Use of a Conductor Screen to Magnetize NdFeB Magnets

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***Abstract*—The magnetizer presented in this paper consists of a magnetic core made with silicon iron sheets with a large airgap in which the permanent magnets to be magnetized are located. This magnetic structure is energized by two symmetrical coils placed on the central leg above and below the airgap. The cross section of the airgap is four times the area of the permanent magnet, so with a copper plate that surrounds the magnet (not completely), effective concentration of the flux density lines is obtained. The copper plate was called "Electromagnetic Conductor Screen".**

The Capacitor-Discharge-Bank was rated 1080µF, 2000V and 3.5 Tesla were obtained in the central airgap.

The paper presents the experimental results and theoretical analysis used to evaluate the conductor screen time-constant of the proposed magnetizing system.

***Index Terms*—Electromagnetic conductor screen (copper plate), low rated capacitor-discharge-magnetizer, magnetic structure, magnetizing.**

I. INTRODUCTION

The application of permanent magnets in the construction of electrical machines was greatly increased in the 1980's with the advent of rare earth magnets [1]. Nd-Fe-B magnets occupy an important place due to their low cost and high basic magnetic parameters (remanent flux density, coercive field and energy product). However, in order to magnetize these rare earth magnets a relative high impulse (3 to 4 Teslas) of applied magnetic field is required.

Such a pulse field is commonly obtained by discharging a capacitor-bank into a coil, inside of which the magnet is located. The phenomenon of this discharge has been well described in [2]-[5]-[9]. For small magnet pieces the magnetic circuit is completely enclosed in air, and for medium size magnets, in order to concentrate the magnetic energy in the airgap (where the magnet is embedded) an iron core is used [9]. An important requirement in order to obtain uniform magnetization is to place the magnet in the central part of the magnetizer [6].

Also great attention has been paid to magnetization in-situ [5]-[6]-[7]-[8] which is applicable to magnets used in dc motors. In this case the unmagnetized magnets are assembled into the rotor or other structure and then magnetized as a finished assembly. In the case of synchronous generators the damping windings (squirrel cage bars) prevent a fast change of the flux density in the permanent magnets of the excitation system, so this procedure is not applicable.

From an energy point of view, the magnetization problem is to transfer the maximal amount of energy from the capacitor-bank to the magnet. The principal losses are the heating in the windings and the hysteresis in the iron core (this last one is proportional to the maximum value of the flux density raised to the Steinmetz coefficient [11]). Also, the total amount of ampere-turns needed to magnetize the permanent magnet is a fixed quantity, so we conclude that the maximum energy transfer occurs for the fastest transient process. In other words, the design must minimize the inductance of the magnetizer circuit and maximize the rated voltage of the capacitor-bank.

The use of the proposed conductor screen (copper plate), that surrounds (not completely) the magnet plays two important roles: 1) to concentrate the energy of the airgap in the magnet, and 2) to reduce the inductance at the magnetizer terminals. Both instances contribute to maximize the energy transfer from the capacitor-bank to the permanent magnet.

II. GENERAL DESCRIPTION OF THE MAGNETIZER

The magnetizer is basically a transformer core with a large airgap in the middle of the central leg. In this airgap is

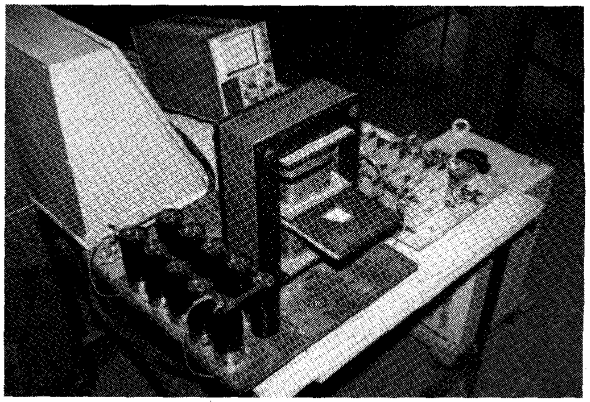

Fig. 1. Photograph showing the magnetizer, the conductor screen, the capacitor-bank and the rapid thyristors and flywheeling diodes.

