is non-trivial for multiple coupled models while there is a growing number of possible permutations.

One of the limitations of the presented framework is the use of fixed time windows for the co-simulation process. On one hand, too large time window may lead to divergent results. On the other hand, too small time windows may translate into large computational time due to the communication and model initialisation overhead. The amount of power flowing between two coupled physical models could be used as input for an adaptive time window selection algorithm [11]. Other criteria could be used like the initial convergence speed. Another concept that promises performance improvements is a parareal algorithm, which allows for parallel execution of multiple consecutive time windows [12]. Each time window can be solved with the waveform relaxation algorithm. The main co-simulation algorithm can be extended in order to account for this type of computations. Currently, the STEAM co-simulation framework only supports scalar waveforms. A natural extension is to account for distributed variables and integrate the capabilities of the MpCCI environment for mesh-based interpolation and model coupling with the co-simulation framework.

There are also several potential improvements to the hierarchical co-simulations. Among others, one could consider energy-based model switching. The energy variation in a model can be used as an input character for the state machine. This would allow to determine what models should be activated as they experience significant energy variation. Similarly, models with negligible changes of internal energy can be deactivated. Such an approach would allow to use the computational resources more efficiently by simulating only the most significant phenomena. For instance, if the variation of a source current in the magneto-thermal model of a magnet results in the temperature variation exceeding a certain threshold, the very model should be introduced to the co-simulation. Similarly, if the power is not dissipated in a magnet anymore and a steady state is reached, it can be deactivated. Another relevant improvement to the hierarchical co-simulation is a posteriori shortening of a time window in order to provide an exact switching moment between states.

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