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Asynchronous operation of round rotor synchronous machines

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ASYNCHRONOUS OPERATION OF ROUND ROTOR SYNCHRONOUS MACHINES

by

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ABSTRACT

After a generating unit loses synchronism, it is usually disconnected from the system. However, tests have shown that if an unsynchronized round rotor machine is left connected to the system, its speed will increase to some steady state asynchronous value at which the electrical power output of the machine (plus windage and friction losses) is equal to the turbine mechanical power input. The machine output is due to induced eddy currents in the rotor surface causing the unit to act as an induction generator.

A method is presented for predicting the asynchronous operating characteristics of a round rotor synchronous machine whose field circuit is open. The method is to adapt the classical equivalent circuit of an induction machine to represent asynchronous operation of a synchronous machine.

The stator resistance, stator leakage reactance, magnetizing reactance and conductance representing stator iron losses are generally known for a large synchronous machine. The equivalent rotor impedance referred to the stator is calculated by first assuming a rectangular magnetization curve for the rotor iron. This results in a

maximum depth of penetration for rotor eddy currents of

$$\delta = \left(\frac{2H_o}{\omega\gamma B_o}\right)^{1/2}$$

and an air gap power transfer of

$$N = \frac{8}{3\pi} \frac{H_o^2}{\gamma\delta}$$

The mmf produced by that component of armature current producing flux linkages with the rotor eddy currents is calculated as

$$\text{mmf} = \frac{\sqrt{2}\, q\, I_2\, N\, K_p\, K_d}{P\, \pi}$$

The mmf corresponding to the assumed applied magnetic field H_o is calculated, and used with the above equations to calculate the rotor resistance referred to the stator by P/I^2. The resultant value is:

$$R_2' = \frac{64}{3\pi^2} \frac{L\, q\, (N\, K_p\, K_d)^2}{\gamma\, \delta\, D}$$

The analysis of rotor eddy currents also results in $X_2' = 1/2\, R_2'$, thus completely determining the equivalent circuit.

I. INTRODUCTION [14, 27, 11]

The accepted practice in power system operation in most Western countries is that, in the event of a generating unit losing synchronism due to loss of excitation or due to a system disturbance, the machine is to be disconnected from the system. Operating practices in the Soviet Union, however, permit asynchronous operation of round rotor machines for up to thirty minutes after loss of excitation. If excitation can be restored during this period, resynchronization is attempted by the method of self-synchronization. Power engineers in the Soviet Union believe this practice significantly improves power system reliability by reducing the forced outage rate of generation. Operating experience in the Soviet Union [26] and numerous tests there and in Great Britain [13, 14, 16, 17, 18, 23, 28] have shown that a significant real power output (about 0.5 to 0.8 per unit) can be obtained at slips of only about 1% or 2%. This output is the result of induced eddy currents in the rotor surface which cause the machine to act as an induction generator.

The advantages of being able to leave a machine connected to the system for a short time after loss of field, such as during periods of minimum reserve generation, are apparent. The principal risks involved in asynchronous operation are:

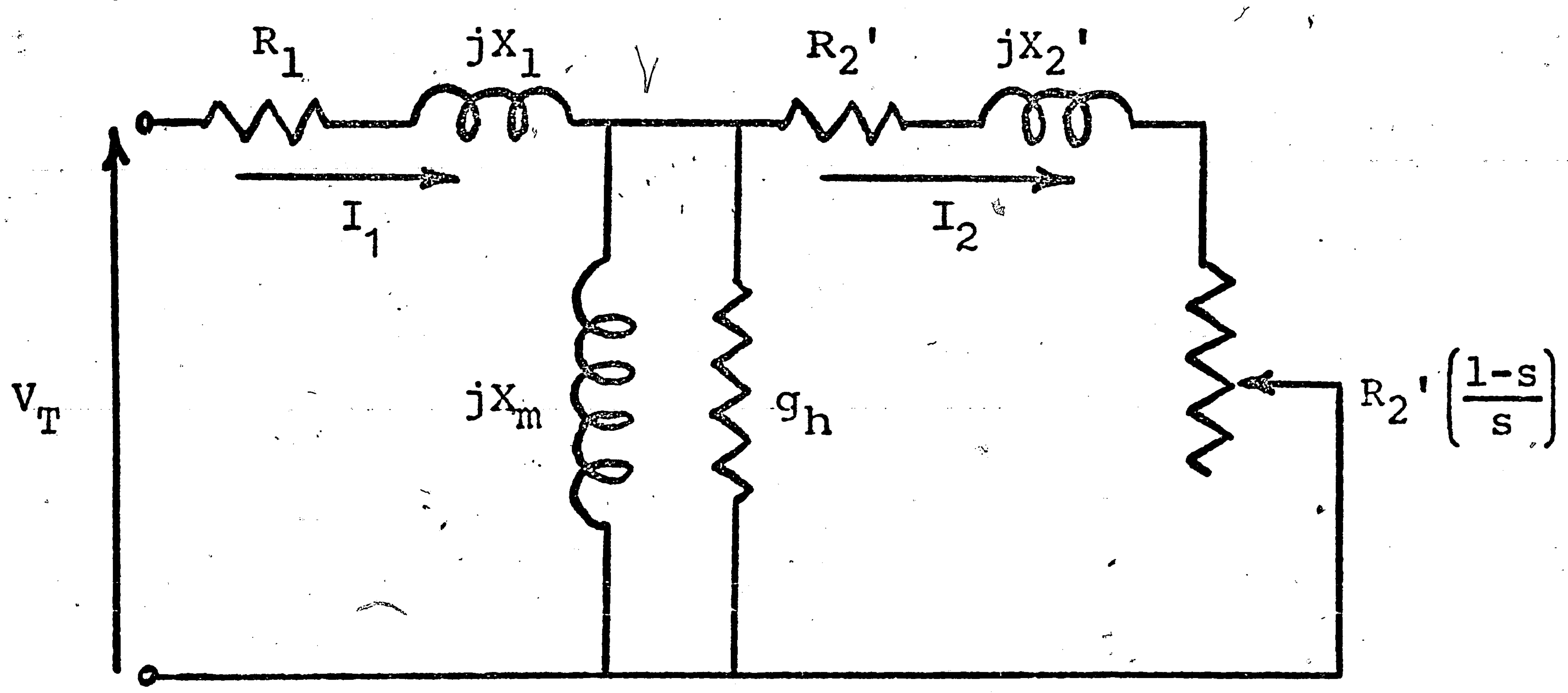
A. excessive rotor heating due to induced eddy currents.

B. excessive armature heating caused by high armature currents due to operation at a very low power factor. (Under asynchronous conditions, the machine must draw all its magnetizing current from the system.)

C. abnormally low terminal voltage causing reduced output of station auxiliaries, again due to the machine drawing its magnetizing current from the system.

D. insufficient power output at low slip to produce the necessary braking torque to prevent over-speed tripping of the unit.

This thesis presents a method for predicting the asynchronous operating characteristics of a round rotor synchronous machine whose field circuit is open. This will be done by determining values for the elements of the classical equivalent circuit of an induction machine shown in Figure 1. The method may also find application in the calculation of damping torques in transient stability studies and in the analysis of induction motors with solid iron cylindrical rotors.