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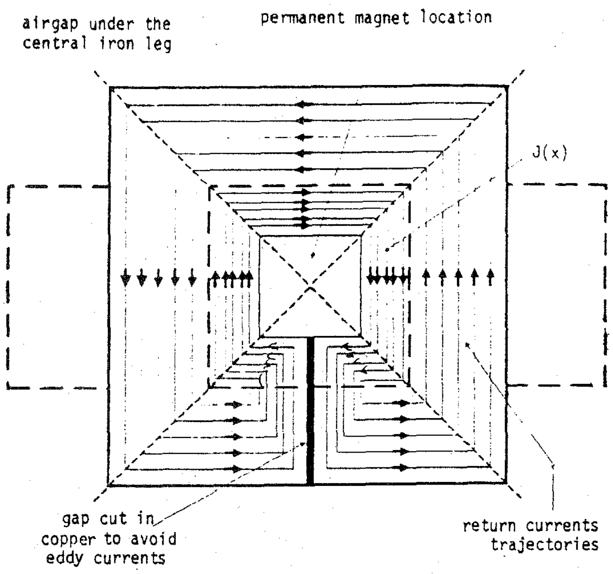

Fig. 2. Approximate distribution of current density in the conductor screen

placed the permanent magnet and the conductor screen (see photograph of figure 1). Two identical coils (each N=360, d_{Cu}=2.05 mm) are located above and below the airgap. The coils are mounted on copper reels to completely isolate the windings from the magnetic iron core. Thus, the leakage inductance due to magnetic flux that does not cross the airgap is minimized. The two coils are connected in parallel and then connected to the capacitor-bank by two series rapid thyristors. Two series rapid diodes are also connected to act as freewheeling diodes (these are SCRs rated at 240 A and 1200 V). The capacitor-bank is rated 1080 μF and 2000 V.

III. MODELING OF THE CONDUCTOR SCREEN

The permanent magnets to be magnetized are sized 50x50x10 mm, the conductor screen is 200x200x10 mm and the central leg cross section is 100x100 mm (dashed line in figure 2). In order to evaluate the conductor screen operation the current density paths shown in figure 2 were assumed. They appear in the screen under rise or decay of the magnetic flux in the central leg. The voltage drop due to vortex currents at the two sides of the cutting was neglected.

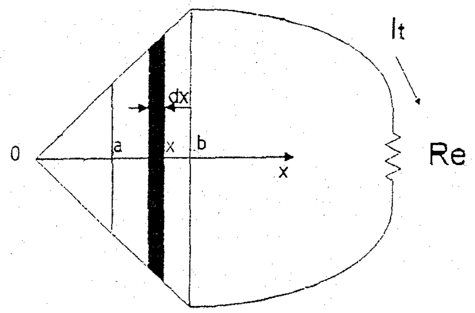

Fig. 3. Segment showing one quarter of the conductor screen.

The central point of the screen was chosen as the coordinate origin. The magnetic flux in the airgap that is not under the central leg is neglected. Magnetic flux was assumed to be perpendicular to the screen. The magnetic flux distribution in the iron core is considered as uniform, but in a zone very close to the airgap the flux density lines are curved. This is the effect of the currents in the screen that concentrates the magnetic flux in the portion of the airgap occupied by the magnet. The return currents are not affected by any magnetic flux, so the voltage drop across the outer part of the screen can be simulated by a resistance R_e (fig. 3).

A. Equations of the Electromagnetic Process in the Conductor Screen

The electromagnetic process in the conductor screen must be in accordance with Faraday's Law (1) and with Ampère's circuital law (2), so we can write the following two equations:

$$-\int_{x}^{b} \frac{\partial B(y)}{\partial t} \cdot y \cdot dy = \rho \cdot x \cdot j(x) + \rho \cdot \beta \cdot \int_{a}^{b} j(x) \cdot dx \quad (1)$$

$$\int_{a}^{x} j(z) \cdot dz = \frac{B(x)}{\mu} + \frac{1}{\mu \cdot \alpha} \cdot \int_{a}^{b} B(x) \cdot x \cdot dx \quad (2)$$

where:

$\rho = 10^6 \cdot \rho_{Cu} = 0.0174\ \Omega$-m $a = 0.025$ m
$\beta = 0.5 \cdot (c+b)/(c-b) = 1.5$ $b = 0.050$ m
$\mu = 10^6 \cdot \mu_0 \cdot (\delta_{Cu}/\delta) = 1.1424$ H/m $c = 0.100$ m
$\alpha = 0.5 \cdot (1+\mathcal{R}_h/\mathcal{R}_{fe}) \cdot a^2 = 0.0600\ m^2$ $L_{fe} = 0.890$ m
$\mathcal{R}_h = \delta/(\mu_0 \cdot 2 \cdot a^2) = 7002817$ AT/Wb $\mu_r = 3826$
$\mathcal{R}_{Fe} = L_{fe}/(\mu_r \cdot \mu_0 \cdot 2 \cdot b^2) = 37022$ AT/Wb
$\delta_{Cu} = 0.010$ m thickness of the conductor screen
$\delta = 0.011$ m length of the airgap

