Modeling HTS dynamo-type flux pumps: open-circuit mode and charge of an HTS coil

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***Abstract*—Dynamo-type flux pumps can be employed to energize high-temperature superconducting (HTS) magnets to maintain the steady current mode or in rotor windings of electrical HTS motors and generators to inject the current without the need for current leads. To understand the complicated operating working mechanism of the flux pump it is necessary to study both in open-circuit and connected to an HTS coil. In this work, we employ two models to analyze these configurations. The first one is the Minimum Electromagnetic Entropy Production (MEMEP). The second one is a segregated H-formulation finite-element model. For open-circuit mode, we investigate the effect of the airgap on DC voltage generation. Later, we also study the energizing process of an HTS coil modeled by a series resistance and an inductance. These models will also be compared to experiments.**

***Keywords*—Dynamo-type flux pump, open-circuit DC voltage, full-circuit mode, REBCO high temperatuere superconductor.**

I. Introduction

HTS dynamo-type flux pumps belong to the category of the traveling magnetic wave type, which uses a moving magnet to create an inhomogeneous traveling magnetic flux across an HTS tape in order to generate voltage. These kinds of flux pumps are simple and easy to maintain because they do not utilize any switches. For this reason, they have become very popular during recent years to be exploited in HTS magnets, motors and generators [1]–[3]. Dynamo-type flux pumps can be employed to energize HTS magnets to maintain the steady current mode or in rotor windings of electrical HTS motors or generators to inject the current without using any brushes in a contactless way.

Among the different types of flux pumps, the dynamo-type is one of the most complicated ones in terms of understanding its mechanism. Modeling has showed to be an effective way to explain the flux pump mechanism. For this reason, several articles have been published in literature to explain the dynamo-type flux pump mechanism [4]–[7].

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To investigate the flux pump mechanism, studying both open-circuit and full-circuit mode is essential. The open-circuit mode is simpler compared to full-circuit mode considering the elimination of the effect of a net current flowing in the HTS circuit. In this work, we utilize mainly the Minimum Electromagnetic Entropy Production (MEMEP) [8], [9] to model a dynamo-type flux pump with realistic superconductor properties ($E-J$ power-law relation with $J_c(B,\theta)$ from critical-current measurements of single tapes) [7]. This variational method solves the local current density as the state variable, only inside the superconducting region, with minimization of a functional, which makes the model fast and efficient. In addition, the results are compared with another one implemented in COMSOL based on a segregated H-formulation finite-element model [10]. This model solves the magnetic field strength $\mathbf{H}$ only inside the superconductor and a thin air layer around it, which allows us to reduce the number of degrees of freedom and the computing time.

This work investigates the effect of airgap on DC voltage generation in a dynamo-type flux pump in open-circuit mode. In addition, we study the charging procedure by the dynamo-type flux pump of an inductance and resistance in series, representing a typical REBCO coil with joint resistance.

II. Airgap Dependence of Open-Circuit Voltage

Fig. 1 shows an overview of the modeling configuration. The flux pump rotates in the xy-plane and the magnetic field $\mathbf{B}$ exist in the same plane. The current density $\mathbf{J}$ flows in the z direction. Therefore, the vector potential $\mathbf{A}$ and electric field $\mathbf{E}$ are parallel to the z axis.

A useful and practical quantity measured experimentally is the output voltage difference between the tape at 77 K (superconducting mode) and at 300 K (normal mode), $\Delta V = V_{77\mathrm{K}} - V_{300\mathrm{K}}$. This quantity ΔV contains the DC component of the open-circuit voltage, ΔV_{oc}. The amplitude of ΔV_{oc} decreases with increasing airgap, which is the result of the reduction in magnetic field density on the tape surface. Fig. 2 shows the calculated results of reduction of ΔV_{oc} for the modeled flux pump from 2.4 mm up to 50 mm. By calculating the ΔV_{oc} signals in Fig. 2 for the airgaps ranging from 2.4 to 50 mm, the stationary average DC voltage per cycle is

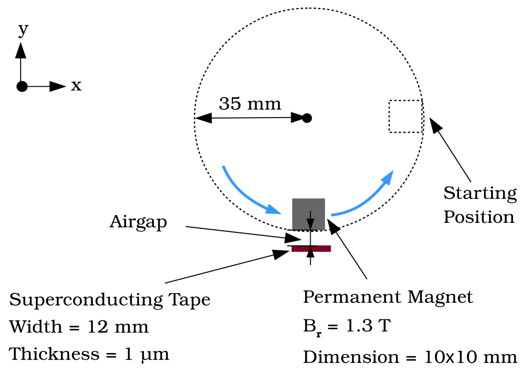

Fig. 1. This 2D cross-sectional model configuration is sufficient to describe the main features of a dynamo-type flux pump.

