CHAPTER - I

EXPERIMENTAL INVESTIGATIONS
ON
THE IMPEDANCE OF FERROMAGNETIC CONDUCTORS

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1 - 1. INTRODUCTION

During the last two decades, a considerable amount of work has been done on the effects of eddy currents in solid and laminated iron cores due to an alternating magnetic field. Pohl[1] investigated the effects of saturation and hysteresis on the eddy current loss in solid iron cores. Gibbs[2] had investigated the same effects and applied results for the design of certain types of induction motors. Extensive theoretical and experimental work has been done by several others, notably; Brailsford[3], Carter[4], Greig and Mukherjee[5], Bondi and Mukherjee[6] and Kesavamurthy and Rajagopalan[7] on the development of a linear theory applicable for the evaluation of pole face losses and eddy current effects due to rotating magnetic fields.

A limiting non-linear theory to take into account the effects of saturation and hysteresis, applicable to highly saturated cores, has been developed by Mc.Connell[8,9]; Agarwal[10], Kesavamurthy and Rajagopalan[11,12] and Kesavamurthy

Rajagopalan and Subbarao[13]. Recently an analytical method has been developed to take into account the effect of saturation in slightly saturated cores, (Kesavamurthy and Rajagopalan[14,15]).

However, very little data is available in the literature on the effects of eddy currents on the field distribution inside ferromagnetic conductors carrying alternating currents. The aim of this Chapter is to present experimental data on the behaviour of ferromagnetic conductors carrying alternating currents over a wide range of frequencies and surface magnetizing forces, with particular reference to the internal impedance of the conductor.

1 - 2. EXPERIMENTAL INVESTIGATIONS

The variable factors involved in the experimental work are :

(i) Material employed (mild steel) ;
(ii) Shape of conductors (rectangular, circular and strips) and size of the conductors (upto 2 sq. cm. in cross-section);
(iii) Surface magnetizing force (ranging from 0.1 A/cm to 100 A/Cm)and;
(iv) Frequencies (30 c/s to 2400 c/s).

The material available (with pronounced nonlinearity and hysteresis) is Mild Steel in the form of long rods of section 2.54 cm x 1.25 cm. A study of the behaviour of magnetic conductors made from this material is required not only at various frequencies and magnetizing forces but also for different sizes and shapes. With this end in view, from the same M. S. rod pieces were cut and finally turned and machined to the following specifications:

(A) M. S. rods of 25 cm. length and rectangular sections
(i) 2 cm. width x 1 cm. depth ,
(ii) 2 cm. width x 0.5 cm. depth,
(iii) 2 cm. width x 0.25 cm. depth,
and (iv) 2 cm. width x 0.175 cm. depth ;

(B) M. S. rods of 25 cm. length and square sections
(i) 1 cm. x 1 cm.,
and (ii) 0.5 cm. x 0.5 cm ;

(C) M. S. rods of 25 cm. length and circular sections
(i) 1 cm. diameter,
and (ii) 0.5 cm. diameter.

(D) M. S. rods of length 25 cm. and square section of 1 cm. side to obtain the magnetic data of the material.

The above conductors of different shapes and sizes are to be subjected to a.c. currents, the choice of the value of the surface magnetizing force must be over the entire linear and nonlinear regions of the magnetization curve of the material. Furthermore, the choice of frequency range should be to furnish information on the behaviour of the conductor right from d.c. to reasonably high power frequencies where a solid magnetic conductor just ceases to be no longer useful as a conductor. For frequencies upto 75 c/s, an alternator driven by variable speed d.c. motor was employed, whilst, for frequencies ranging from 200 c/s to 2500 c/s, a high stability variable frequency electronic generator was employed. A note on the specialities of this commercial equipment and the preliminary adjustments prior to use are now in order.

The Elliott High Stability Generator is designed to provide a source of a.c. supply, upto a maximum of 70 VA, for testing precision measuring instruments or for any other purpose for which a highly stable low-impedance supply is essential. For majority of purposes, its impedance, as a circuit parameter, can be considered negligible. It has two independent output circuits the phase angle difference between which is continuously adjustable over 360°. One of them is referred to as 'Voltage Channel' meant for application of voltages across impedance values from a minimum of 225 ohms and above. Output voltage from this channel is continuously variable from zero to 750 volts. The second channel is referred to as 'Current Channel', meant for application of currents through impedance values upto a maximum of 280 ohms. Output current from this channel is continuously adjustable from zero to 5 Amps but subjected to a maximum output of 70 VA. The voltages and currents from the above two channels are obtained at any frequency from 40 c/s to 2400 c/s, available in four steps. The generator mainly comprises a highly stable, two-phase, RC oscillator, terminated by two high grade, high power, low output - impedance amplifiers for the above-mentioned two output channels. The oscillator feeds voltages in quadrature to the stator windings of a phase shifter. The voltage induced in the rotor winding of the phase shifter is the source of e.m.f. for the 'Current channel' whilst the "Voltage Channel" is tapped directly from one phase of the oscillator. The phase dial is provided with a slow-motion drive facilitating comfortable reading upto 0.05°. A check on the phase-shift measurement can be carried out by observing the current channel output when the rotor shaft is taken through 360 electrical degrees. If the voltages to the stator windings of the phase shifter are equal and at exact quadrature, the output current should remain constant throughout the rotation. Set controls are provided in the oscillator for correction, if necessary. Such a check, repeated often, avoids any uncertainity in the measurement of phase angle, the resulting error, in any case, not exceeding ± 0.1° for angular movements corresponding to a phase shift of 45°.

1 - 2.1 Magnetic Data of the Material

Sets of B-H loops are obtained for each of the materials using an Illiovici permeameter. For extremely small values of the magnetizing force, the permeameter is used in conjunction with a sensitive ballistic galvanometer whilst, for large values the galvanometer is replaced by a fluxmeter. In Fig. 1.1 is shown a set of hysteresis loops for Mild Steel over a range of magnetizing force from 0.1 A/cm to 160 A/cm. The ratio $\mu = B_m/H_m$ for each value of H_m can be got by joining the tips of all the loops and this ratio corresponds to the absolute value of the average permeability. For the case of a.c. magnetization, for each loop the distorted waveform of the flux-density due to a sinusoidal magnetizing force, H_m Sin wt, has a fundamental component expressed as B_1 Sin (wt - σ). The ratio, $\mu_1 = B_1/H_m$, is the effective permeability and the angle of lag given by σ is the hysteresis angle. Sets of waveforms are analysed and the values of μ_1 and σ are derived from them. In Fig. 1.2 is shown the variation with respect to H_m of the effective permeability, μ_1, the average permeability, μ and the hysteresis angle, σ, for Mild steel.

An alternative method of determining B_1 and σ is based on the suggestion by Middleton[16] that an analytical hysteresis function for a loop with a coercive force, H_c and remnance, B_r is related by

$$H = H_m \operatorname{Sin} (\theta + \phi)$$

$$B = B_m \frac{\operatorname{Tan}^{-1}(K \operatorname{Sin} \theta)}{\operatorname{Tan}^{-1} K}$$

where θ is a parameter ranging from 0 to 2π, linking H and B; ϕ, K are given by

$$\frac{H_c}{H_m} = \operatorname{Sin} \phi ;$$

$$B_r = - B_m \frac{\operatorname{Tan}^{-1}(K \operatorname{Sin} \phi)}{\operatorname{Tan}^{-1} K}$$

The function was verified for all the hysteresis loops in Fig. 1.2; representative curves indicating the nature of fit for two loops are shown dotted in the same figure. Now, for a sinusoidal variation of H with time, B_1 and σ can be obtained from the expressions