V_T - machine terminal voltage

R_1 - stator resistance

X_1 - stator leakage reactance

R_2' - rotor resistance, referred to the stator

X_2' - rotor leakage reactance, referred to the stator

X_m - stator magnetizing reactance

g_h - conductance representing losses in stator due to eddy currents and hysteresis

Figure 1

Classical Equivalent Circuit of an Induction Machine

II. EDDY CURRENT EFFECTS [12, 20, 24, 25, 10]

A. Introduction

When iron is subjected to an alternating mmf, energy is lost in the iron due to eddy currents and hysteresis. The difficulty in accurately calculating these losses is due to the extremely nonlinear relation between B and H. An approximate solution, valid for small values of H, may be obtained by assuming the magnetic permeability to be constant. Hysteresis losses, which may predominate at these low values of H, must be estimated and added to the calculated eddy current losses. For large values of H (those well into the saturation region) eddy current losses predominate and hysteresis losses become less significant. This is particularly true of the rotor losses in a synchronous machine operating asynchronously, since the rotor iron surface is saturated and the frequency of applied mmf (which is equal to the slip frequency) is low.

B. Electric and Magnetic Fields in the Iron

To calculate fields within the iron, consider a semi-infinite, conducting, ferromagnetic solid extending in the +z direction with a plane face in the x - y plane. (See Figure 2.) Since the rotor iron can be expected to operate well into the saturation region, the idealized rectangular B-H curve of Figure 3 will be assumed.

At $z = o$, let a magnetic field be applied which has only a y-component equal to:

$$H = H_o \sin \omega t \tag{1}$$

The corresponding electric field will be normal to the magnetic field and in the x-direction. Maxwell's equations then reduce to:

$$-\frac{\partial h}{\partial z} = \gamma e \qquad \text{where: } \gamma = \text{conductivity} \tag{2}$$

$$\frac{\partial e}{\partial z} = -\frac{\partial b}{\partial t} \tag{3}$$

Since, in this case, with a rectangular saturation curve $\partial b/\partial t$ may be infinite, define:

$$\phi = \int_z^{\infty} b \, dz \tag{4}$$

Rewrite Maxwell's equations as:

$$-\frac{\partial h}{\partial z} = \gamma e \tag{5}$$

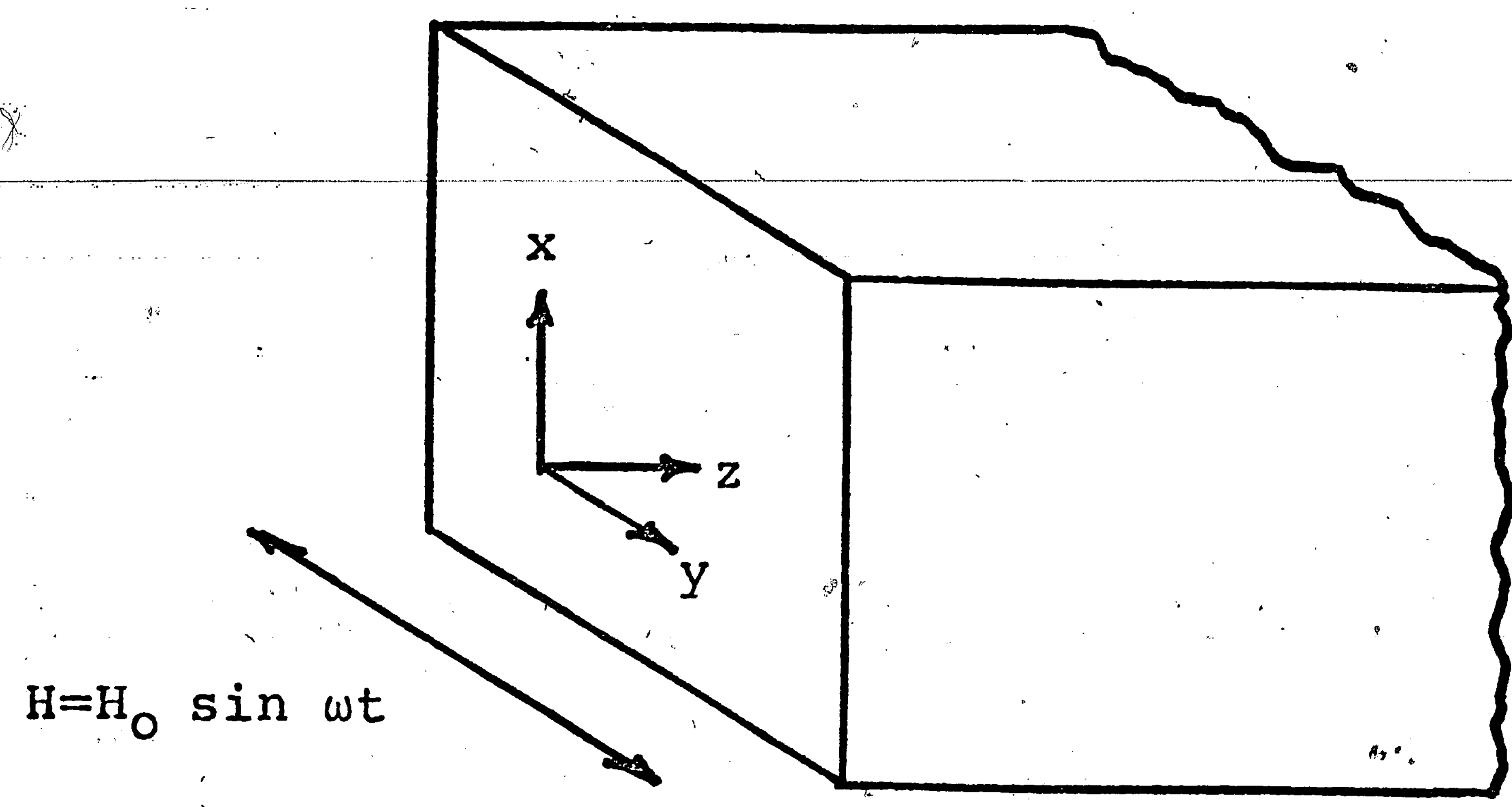


Figure 2

Assumed Semi-infinite, Conducting Ferromagnetic Solid

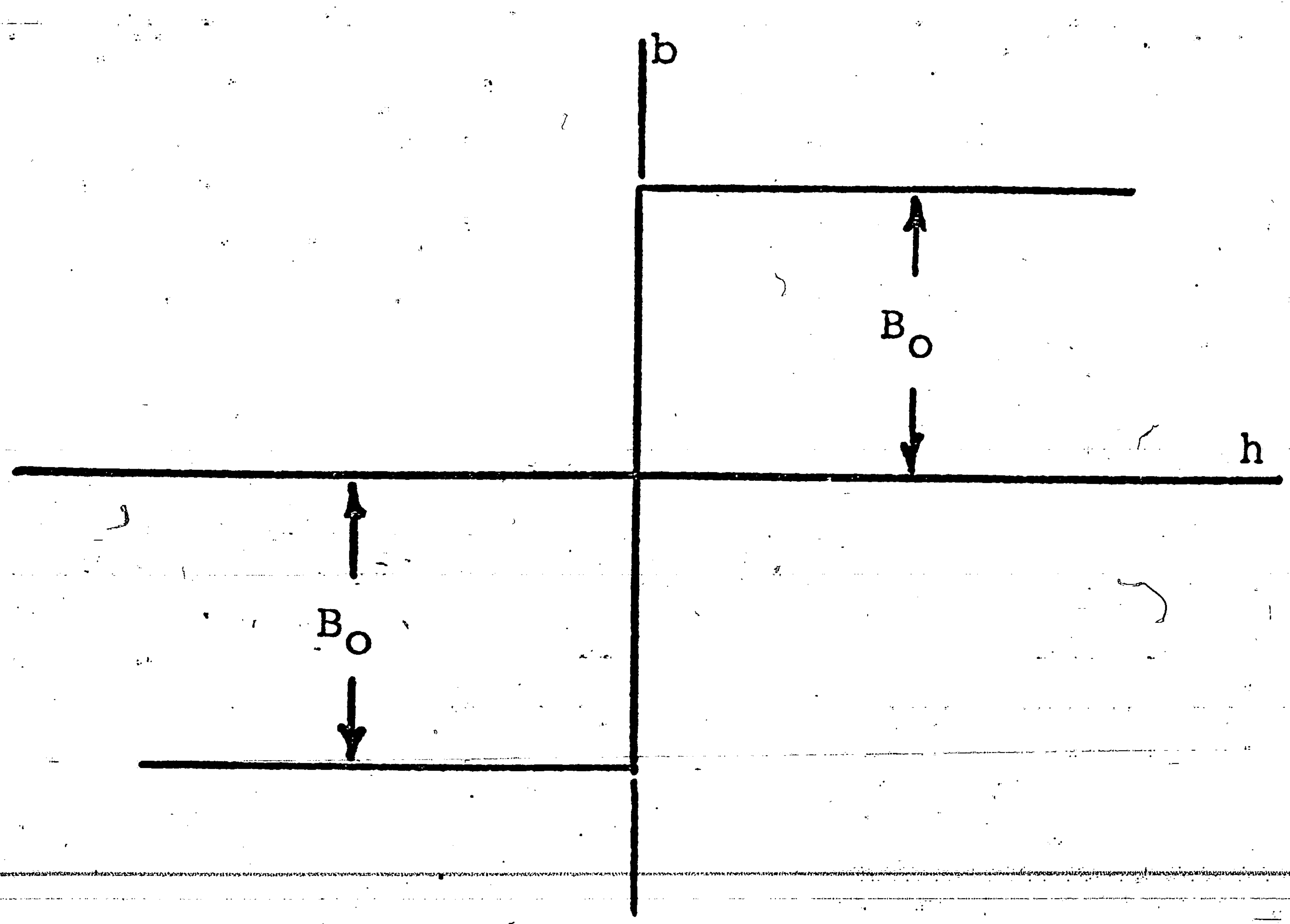


Figure 3

Idealized Rectangular B-H Curve

(6) $$e = \frac{\partial \phi}{\partial t}$$

The approach will be to assume a solution and then show that it meets the boundary conditions and checks against equations (5) and (6).

The solution assumed is as follows:

1. $B = \pm B_o$ or $B = B_o \text{ sig } H$ (where sig $H \equiv$ "the sign of H").
2. A plane interface between the region where $B = +B_o$ and the region where $B = -B_o$ (called the "separating surface") travels into the semi-infinite solid in the +z direction with a velocity v. It reaches its maximum depth of penetration, δ, when H changes sign ($\omega t = n\pi$). A new separating surface begins at $z = o$ and travels to $z = \delta$. During the half-cycle when H is positive, $B = +B_o$ to the left of the separating surface and $B = -B_o$ to the right of the separating surface. During the second half-cycle, $B = -B_o$ to the left of the separating surface and $B = +B_o$ to the right of the separating

surface. At any given time, let the separating surface be at $z = \zeta$. (See Figure 4.)

3. h is equal to H at $z = o$ and decreases linearly (in space) to zero at $z = \zeta$. (See Figure 5.)

4. e is equal to E to the left of $z = \zeta$ $(o<z<\zeta)$ and e is zero to the right of $z = \zeta$ $(z>\zeta)$. (See Figure 6.)

The proposed solution meets the boundary conditions:

$$B = B_o \text{ sig } H$$

and

$$H = H_o \sin \omega t \ .$$

It remains only to check it against equations (5) and (6).

From equation (5):

$$\frac{H}{\zeta} = \gamma E \qquad (o<z<\zeta) \tag{7}$$

From the assumed solution:

$$\frac{\partial \phi}{\partial t} = 2B_o \frac{d\zeta}{dt} \qquad (o<z<\zeta) \tag{8}$$