Equations (1) and (2) completely describe the functionality of the conductor screen, and the homogeneous (or natural) solutions are in the form of (3). If an external magnetomotive force needs to be considered, then particular solutions with the corresponding time function can be added.

$$B(x,t) = \sum_{j=1}^{\infty} B_j \cdot e^{-t/T_j} \cdot B_j(x) \quad (3.a)$$

$$J(x,t) = \sum_{j=1}^{\infty} J_j \cdot e^{-t/T_j} \cdot J_j(x) \quad (3.b)$$

Coefficients B_j and J_j must be determined from the initial distributions of the functions B(x,0) and J(x,0).

B. Determination of the Lowest Screen Time Constant

For a direct current of 10 A applied to the coils connected in series, a flux density of 0.88 Tesla is obtained in the airgap. If the direct current is interrupted, only the

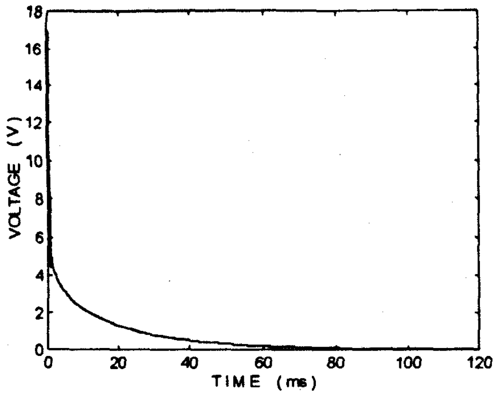

Fig. 4. Oscillogram of the magnetic flux decay under the action of the screen.

screen current distribution will maintain the magnetic flux in the system, which will decay with different time constants. In effect, initially the flux density distribution is uniform and the resulting current is distorted. This distortion of the current causes fast time constants. Immediately after the current becomes more uniform and the process is governed by the lowest time constant. It is important to note that the flux density experiences a low distortion due to the high value of relative permeability of the iron ($\mu_r = 3826$).

For uniform values of B(x) and J(x) from (1) and (2) the lowest time constant (**T = 24 ms**) is obtained. The measured value from the transient oscillogram (figure 4) gives a value of **T = 22 ms**. The difference can be explained as a consecuence of a low distortion in the actual implementation.

IV. MAGNETIZATION OF Nd-Fe-B PERMANENT MAGNETS

The oscillograms with the most important variables obtained during the magnetization of Nd-Fe-B permanent magnets are shown in figure 5. The bottom oscillogram shows the capacitor-bank voltage. The next shows the current in the parallel coils. The third from the bottom is the ratio: (B in the magnet)/(B in the core). The fourth shows the effect of concentration of the magnetic flux density in the magnet under the action of the conductor screen. It should be noted that it is possible to increase the effect of the screen by lowering the inductance of the electric circuit or increasing the capacitor-bank voltage.

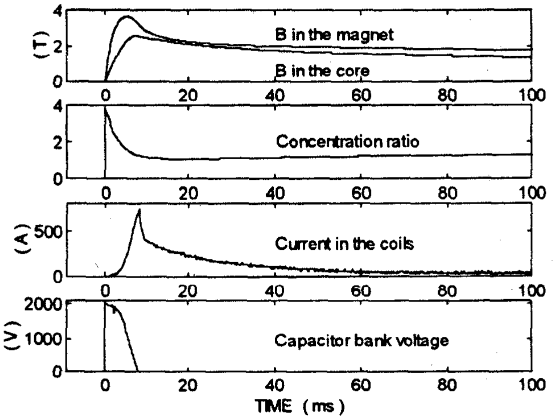

Fig. 5. Oscillograms obtained during the magnetization of a Nd-Fe-B magnet.

IV. CONCLUSIONS

The evaluation, design data, modeling and calculation of the lowest time-constant of the conductor screen used to magnetize Nd-Fe-B permanent magnets were presented. The screen enables the maximum energy transfer from the capacitor-bank to the permanent magnets.

The use of the electromagnetic conductor screen allows 1) a low capacitance of the capacitor-bank (1080 μF), 2) the rated value of the remanent flux density and 3) a high homogeneity of the magnetization of the Nd-Fe-B permanent magnets. Therefore its utilization is advisable specially when it is necessary to magnetize large magnets.

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