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**EDDY CURRENT MODELING AND MEASURING
IN FAST-PULSED RESISTIVE MAGNETS**

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Abstract

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Linac4

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Eddy Current Modeling and Measuring in Fast-Pulsed Resistive Magnets

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Abstract — A method for modeling and measuring electromagnetic transients due to eddy currents in fast-pulsed resistive magnets is proposed. In particular, an equivalent-circuit model and a method for time-domain measurements of eddy currents are presented. The measurements are needed for an accurate control of the magnetic field quality to ensure adequate stability and performance of the particle beam in particle accelerators in dynamic conditions (field ramps up to about 700 T/s). In the second part, the results of experiments for model definition, identification, and validation are discussed. The tests were carried out on a quadrupole of Linac4, a new linear particle accelerator under construction at CERN (European Organization for Nuclear Research).

Keywords- Accelerator magnets, Eddy currents, Load modeling.

I. INTRODUCTION

Linac2, the injector of the CERN Proton Synchrotron Booster (PSB), limits the performance of the proton accelerator complex owing to its low output energy (50 MeV). This bottleneck is going to be removed by means of a higher-energy linear accelerator under development (Linac4), which will double the brightness and the intensity of the beam delivered by the PSB and will ensure the “ultimate” beam needed for the Large Hadron Collider [1]. The beam is focused by means of several narrow-aperture quadrupole electromagnets along the acceleration path. The magnet coils are air-cooled, thus only pulsed operation at 1 Hz is allowed. Consequently, the field is switched on and off in synchronization with the passage of particle bunches.

A difficult measurement problem arises from the dynamic requirements for the field quality inside such a magnet. The present work focuses on a so-called Type III quadrupole, installed in the Chopper line of Linac4 [2]. This 60 mm long, 29 mm aperture magnet is powered by the current cycle of Figure 1. The current ramp-up lasts 200 μ s and is followed by a flat-top of 600 μ s at a nominal current of 200 A, where the field is required to be stable within 10^{-3} . The flat top stability is determined essentially by the decay of the eddy currents

induced during the ramp, as well as by other parasitic effects [3]. In general, the main effects of eddy currents are: (i) to screen flux changes, (ii) to delay the achievement of nominal DC field, (iii) to introduce high harmonic content perturbing the field [4]. An equivalent circuit model is necessary to fully understand the eddy currents effects, as well as to plan possible corrective actions [5]-[6]. Eddy current effects are hard to predict accurately because they depend on a number of uncertain parameters, such as the magnetic properties of the iron yoke, its temperature, the surface resistivity of the laminations [7], the mechanical tolerances leading to unwanted air gaps in the magnetic circuit, etc. As a consequence, an experimental approach is necessary to validate both design calculations and manufacturing quality [3].

In this paper, a method for modeling and measuring electromagnetic transients due to eddy currents in fast-pulsed resistive magnets is proposed. In particular, in Sections 2 and 3, an equivalent-circuit model and a measurement method of eddy currents are respectively proposed. In Section 4, the experimental results related to model definition, identification and validation carried out on a quadrupole of Linac4 are discussed.

Figure 1: current excitation waveform for the laminated iron-core magnet “Type III quadrupole”.

II. THE PROPOSED MODEL

The eddy currents are generated by electric fields arising from variable magnetic fluxes [7]. They build up during the current pulse ramp-up and decay during the constant portion. In the proposed model, their effect is considered as a bypass current, flowing through a chain of R/L circuits connected in parallel to the main coil (Figure 2).

