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Modelling the Dynamic Charging Process of High- T_c Coils by a Dynamo-type Flux Pump

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Abstract—The high- T_c superconducting (HTS) dynamo-type flux pump provides the possibility of charging HTS coils without any electrical contact, removing the need for current leads and their associated thermal loss. Although there are a number of numerical methods that have been proposed for the characterization of HTS dynamo, the dynamic behavior of the HTS dynamo as well as its impact on the HTS coils during charging process have not been deeply studied yet. The crucial point is the parallel dynamic calculation of the HTS dynamo along with the HTS coil. 3D modelling can provide a more precise solution than 2D, but with the cost of massive computation time. In this study, we couple two distinct models of the HTS dynamo and HTS coil together via their lumped parameters to reproduce the dynamic charging process. To predict the AC losses of the whole system during different charging stages, one can firstly extract the time-dependent DC charging current by pre-calculation for shortening the calculation time. In addition, this methodology has the potential of coupling different types of FEM models, including various types of superconducting elements. Moreover, the versatility of this methodology will be validated in our further work.

Keywords—HTS dynamo, finite-element model, electrical circuit, AC losses

I. INTRODUCTION

Superconducting flux pumps have been shown to be a promising candidate for charging high- T_c superconducting (HTS) coils without any electrical contact, avoiding the thick current leads and the consequent heat load. More importantly, they provide the possibility of achieving the persistent current mode operation of a closed-loop HTS coil [1]. Among different categories of flux pumps, the HTS dynamo is popular due to its simple construction and low maintenance [2].

Although the effectiveness of the HTS dynamo-type flux pump has been verified through its implementation in HTS motors and other applications [3], [4], the explanation of

its underlying physical mechanism is widely debated. More specifically, since the topology of the HTS dynamo is similar to the AC homo-polar generator, according to Faraday's law, there should not be any DC component generated inside the HTS stator wire. To explore the abnormal phenomenon of HTS dynamo, Geng *et al.* [5] theoretically proposed an explanation, indicating the non-linear behavior of superconductor is the main reason for that. Then, Bumby *et al.* [6] have measured the open-circuit voltage of a HTS dynamo and they concluded that the time-varying circulating eddy currents within the HTS stator wire results in the rectification of the output voltage. Later, Mataira *et al.* [7] proved that the classical electromagnetic theory can be used for qualitatively and quantitatively reproducing the measured open-circuit voltage. They numerically validate the existence of overcritical eddy currents in the HTS stator wire and support the explanation of rectification effect originated from the non-linear conductivity of superconductor. In addition, other explanations have been proposed, including quantum flux-coupling mechanism [8], and flux-trapped within an extended closed superconducting loop [9].

Inspired by Mataria's work, the modelling of HTS dynamo has become a new benchmark problem for the HTS modelling community [10]. Until now, most of the numerical works have focused on the open-circuit DC voltage of HTS dynamo or its behavior with a DC transport current. However, in practice, other than the DC component, there is also generated AC voltage. Even though this voltage does not contribute to the accumulation of DC current in the HTS coil, it induces AC ripples as well as AC losses in the HTS stator wire and the HTS coil [11]. Meanwhile, the critical current of the HTS coil is also a crucial factor impacting the charging by limiting the value of the saturated current [12].

In this work, by coupling two distinct finite-element models, we propose a method for modeling the dynamic charging process of HTS coils by an HTS dynamo. This model is capable of investigating the dynamic behavior of the HTS dynamo-type flux pump and its impact on the charging pro-

cess. Furthermore, the charging limitation due to the critical current of the HTS coil can also be considered.

