Improved full-range equivalent circuit of the flux pump

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***Abstract*— The energy behavior of the flux pump is numerically investigated and the operational limits are explored, showing that the generator operation, involving an electric power delivered to the load combined with a mechanical power supplied to the rotor, can only be achieved in a restricted range of current and voltage at the terminals. In no conditions the mechanical torque produced on the rotor can be reversed, reaching the motor mode involving an electric power absorbed at the terminals combined with a mechanical power produced on the rotor. A revised equivalent circuit comprising, besides the effective resistance commonly reported in the literature, a further intrinsic resistance is proposed, on an empirical base, in the paper for taking the dissipation mechanism into account. It is shown that this equivalent circuit is able to predict, with excellent agreement with finite element models, the energization of an RL load both concerning the final steady values and the full time-domain behavior of the current (including ripples), while taking the loss properly into account.**

Keywords—flux pump, HTS dynamo, equivalent circuit

I. Introduction

Exploring flux pumps behavior through accurate numerical models represents a fast and efficient method for assessing the performance and provide optimal design criteria [1-2]. In particular, the identification and the quantitative assessment of loss phenomena during operation and the identification of possible current and voltage limits that the flux pump cannot overcome, is of utmost importance for practical applications

In this paper, the energy behavior and efficiency of the flux pump reported in [2-3] are numerically investigated via the volume integral equation-based equivalent circuit model (VIE). The operational limits in which the device can operate as a generator, delivering electric power to the load and absorbing mechanical power on the rotor, are also investigated. A revised empirical equivalent circuit, able to properly take all dissipation mechanisms into account, is also proposed and used for reproducing the energization of an RL load both concerning the final steady values and the full time-domain behavior of the current (including ripples).

II. Mathematical Model of the flux pump – 2D FEM model, energy balance and efficiency calculation

The numerical model is obtained in the form of an equivalent circuit by means of the volume integral equations method [4]. The numerical solution of the 2D infinitely long problem is obtained by subdividing the superconductor domain into a finite number of wires, and by enforcing Faraday's Law to be satisfied, in the weak form, over each element of the discretization. The total electromotive force at any point of the superconductor is split into two contributions: one contribution due to the time varying field produced by the current induced in the superconductor and a second contribution due to the movement of the permanent magnet. The following equation is finally obtained

$$(1)\quad l^{PM}\,\mathbf{M}\frac{d}{dt}\mathbf{I}_{\mathrm{w}} = -l^{PM}\,\mathbf{R}\,\mathbf{I}_{\mathrm{w}} + l^{PM}\,\mathbf{U} - \mathbf{1}V$$

where l^{PM} is the depth of the permanent magnet, $\mathbf{I}_{\mathrm{w}}$ is the set of currents of the thin wires, **1** is a column vector of as many ones as the number of thin wires of the subdivision, **M** is the matrix of self/mutual induction coefficients, **R** is the diagonal matrix of resistances, **U** is the vector of motional electromotive forces acting on the thin wires with unit length.

Two different operating conditions are considered for the flux pump, correposndig to two different versions of the model:

1. *Current driven operation* – the flux pump is connected to an external ideal current source that imposes the total current *I*.
2. *RL load* – the flux pump is connected to an HTS coil, with given inductance and resistance accounting for overall dissipation.

The operating condition 1 (*current driven*) is reporduced by setting the sum of currents of the wires equal to total current *I* of the flux pump. In this case equation (1) is supplemented with

(2) $I = \mathbf{1}^t \, \mathbf{I}_w$

The operating condition 2 (*RL load*) is obtained by setting in equation (1) :

$$V = R_{ext}\, I + L_{ext}\, \frac{d}{dt} I \tag{3}$$

with resistance R_{ext} and inductance L_{ext} accounting for the total resistance and inductance of the supplied winding respectively.

The energy balance si obtained from the dot product of equation (1) by the vector of currents, that after manipulation gives:

$$-T\omega = V\, I + P_J + \frac{d}{dt} W_{mag} \tag{4}$$

where P_J is the total joule loss occurring in the superconductor, W_{mag} is the stored magnetic energy and T is the resistant mechanical torque produced onto the rotor, via the Lorentz force, by the current of the superconductor.