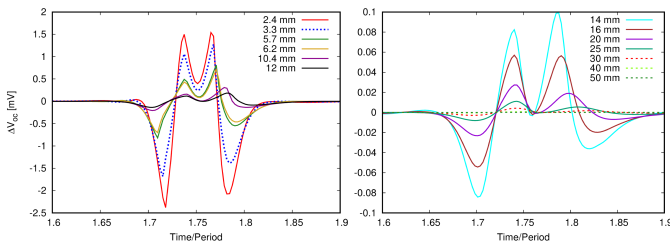

Fig. 2. Calculated results showing the trend in the reduction of ΔV_{oc} with increasing airgap up to 50 mm for the case with $J_c(B,\theta)$ dependence and rotating frequency of 12.3 Hz. (ΔV_{oc} as calulated in [7]).

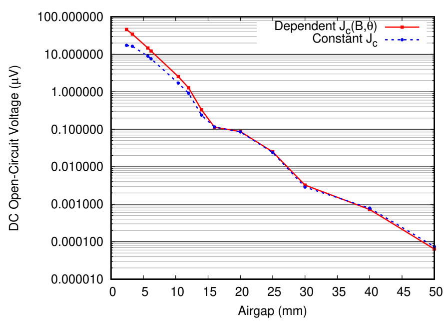

Fig. 3. Calculated ΔV_{oc} for the cases of constant J_c and magnetic-field dependent $J_c(B,\theta)$ for airgaps in the range of 2.4 to 50 mm.

obtained. Fig. 3 shows the trend of changing DC voltage with increasing airgap. This figure also shows the DC value of the open-circuit voltage assuming constant J_c for comparison with the case of dependent $J_c(B,\theta)$.

III. Charging process of HTS coil

Studying the full-circuit mode with transport current is essential to understand the flux pump mechanism that energizes superconducting windings. Fig. 4 shows the circuit diagram of the flux pump in open-circuit and connected to an HTS coil, respectively. In Fig. 4(left) the net transport current is zero, and hence the generated voltage by the flux pump V_{FP} is equal to V_{oc} as calculated in the previous section. However,

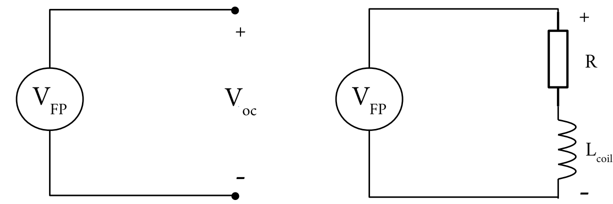

Fig. 4. Circuit diagram of a dynamo-type flux pump in open-circuit mode (left) and in full-circuit mode (right). V_{oc} is the open-circuit voltage and R denotes the joint resistance. L_{coil} denotes the load inductance.

in the full circuit of Fig. 4(right), the output voltage for the flux pump is related to the transport current by

$$V_{FP}(I(t),t) = RI(t) + L_{\rm coil}\frac{{\rm d}I(t)}{{\rm d}t} \tag{1}$$

where R denotes the joint resistance and L_{coil} is the load inductance. Solving the non-linear differential equation above requires numerical methods. Using similar arguments as in [11], the full circuit mode in MEMEP can be solved by minimizing the functional in [8] for the current density at each time step with the additional term $RI^2/2+L_{\rm coil}(\Delta I)^2/2$, where ΔI and Δt are the time and current increments between two time steps, and ΔI is found during minimization. For the segragated H-formulation model, (1) is solved together with the H-formulation flux pump model using a bidirectional circuit coupling scheme.

Modeling results will also be compared to experiments.

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