II. MODEL DESCRIPTION

For modelling the charging process, two superconducting parts need to be considered: one is the HTS dynamo, including the rotating magnets and the HTS stator wire, another is the load HTS coil. Normally, to estimate the physical behavior as well as the AC losses of superconductor, a finite-element (FEM) model is indispensable while each FEM model can only tackle one superconducting part. Realizing the parallel calculation of multi-superconducting parts is the focus of this work. In a recent publication, Santos *et al.* [13] have proposed a coupling method to link the superconducting devices modelled by FEM to the electrical system. The idea is to present the superconducting device as voltage drop in the lumped electrical circuit. Based on this methodology, we present a method to couple the HTS dynamo and HTS coil to electrical circuit, which can be seen in Fig.1. According to [14], in the lumped circuit model, the HTS dynamo can be represented as a source of voltage $V(t)$ in series with internal resistance R_{int} . As for the HTS coil, it can be seen as a perfect inductor in series with an equivalent resistance corresponding to dissipation and flux creep. The superconducting voltages of the dynamo and coil are V_{out} and V_{coil} in the circuit, respectively, and can be obtained by,

$$V_{out/coil} = \int_{l_{sc}} \mathbf{E} \cdot d\mathbf{l} + \int_{l_{sc}} \frac{\partial \mathbf{A}}{\partial t} \cdot d\mathbf{l}, \quad (1)$$

where l_{sc} is the path of the superconducting domain. The transport current $I(t)$ of the circuit is given by,

$$I(t) = \frac{V_{out} - V_{coil}}{R_j} \quad (2)$$

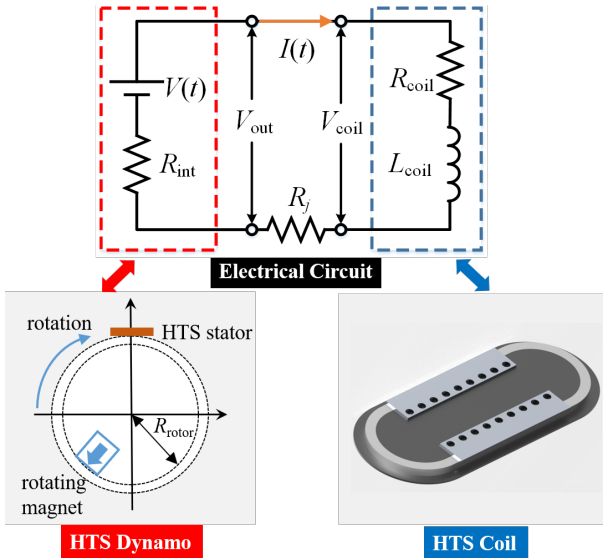


Fig. 1. Coupling schematic method of the HTS dynamo and HTS coil to the electrical circuit.

TABLE I
CONFIGURATION PARAMETERS.

Rotating Magnet	width	6 mm
	height	12 mm
	Effective length	12.7 mm
	Remanent flux density	1.25 T
HTS tape	Width	12 mm
	Thickness	1 μm
	Critical current	104 A
HTS coil	number of turns	20
	inner diameter	0.2 m

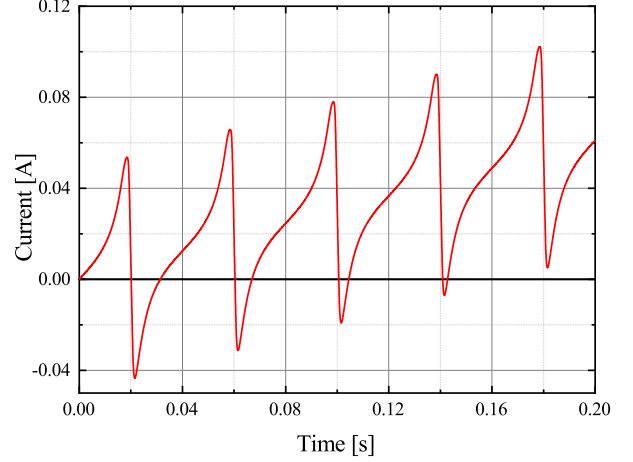


Fig. 2. Charging current in the HTS coil.

where R_j is the joint resistance within the superconducting circuit. The current is enforced by a Dirichlet boundary condition to the HTS stator wire and HTS coil respectively.

III. CALCULATION RESULTS

In this study, the HTS dynamo used in the benchmark problem [10] have been adopted. The load HTS coil is wound with 4-mm wide HTS tape. The characteristics of the HTS dynamo and the HTS coil used in this model are summarized in I. The calculated results can be seen in Fig. 2.

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