$$\frac{\partial \phi}{\partial t} = 0 \qquad (z>\zeta) \tag{9}$$

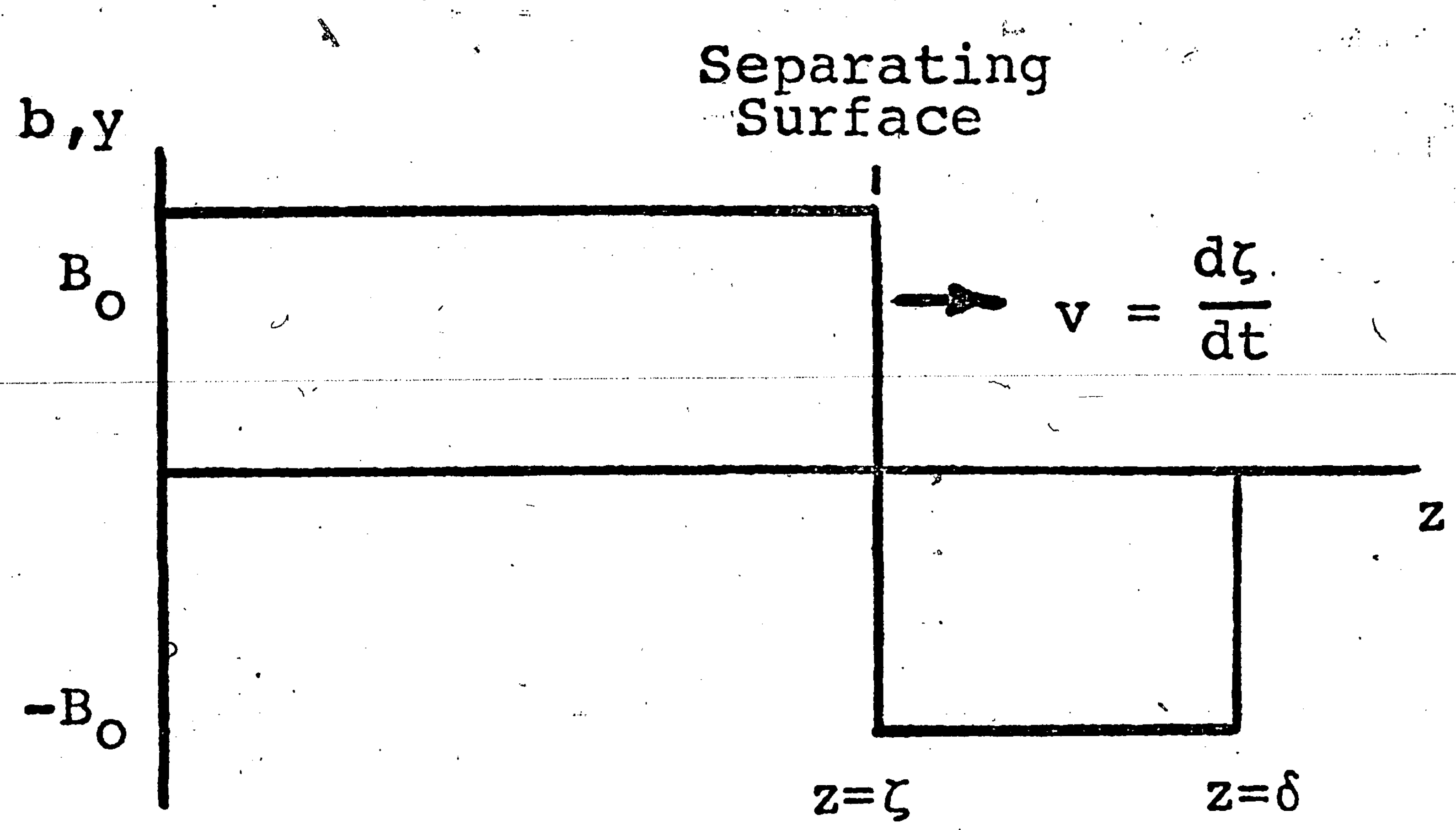


Figure 4

Distribution of Magnetic Intensity B and Position of Separating Surface

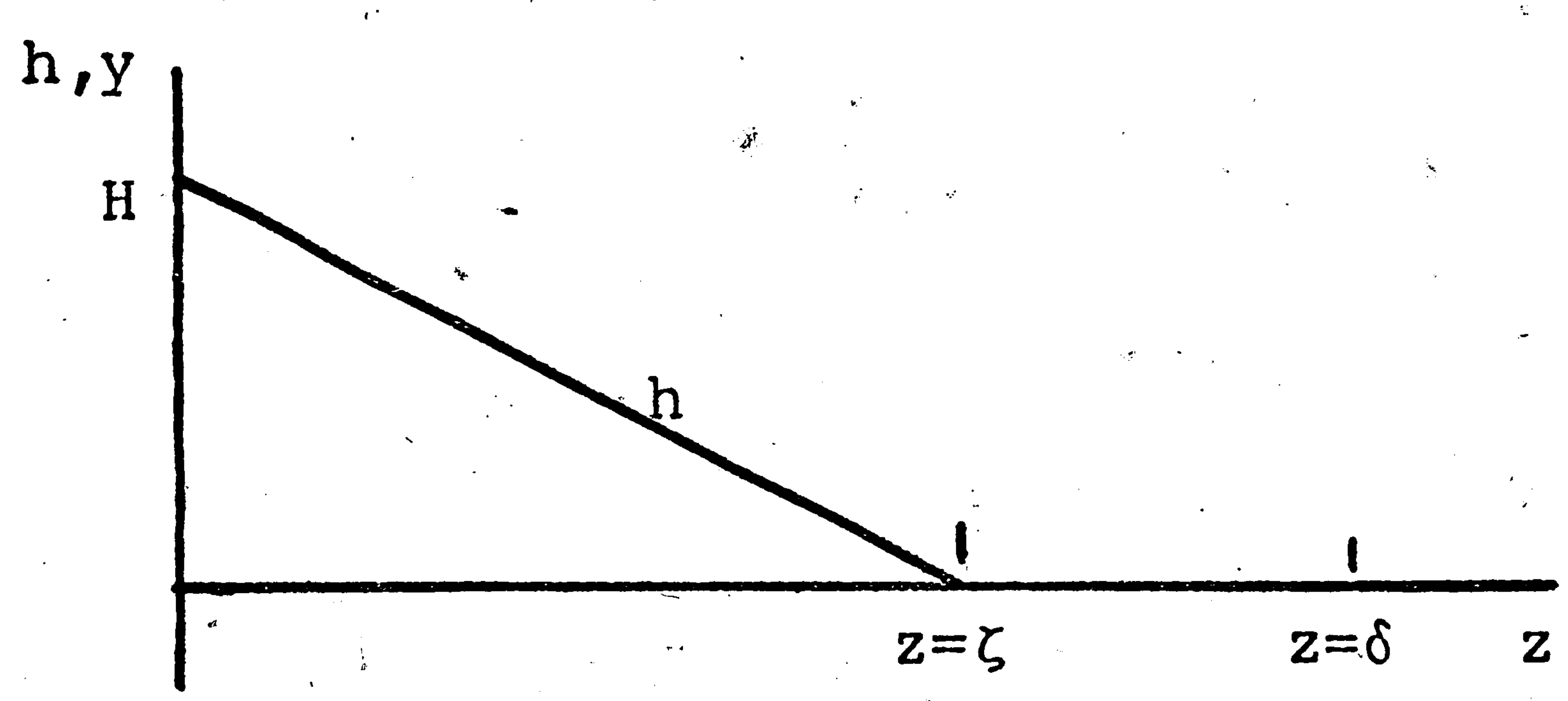


Figure 5

Distribution of Magnetizing Force

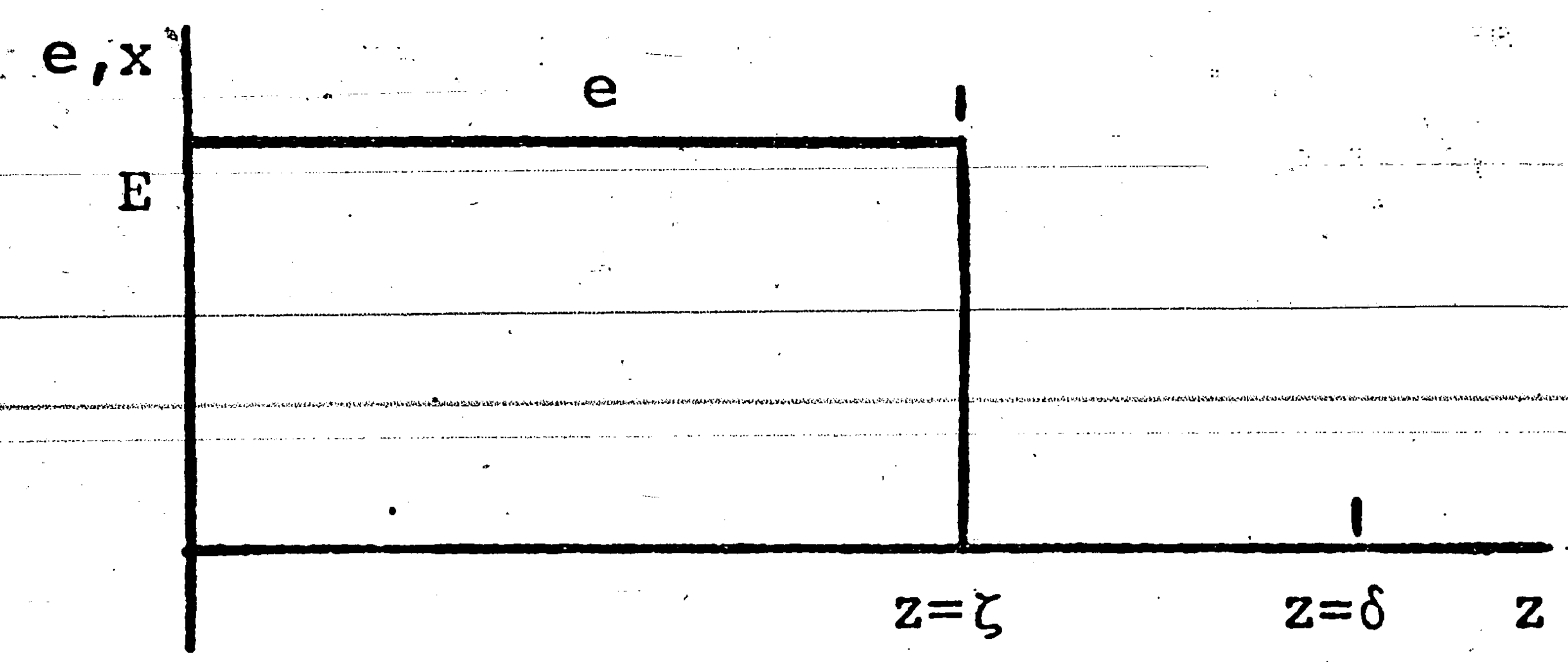


Figure 6

Distribution of Electric Field

(10) $$e = E \qquad (o<z<\zeta)$$

(11) $$e = o \qquad (z>\zeta)$$

From equation (6):

