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Modelling the behavior of HTS coils under overcurrent conditions

Gabriel Hajiri
*Université de Lorraine,
 GREEN, F-54000, Nancy, France*
 0000-0003-0325-0788

Kévin Berger
*Université de Lorraine,
 GREEN, F-54000, Nancy, France*
 0000-0001-8841-917X

Jean Lévêque
*Université de Lorraine,
 GREEN, F-54000, Nancy, France*
 0000-0002-1975-4860

Frederic Trillaud
*Instituto de Ingeniería, Universidad
 Nacional Autónoma de México, Ciudad de
 México, Mexico*
 0000-0002-6964-5603

Abstract—To improve the understanding of High-Temperature Superconducting (HTS) devices in electrical systems, it's important to couple Finite Element Models (FEM) with Electrical Circuits (EC). This coupling should consider superconducting behavior and how HTS devices affect electrical systems. Some HTS devices shift from the superconducting state to the normal resistive state, like fault current limiters, which requires modelling dynamic state changes. This transition leads to modelling challenges due to the current redistribution among the superconductor and the surrounding conductive materials. In this study, a Multiphysics FEM coupled with an EC was developed to address specific challenges of 2G HTS coil overcurrent operations. In addition, this study presents methods for reducing the Electrical Circuit Model (ECM), significantly reducing computational costs by a factor of 6 while maintaining a remarkable agreement with experimental results and full models.

Keywords—HTS coil, T-A formulation, coupling FEM and EC, model reduction.

I. INTRODUCTION

The coupling of FEM with EC to simulate superconducting devices is becoming more and more common. This allows for a better understanding of how superconducting devices behave in the electrical grid [1]. Many studies have been conducted in this direction in recent years. Some of these studies aim to connect the FEM with the EC to evaluate the superconductor in operational conditions, meaning when the transport current is below the critical current [2]. It has been shown that the voltage across the superconductor can be modeled in two parts: a resistive part related to the nonlinear resistivity of the superconductor [3] and an inductive part. where, the inductive voltage is defined through the integral of the variation of the magnetic vector potential \mathbf{A} overtime [4]. In this paper, the modelling and coupling between a Thermo-Electromagnetic Finite Element Model (TEFEM) and Electrical Circuit Model (ECM) is introduced. Additionally, a more detailed study of discretizing the HTS coil in ECM is presented. The previous coil modelling offers a wider operating range, extending both below and above the critical current. Essentially, this encompasses both the current-sharing region and the complete coil transition.

II. OVERVIEW OF THE TEFEM - ECM

In this section, we aim to describe the different physics used, as well as the complete coupling between the EF model and the ECM. Figure 1 shows the entire TEFEM - ECM block diagram with the variables exchanged. It is made up of three sub-models corresponding to EFEM, TFEM and ECM. The first one is the electromagnetic FE submodel (EFEM) which makes use of the full T-A formulation [5]. The magnetic flux density \mathbf{B} is computed in the whole domain from the magnetic

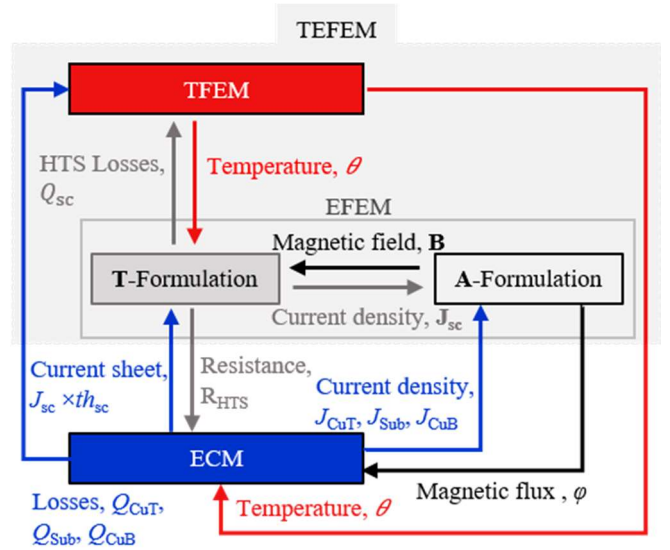


Fig. 1. Block diagram of the entire TEFEM – ECM model for overcurrent simulations of inductive HTS coils. It is composed of three coupled sub-models: 1) the electromagnetic FE model or EFEM (T-A formulation), 2) the thermal FE model or TFEM, and 3) the electrical circuit model or ECM.