Finally, by denoting with E and $E_{mechanical}$ the transferred electrical energy and the mechanical energy supplied to the rotor respectively, the efficiency of the flux pump is obtained as:

$$\eta = \frac{E}{E_{mechanical}} = \int_t^{t+T} VI\, dt' \Big/ -\int_t^{t+T} \omega T\, dt' \tag{5}$$

III. Numerical Results

The averages voltage V in one cycle at the terminals of the rotating flux pump is shown in figure Fig. 1.a. The figure also shows the voltage in case of no roation (that is, with the HTS tape subject to impressed transport current only). It is clear from the figure that the effects of the rotation are 1) shifting the VI curve into the first quadrant allowing power generation, and 2) increasing the power to be supplied for impressing a DC current when the flux pump does not operate in the generation mode. Fig 1.b is a magnification showing that the dynamo is able to operate as a generator within limit values V_0 and I_0. The former is the average open circuit voltage over one cycle, the latter is the dynamo transport current that produces average zero voltage at flux pump terminals (different from the current of the flux pump operating in short circuit condition). The complete empirical equivalent circuit of the flux pump, able to take internal dissipation into account is shown in Fig. 2.a [5]. The parameters of the circuit are derived from the energy balance as follows:

$$R_{intrinsic} = \frac{V_{rms0}^2}{P_{joule0}}\ ; \ R_{effective} = \frac{V_0}{I_0} \tag{6}$$

where V_{rms0} is the rms value of the open circuit voltage and P_{joule0} with the average joule dissipation in one cycle occurring in no load conditions. In Fig. 2.b the transient current of a RL load obtained by meas of the complete VIE model and by means of the empirical equivalent circuit is compared, showing that coincident results are obtained.

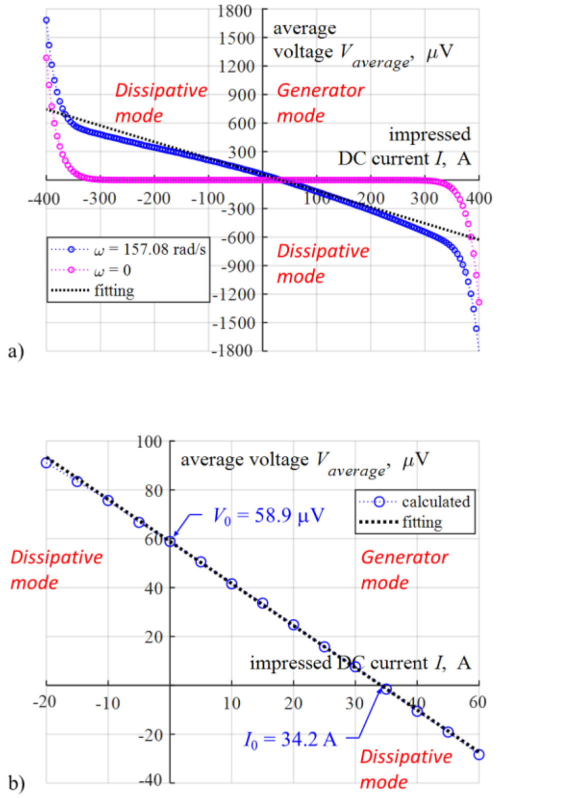

Fig. 1. A) Average voltage of the flux pump rotating at 157.08 rad/sec (25 Hz) compared with the voltage developing at the tape's terminal in case of no rotation. The dotted line represents the linear V-I trend. b) Magnification the *V-I* points in the first quadrant.

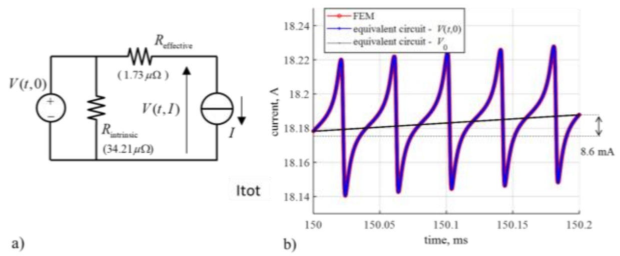

Fig. 2. a) complete time-domain empirical equivalent circuit of the flux pump taking internal dissipation into account, b) Detail of the current during 5 cycles.

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