(12) $$E = 2B_o \frac{d\zeta}{dt} \qquad (o<z<\zeta)$$

Maxwell's equations are now represented by (7) and (12). Eliminating E between them:

(13) $$2\zeta \frac{d\zeta}{dt} = \frac{H}{\gamma B_o}$$

or:

(14) $$\frac{d\zeta^2}{dt} = \frac{H_o\,|\sin \omega t|}{\gamma B_o} \qquad (o<z<\zeta)$$

(15) $$\frac{d\zeta^2}{dt} = \frac{H_o \sin \omega t}{\gamma B_o} \qquad (o<z<\zeta \text{ and } o<\omega t<\pi)$$

(16) $$\zeta = \left(\frac{2H_o}{\omega\gamma B_o}\right)^{1/2} \sin\frac{\omega t}{2} \qquad (o<z<\zeta \text{ and } o<\omega t<\pi)$$

Since the maximum depth of penetration ($\zeta=\delta$) is attained at the end of each half-period:

(17) $$\delta = \left(\frac{2H_o}{\omega\gamma B_o}\right)^{1/2}$$

To find E(t), rewrite equation (7) as:

(18) $$E = \frac{H}{\gamma\zeta} = \frac{1}{\gamma}\,\frac{H_o \sin\omega t}{\delta \sin\frac{\omega t}{2}} \qquad (o<z<\zeta \text{ and } o<\omega t<\pi)$$

(19) $$E = \frac{2H_o}{\gamma\zeta}\cos\frac{\omega t}{2} \qquad (o<z<\zeta \text{ and } o<\omega t<\pi)$$

Since, in successive half-periods, H reverses sign and ζ does not, equation (19) shows that E does reverse sign in each successive half-period. Equation (19) also shows that E is not a function of z for $o<z<\zeta$. Figure 7 shows E and ζ as functions of ωt. This completes the verification of the assumed solution.

C. Eddy Current Power Loss

Let $\overline{H}$ be the peak complex amplitude of H and E be the fundamental component of E. The Poynting vector into the material:

$$(20) \qquad \overline{N} = N + jM = 1/2\, \overline{E}\times\overline{H}^*$$

gives the complex power transfer per unit area and hence its real part gives the eddy current loss per unit surface area. The real part of $\overline{N}$ from equation (20) can be written as:

$$(21) \qquad N = 1/2r\, H_o^2$$

where r is the real part of the complex surface impedance:

$$(22) \qquad \overline{\eta} = r + jx = \frac{\overline{E}}{\overline{H}}$$

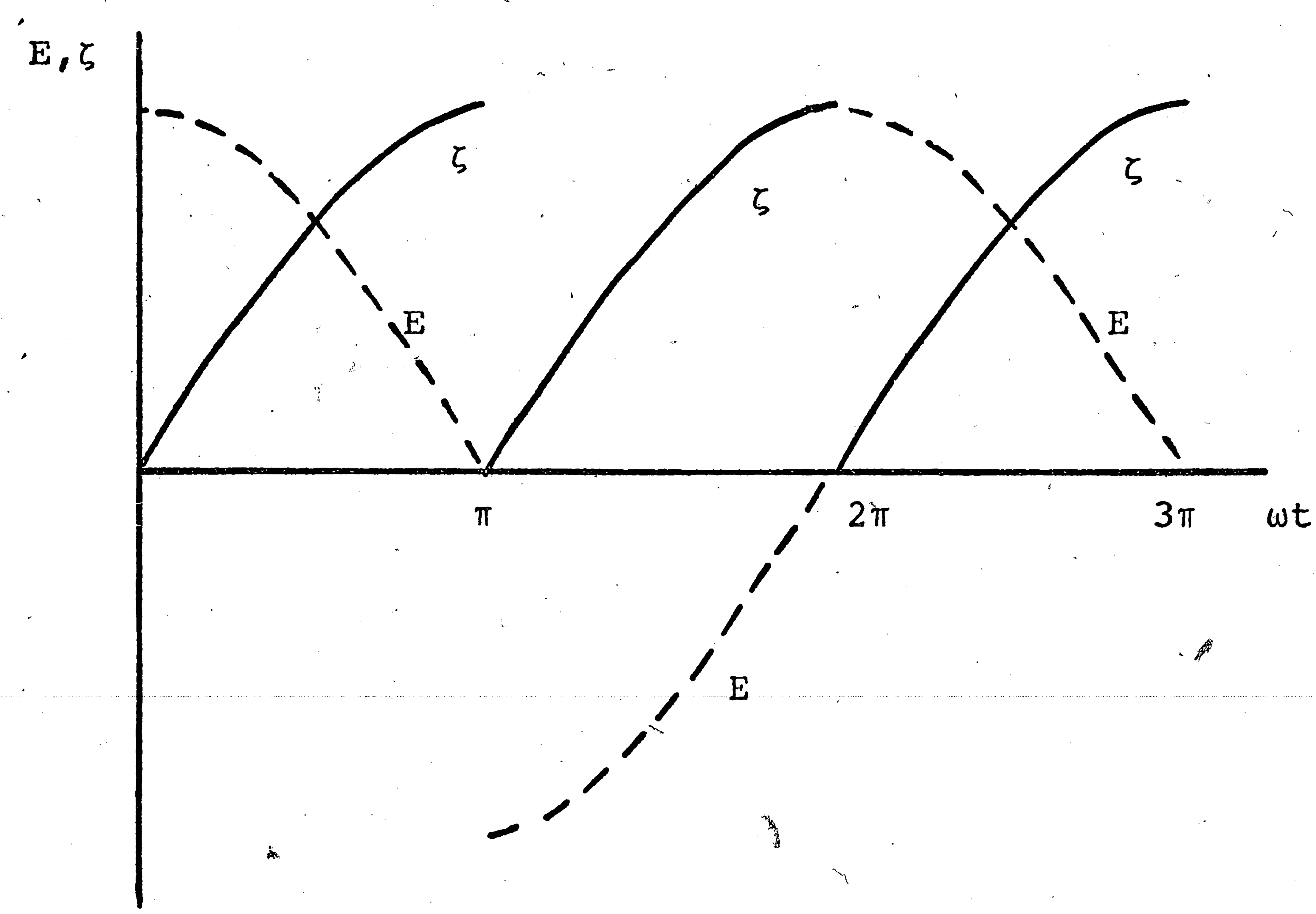


Figure 7

E and ζ as Functions of ωt

Calculating the fundamental of E:

(23) $$E = 2 \sum_{1}^{\infty} (A_n \cos n\omega t + B_n \sin n\omega t)$$

(24) $$A_n = \frac{1}{T} \int_o^T E(t) \cos n\omega t \, dt$$

(25) $$B_n = \frac{1}{T} \int_o^T E(t) \sin n\omega t \, dt$$

(26) $$A_1 = \frac{2H_o}{\gamma\delta} \frac{1}{2\pi} 2 \int_o^{\pi} \cos \frac{(\omega t)}{2} \cos (\omega t) \, d(\omega t)$$

(27) $$A_1 = \frac{H_o}{\gamma\delta\pi} \left(-\frac{2}{3} + 2 \right)$$

(28) $$B_1 = \frac{2H_o}{\gamma\delta} \frac{1}{2\pi} 2 \int_o^{\pi} \cos \frac{(\omega t)}{2} \sin (\omega t) \, d(\omega t)$$

(29) $$B_1 = \frac{H_o}{\gamma\delta\pi}\left(\frac{2}{3} + 2\right)$$

(30) $$\bar{E} = (\text{fundamental of } E) = \frac{8H_o}{3\gamma\delta\pi}(\cos\omega t + 2\sin\omega t)$$