vector potential \mathbf{A} as $\mathbf{B} = \nabla \times \mathbf{A}$ and the current density \mathbf{J}_{sc} is derived from the current vector potential \mathbf{T} as $\mathbf{J}_{sc} = \nabla \times \mathbf{T}$ considering the non-linearity of the HTS.

The current vector potential \mathbf{T} is solved in the Partial Differential Equation (PDE) module of COMSOL assuming that the superconductor is a 1D line. Besides the superconductor, the electromagnetic contributions of the Cu stabilizer (“Cu”), through its top (“CuT”) and bottom (“CuB”) layers, and the substrate (“Sub”) are taken into account during the transition of the superconductor to its normal resistive state. These conductive layers are given as current density sources \mathbf{J}_{CuT} , \mathbf{J}_{CuB} and \mathbf{J}_{Sub} in the \mathbf{A} formulation. Then, the current distribution across the different layers follows their respective electrical resistances. The second submodel (TFEM) solves the heat balance equation with heat sources computed from the respective Joule losses in the superconductor, the top and bottom Cu layers and the substrate using the heat transfer module of COMSOL. The third and last submodel is the electrical circuit model (ECM) which is solved via the ordinary differential equation (ODE) module of COMSOL. This model provides the resistances of the different layers which are used to estimate the redistribution of current between them.

III. REDUCTION OF THE ELECTRICAL CIRCUIT MODEL

The first ECM given in Fig. 2 (a) is the most accurate representation of the actual electrical behavior of the coil. It is referred to as the layer-based model or LBM as each layer holds a layer resistance in series with a layer electromotive

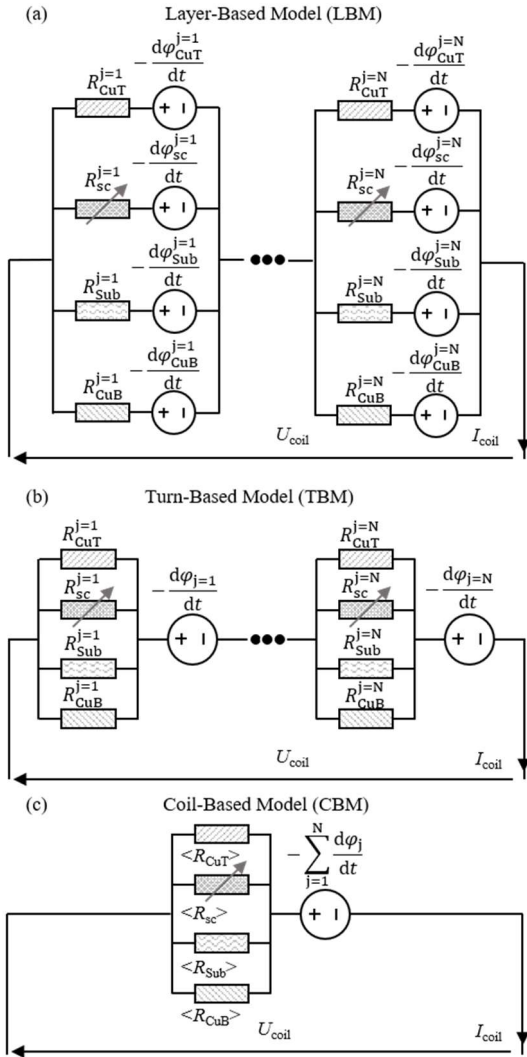


Fig. 2. (a) provides the most accurate ECM of the inductive coil in transient (layer-based model or LBM); (b) shows the intermediate model (turn-based model or TBM) leading to the reduction of the ECM given in (c) (coil-based model or CBM).