Figure 2: equivalent model circuit of eddy current effect

For a short magnet such as a Type III, the contribution of the fringe field may be dominant [8]-[9], thus two R/L chains are considered in order to take into account: (i) the eddy currents parallel to the main coils (i.e. across the laminations), which have a short time constant, and (ii) the eddy current circuit, in the plane of the end laminations (i.e. perpendicular to the magnet axis) due to the fringe field. The model also takes into account the parasitic capacitance of the magnet coil that could influence the main field at high frequency (about 1 MHz or above). The bypass eddy currents (I_1 and I_2) are negligible with respect to the main current, thus can be considered as mutually independent and the analysis can be simplified [8]. The current I_m flowing through the main coil of the magnet is given by:

$$I_m = I_0 \left(1 - \frac{L_m}{L_1 + L_m} \exp\left(-\frac{R_1}{L_m + L_1} t\right) - \frac{L_m}{L_2 + L_m} \exp\left(-\frac{R_2}{L_m + L_2} t\right) \right) + I_p \quad (1)$$

where I_0 is the current source, L_m the main coil inductance, R_1 , R_2 , L_1 , and L_2 are the equivalent resistance and inductance of the eddy current circuits, respectively. The current I_p flowing through the parasitic capacitor will introduce small ripples in the flux. Assuming the static field B to be simply proportional to the magnet current, the main field component can be described by:

$$B = B_0 \left(1 - \alpha \exp\left(-\frac{t}{\tau_1}\right) - \beta \exp\left(-\frac{t}{\tau_2}\right) \right) + B_{ac} \quad (2)$$

where B_0 is the main field at the end of the double exponential decay and B_{ac} is the high-frequency ripple introduced by I_p ; α and β are the amplitudes of the exponential decays, and τ_1 and τ_2 are the time constants delaying the field response.

III. THE PROPOSED MEASUREMENT METHOD

The e.m.f. V_C induced in the coil has to be integrated in order to obtain the linked flux ϕ . Assuming that the quadrupole is excited starting from a demagnetized state at $t=t_0$, the flux ϕ seen by a search coil with N_t turns inserted in the magnet is calculated as:

$$\phi(t) = \frac{1}{N_t} \int_{t_0}^t V_C(t) dt \quad (3)$$

In the ideal (linear) case, this flux would be simply proportional to the excitation current via the mutual inductance L_{CM} , depending on the geometry and on the magnetic permeability of the iron core [10]:

$$\phi(t) = L_{CM} I(t) \quad (4)$$

In actual conditions, a current difference ΔI can be defined as:

$$\Delta I = \frac{\phi(t)}{L_{CM}} - I(t) \quad (5)$$

The current difference (5) includes contributions from all non-ideal effects, builds up during the ramp and decays over the flat-top. Assuming that the transient has completely died out at the end of the flat top, i.e. $\Delta I(t_S) = 0$, one can derive:

$$\frac{1}{L_{CM}} = \frac{N_t I(t_S)}{\int_{t_0}^{t_S} V_C(t) dt} \quad (6)$$

By considering that the measured signals are affected by electrical noise, mains hum, power supply ripple and so on, the accuracy of the ratio (6) can be increased by averaging both the terms, the current excitation and the voltage coil integral over a short time interval $t_S - \Delta t \leq t \leq t_S$.

IV. EXPERIMENTAL RESULTS

In the following, the experimental results related to (i) the *model definition*, (ii) the *model identification*, and (iii) the *model validation* carried out on a Type III quadrupole are illustrated.

A. Model Definition

In the model definition, the main problem is to take into account both the eddy current circuit in the iron yoke lamination and the other circuit created by the fringe field in the plane perpendicular to the magnet axis.

To understand how the different eddy current circuits influence the time domain integral measurements a small coil of 4.5 mm diameter was used to scan the field inside the aperture in different positions with a 5 mm longitudinal step. The observed variation of the eddy current decay is function of the position inside the magnet aperture [11]. The decay includes two contributions: a slow one which tends to disappear when the coil is in the middle of the magnet

aperture, and a fast one which is present along the whole magnet length.