(31) $$\bar{E} = \frac{8H_o}{3\gamma\delta\pi}(1 - 2j)$$

Calculating the real part r of the complex surface impedance $\bar{\eta}$:

(32) $$H = H_o \sin\omega t$$

hence:

(33) $$\bar{H} = -jH_o$$

(34) $$\bar{\eta} = \frac{\bar{E}}{\bar{H}} = \frac{16}{3\pi\gamma\delta}(1 + j\ 1/2)$$

(35) $$r = \frac{16}{3\pi} \frac{1}{\gamma\delta} = \frac{16}{3\pi} \left(\frac{\omega B_o}{2\gamma H_o}\right)^{1/2}$$

(36) $$x = \frac{8}{3\pi} \frac{1}{\gamma\delta} = \frac{8}{3\pi} \left(\frac{\omega B_o}{2\gamma H_o}\right)^{1/2}$$

The eddy current loss per unit surface area then becomes:

(37) $$N = \frac{1}{2} r \; H_o^2$$

(38) $$N = \frac{1}{2} \frac{16}{3\pi} \left(\frac{\omega B_o}{2\gamma H_o}\right)^{1/2} H_o^2$$

(39) $$N = \frac{8}{3\pi} \frac{H_o^2}{\gamma\delta}$$

D. Rotor Eddy Currents

The eddy current analysis given above is for a surface subjected to a magnetic field varying sinusoidally with time. In the case of a machine operating asynchronously, the rotor surface is subjected to a field rotating at slip frequency and sinusoidally distributed in space. Thus, any point on the rotor surface sees a magnetic field varying sinusoidally in time.

Figure 8 shows qualitatively the eddy current paths in the surface of a rotor at one point in time. These eddy currents produce a field rotating at slip speed relative to the rotor and at synchronous speed relative to the stator. Figure 9 shows, for a two-pole machine, the position of the separating surface and the distribution of the magnetic intensity B in a machine rotor.

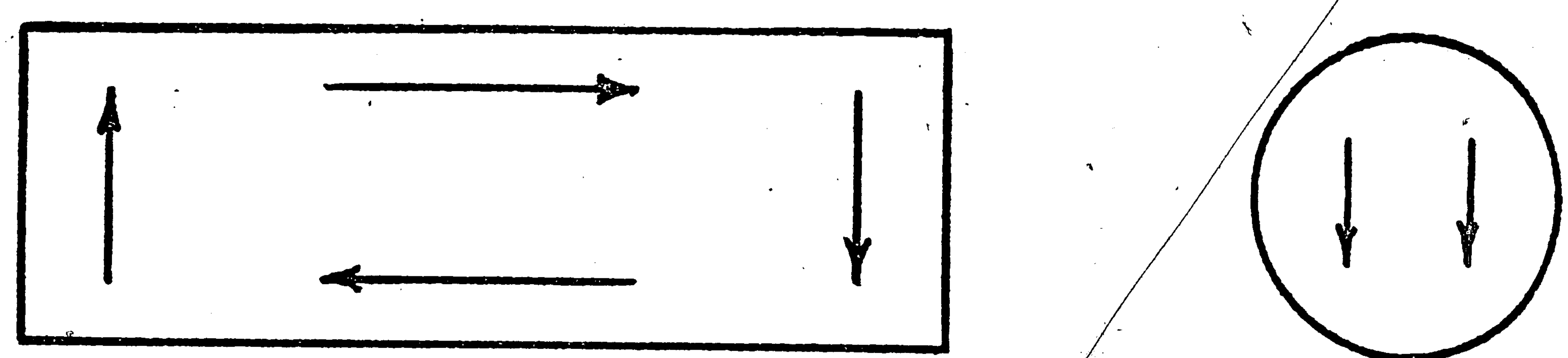


Figure 8

Eddy Current Paths in Rotor Surface

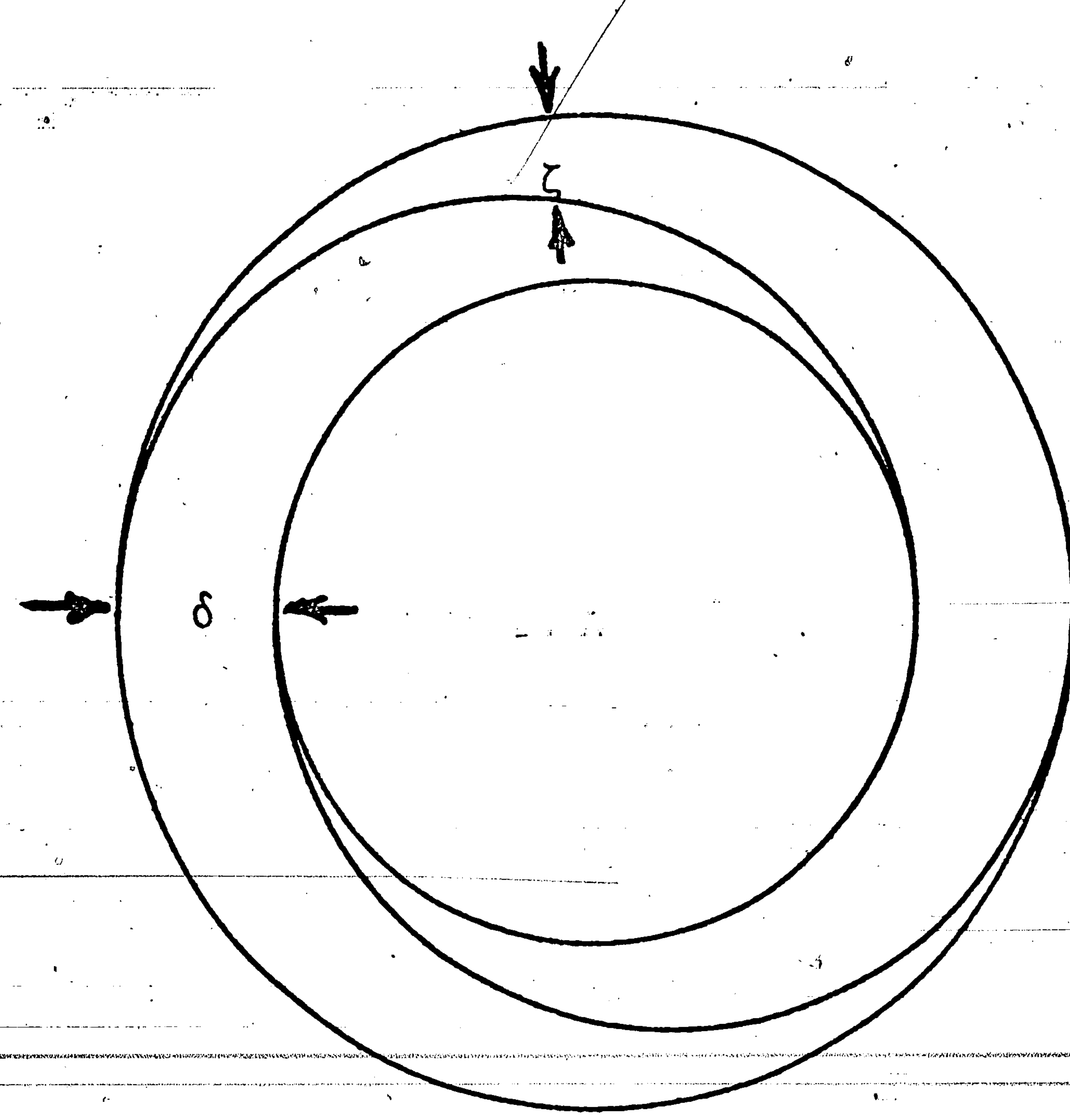


Figure 9

Position of Separating Surface and Distribution of B in Machine Rotor

III. EFFECTIVE ROTOR IMPEDANCE REFERRED TO THE STATOR [1, 2, 17, 5, 6]

A. Introduction

To find the effective rotor resistance and reactance referred to the stator (R_2' and X_2' in Figure 1), the approach will be as follows:

1. By conventional induction machine theory, the mmf produced by the load current in the stator (I_2 in Figure 1) must be equal and opposite to the mmf produced by eddy currents in the rotor. In other words, I_2 in the equivalent circuit is that component of stator current producing flux linkages with the rotor.
2. Determine the mmf in terms of I_2 and the stator winding configuration.
3. Determine the mmf corresponding to equation (1), the assumed applied magnetic field.
4. Eliminate the mmf between the equations under 2 and 3 above and solve for I_2. Knowing I_2 and N (the power

transfer per unit area in equation (39)) we can solve for R_2'. From equations (35) and (36), we know that $X_2' = 1/2\ R_2'$.

B. Stator mmf Due to I_2

Figure 10 shows, in a developed view, the mmf of a single coil of pitch p carrying DC. For this case, the mmf is:

$$\text{mmf} = -pM \qquad \left(\pi < x < -\frac{p\pi}{2}\right) \tag{40}$$

$$\text{mmf} = (2-p)M \qquad \left(-\frac{p\pi}{2} < x < \frac{p\pi}{2}\right) \tag{41}$$

$$\text{mmf} = -pM \qquad \left(\frac{p\pi}{2} < x < \pi\right) \tag{42}$$

where M is the ampere turns of the single coil. Written as a Fourier Series:

$$\text{mmf} = \sum_{k=1}^{k=\infty} \frac{4M}{\pi k} \sin \frac{kp\pi}{2} \cos kx \tag{43}$$

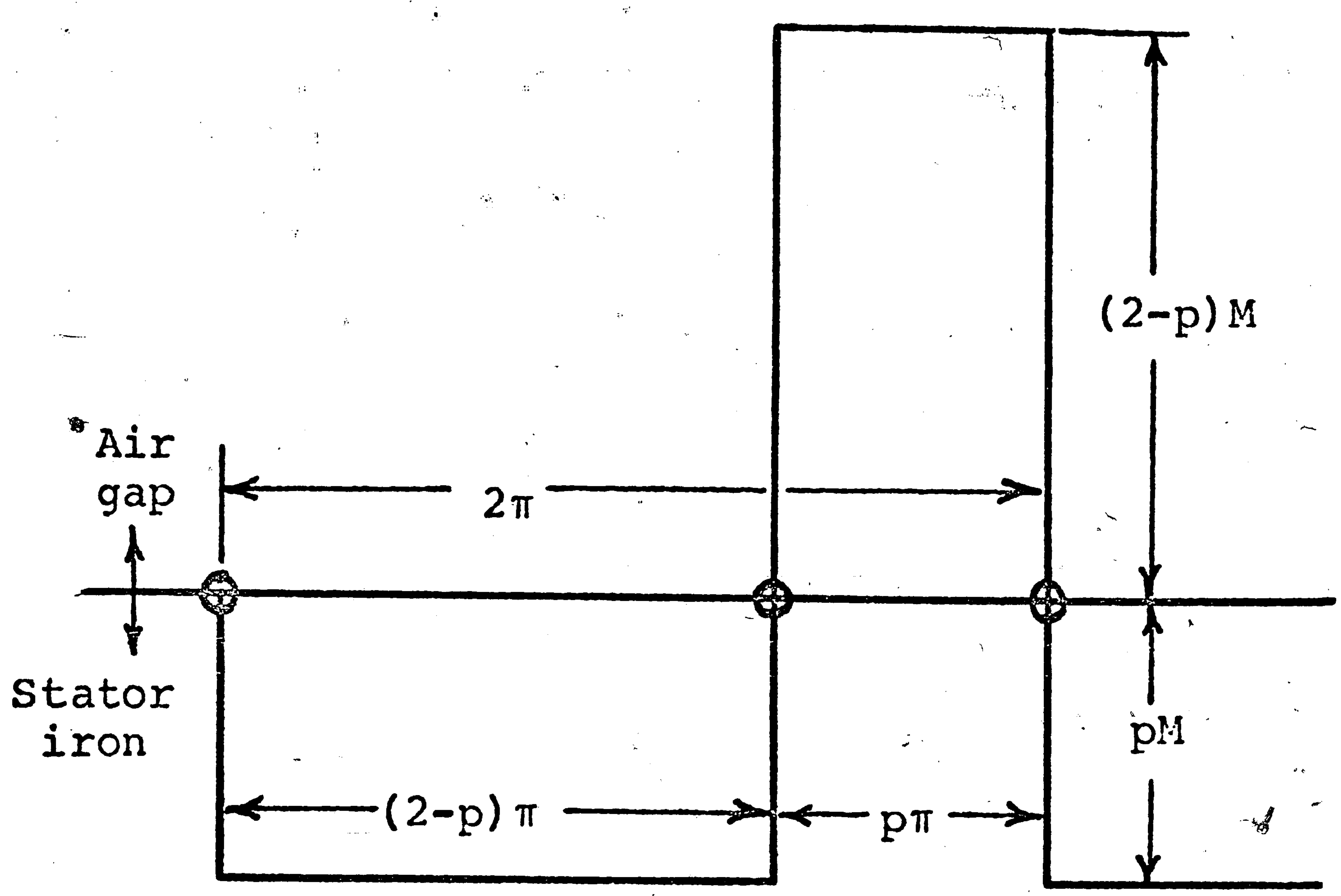


Figure 10

Mmf Due to a Single Coil of Pitch p

Note that the term $\sin \frac{kp\pi}{2}$ is the pitch factor for the k^{th} harmonic, K_{pk}.

Applying a sinusoidal current in place of DC to the single coil of pitch p:

$$(44) \qquad mmf = \sum_{k=1}^{k=\infty} \frac{4M}{\pi k} \sin \frac{kp\pi}{2} \cos kx \cos \omega t$$

Resolving this pulsating field into forward and backward rotating fields, equation (44) can be rewritten:

$$(45) \qquad mmf = \sum_{k=1}^{k=\infty} \frac{2M}{\pi k} \sin \frac{kp\pi}{2} [\cos(kx-\omega t) + \cos(kx+\omega t)]$$

In a practical polyphase machine, let:

q = number of phase belts per pole.

P = number of pole pairs.

n = number of slots per phase belt per pole (or, number of coils per coil group in a distributed winding).

T = turns per coil.

N = total turns in series per phase = 2PnT.

In a q-phase winding, the phase belts are $2\pi/q$ electrical radians apart, and the time phase of currents in adjacent phase belts are $2\pi/q$ electrical radians apart. Therefore, the forward rotating components of the fundamentals of the mmf waves produced by the phase currents are in phase and may be added directly. Similarly, the backward rotating components of the fundamentals are each spaced $-2\pi/q$ electrical radians apart in time and add to zero. Hence:

$$\text{mmf (fundamental)} = q(2M/\pi)(K_p)(nK_d)\cos(x-\omega t) \tag{46}$$

where K_d is the distribution factor for a distributed polyphase winding and is given by:

$$K_d = \frac{\sin\frac{\pi}{2q}}{n\sin\frac{\pi}{2nq}} \tag{47}$$

Now:

$$M = \sqrt{2}\, I_2\, T \tag{48}$$

and

$$(49) \qquad N = 2PnT$$

therefore

$$(50) \qquad M = \frac{I_2 N}{\sqrt{2}\ Pn}$$

Substituting equation (50) in equation (46):

$$(51) \qquad \text{mmf (fundamental)} = \frac{\sqrt{2}\ q\ I_2 N\ K_p\ K_d}{P\pi} \cos (x-\omega t)$$

Equation (51) is the expression for the fundamental component of the mmf wave produced by an rms load current I_2 per phase in a machine having q phases, N turns in series per phase, P pole pairs, and wound with distribution factor K_d and pitch factor K_p.