force. This model is subsequently simplified by moving out the electromotive forces of each layer to build a single turn-based electromotive force, see Fig. 2 (b). This electromotive force on a turn basis represents the induction of one turn of the coil. The parallel resistances are computed on a turn basis as well but distinguishing each individual layer in the turn. This model is referred to as turn-based model or TBM. Finally, the turn-based electromotive forces and the turn-based parallel resistances are lumped into a single set of equivalent parallel resistances in series with one electromotive force as illustrated in Fig. 2 (c), referred to as Coil-Based Model or CBM.

IV. RESULTS AND DISCUSSION

The electrical circuit used in this study includes a specific discharge system. It consists of a battery of capacitors (K-series impulse magnetizer) capable of delivering up to 10 kJ under 2 kV. Its equivalent capacity is 5 mF. The current passing through the superconducting coil depends on the capacitor's charging voltage, U_{c0} . As shown in Fig. 3, whenever U_{c0} is high, the current value is higher, resulting in a higher HTS coil voltage. Additionally, we notice that in terms of precision, the LBM, TBM, and CBM models are in good agreement with each other. However, Fig. 4 shows the computation time of TEFEM - ECM for the three ECMs. There is a significant improvement when moving from LBM to CBM. This difference in magnitude cannot be solely explained by the 20% increase in DOF between TBM (or CBM) and LBM. The most probable explanation lies in the

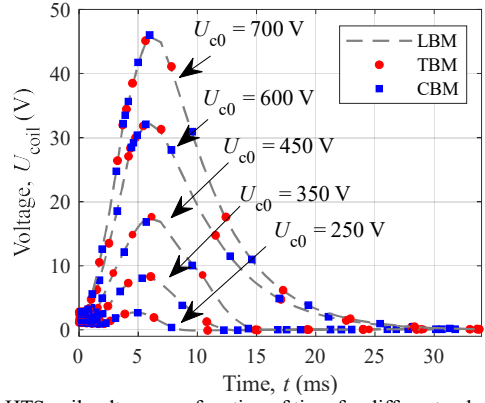


Fig. 3. HTS coil voltage as a function of time for different values of the capacitor voltage U_{c0} .

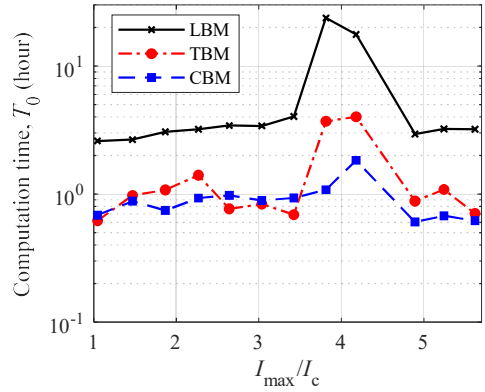


Fig. 4. Computation time for the different ECM. Overall, the fastest model (TEFEM - ECM) is the CBM.

convergence slowness, given the non-linearity based on a layer. Overall, TBM and CBM have similar computation speeds, with CBM being the fastest. It is worth noting that around $I_{max}/I_c = 4$, all models experienced an increase in computation time due to slower convergence on the non-linear system. For this particular point, the temperature is close to the critical temperature and the current sharing between the different layers is widespread. The solver then automatically adopts a lower time step as the problem becomes steeper. Finally, while the computation time for LBM ranges from less than 3 hours to over 20 hours, TBM does not exceed 4 hours, and CBM remains below 2 hours for an overall simulation time equal to 35 ms.

In the full version of the paper, a more detailed study is conducted to clarify both the details of the TEFEM - ECM model and the advantages brought by the reduced CBM model in modelling superconducting devices for electrical networks.

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