B. Model Identification

The equivalent magnet impedance was measured in order to determine the values of the model parameters from 500 Hz up to 1 MHz. A gain phase analyzer (Powertek® GP102) was used to measure the phase and the amplitude of the impedance. The measurement was performed at low current (200 mA), thus the model does not take into account the effects due to the nonlinearity of the permeability (saturation effects of the iron yoke) that might affect the measurements. The obtained data were validated through a crosscheck with a CERN-built system, the PROMIT [12], capable of analyzing gain and phase up to 20 kHz by forcing a sinusoidal current up to 5 A.

In Figure 3, the results of two typical measurements in the frequency domain at 0.2 and 3.0 A are reported as an amplitude bode diagram. In the range from 500 Hz to 20 kHz, the two curves overlap. This confirms that in this range the magnet has a linear behavior not related to the excitation current (from independent measurements, iron yoke saturation is expected at current values well above 100 A).

C. Model Validation

The model was validated according to the following procedure:

- measure the magnet impedance vs. frequency;
- evaluate the unknown model parameters R_1 , R_2 , L_1 , L_2 and C_p with a non linear complex fitting method [13];
- compare the measurement data in the time domain [11] with the DC model simulation results;
- calculate the residual between the model and the measurements.

The results of the frequency-domain measurement were used to determine the five unknown model circuit parameters. The main coil inductance L_m was obtained from design specifications, while the resistance R_m was calculated by considering the winding wire cross section and length and cross-checked by four-wire measurement. A non linear least square method was used to estimate R_1 , R_2 , L_1 , L_2 and C_p (see Table 1).

In Figures 4-5, the results of the fitting are shown. The model fits the impedance measurement with a residual less than 10 % for the absolute value of the impedance up to 750 kHz, and less than 10 % of error between the measured value and the simulated impedance phase. The maximum difference between the model and the measurement curves occurs for frequency higher than 600 kHz. In any case, in the range of interest (from 500 Hz to 450 kHz) the model is able to replicate the magnet behavior.

Figure 3: amplitude Bode diagram of the magnet.

Table 1: eddy currents parameter calculation

Parameter	value
R_1 (Ω)	110
L_1 (μH)	957
R_2 ($\text{k}\Omega$)	1.42
L_2 (μH)	583
C_p (pF)	280

Figure 4: modeled and measured amplitude Bode diagram of the impedance (up) and residual (down).

In Figure 6, the complete model for the transient analysis is shown. The circuit reproduces the time domain measurement scheme proposed in [11]. It simulates the flux linked to the pick up coil used to measure the field inside the magnet aperture. The excitation current waveform (Figure 1) is applied as input to the model in order to understand the behavior of the time integral of the voltage generated at the ends of the transformer secondary winding (Figure 6) representing the pick-up coil. The resistance of 10 G Ω is the acquisition system resistance.

In Figure 7, the time response of the equivalent circuit to the excitation current is shown. The flux simulated at the end of the acquisition chain, and the acquired actual flux expressed as described in (5), are shown.

The circuit is able to replicate the decay effect due to the eddy currents but is still missing the contribution of the mutual

coupling of the parasitic circuits with the pick-up coil in the flux measurements. The difference between measurement and simulation in the time domain still evidences a very small-amplitude slow decay during the flat-top. In the future work all the mutual couplings between the coil and the circuits will be taken into account.

Figure 5: modeled and actual impedance: phase diagram (up) and percentage residual error (down).

Figure 6: complete circuit model of the eddy current and of the measurement system.

Figure 7: measured and modeled flux scaled by the mutual inductance L_m : time domain transients (up), and residual (down).

V. CONCLUSIONS

A model-based method is proposed for measuring electromagnetic transients due to eddy currents in a short quadrupole magnet in time and frequency domain. The effects of eddy currents in the pole lamination and in the plane perpendicular to the magnet axis are modeled by two R/L chains.

The residual between equivalent impedance measurements and model predictions below 750 kHz is less than 10% for both the amplitude and phase.

The model describes the decay effect in the time domain measurements by using an actual excitation current curve. In this case, the residual presents a slow decay effect during the current flat-top probably due to direct coupling between the coil and the two parasitic circuits.

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