The magnetizing force assumed at the rotor surface is given by equation (1), namely:

(52) $$H = H_o \sin \omega t$$

This relation holds for any given point on the rotor surface. For the entire rotor circumference at a given point in time, the magnetizing force is

(53) $$H = H_o \sin (P\theta)$$

where P is the number of pole pairs and θ is the position on the rotor circumference in radians. The peak mmf at the rotor surface is therefore the integral of Hdx over one-half pole pitch. (See Figure 11.)

(54) $$\text{peak mmf} = \int_{x=o}^{x=\frac{\pi D}{4P}} H_o \sin(P\theta)\,dx$$

(55) $$\text{peak mmf} = \int_{x=o}^{x=\frac{\pi D}{4P}} H_o \sin \left(P \frac{2x}{D}\right) dx$$

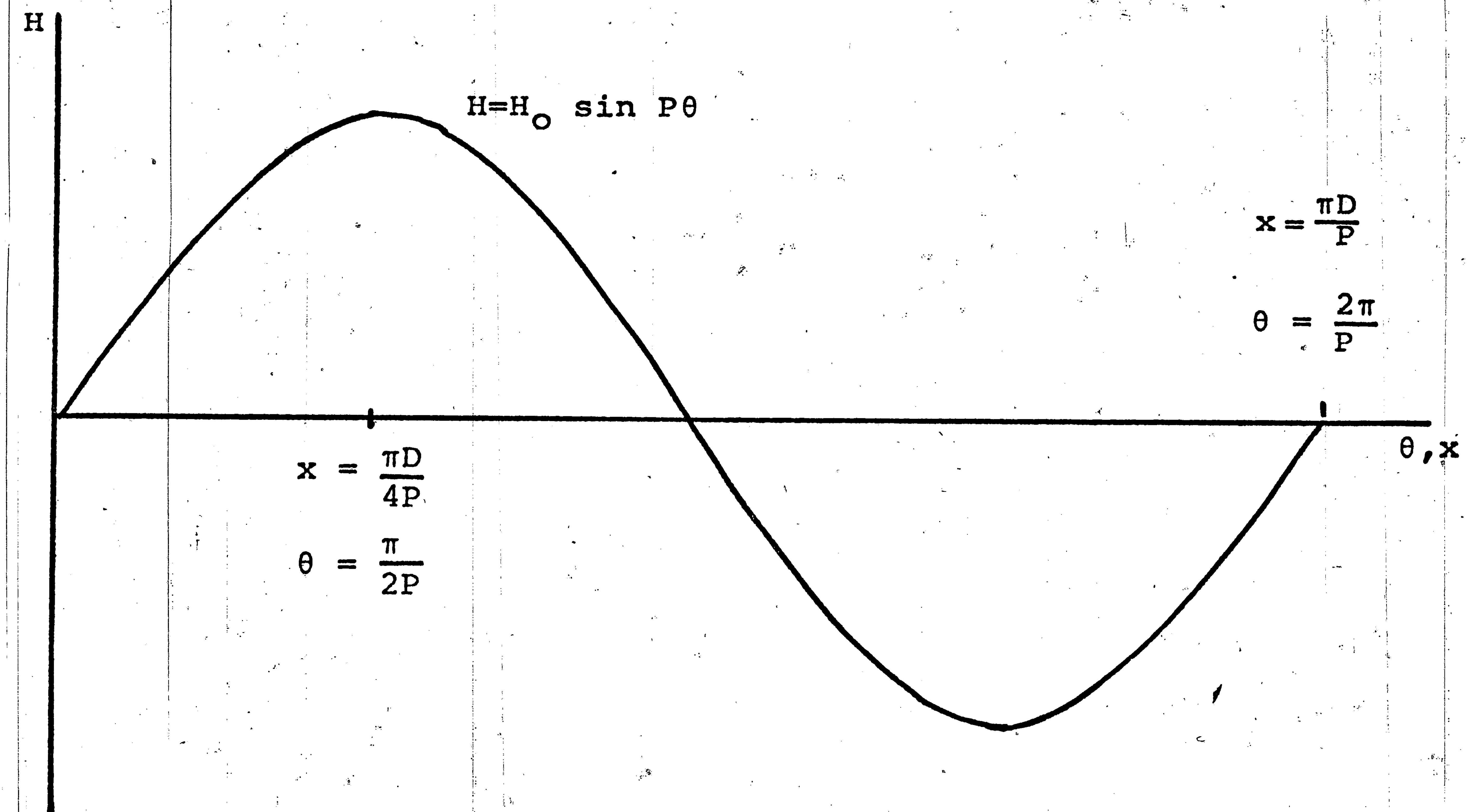


Figure 11

Mmf Corresponding to the Assumed Applied Magnetic Field

(56) $$\text{peak mmf} = \frac{H_o D}{2P}$$

where D is the rotor diameter.

C. Calculation of R_2' and X_2'

Eliminating the peak mmf between equations (56) and (51) and solving for I_2:

(57) $$\frac{H_o D}{2P} = \frac{\sqrt{2}\, q\, I_2\, N\, K_p\, K_d}{P\, \pi}$$

(58) $$I_2 = \frac{H_o\, D\, \pi}{2\sqrt{2}\, q\, N\, K_p\, K_d}$$

Find R_2' using equations (39) and (58):

(59) $$R_2' = \frac{(N) \times (\text{Rotor surface area})}{(q) \times (I_2)^2}$$

(60) $$R_2' = \frac{64}{3\pi^2} \; \frac{L\, q\, (N\, K_p\, K_d)^2}{\gamma\, \delta\, D}$$

$$X_2' = \frac{32}{3\pi^2} \frac{L\ q\ (N\ K_p\ K_d)^2}{\gamma\ \delta\ D} \tag{61}$$

where

$$\delta = \left(\frac{2H_o}{\omega\gamma B_o}\right)^{1/2}$$

$$H_o = \frac{2\sqrt{2}\ q\ I_2\ N\ K_p\ K_d}{D\ \pi}$$

IV. THE EQUIVALENT CIRCUIT [1, 2, 17, 5, 6]

In the equivalent circuit of Figure 1:

A. R_1 - stator resistance

B. X_1 - stator leakage reactance

C. X_M - magnetizing reactance of stator

D. g_h - conductance representing losses in stator due to eddy currents and hysteresis

E. R_2' - equivalent rotor resistance, referred to the stator, given by equation (60)

F. X_2' - equivalent rotor leakage reactance, referred to the stator, given by equation (61)

The equivalent circuit (and hence operating characteristics) for asynchronous operation of a round rotor synchronous machine has been completely determined, since A through D are available for a given machine from design and test data, and expressions have been derived for E and F.

In a machine operating above synchronous speed, the slip s is negative, since it is defined by:

$$s = \frac{\omega_o - \omega_{as}}{\omega_o} \qquad (62)$$

where s = slip

ω_o = synchronous speed

ω_{as} = rotor speed

Therefore, $R_2'\left(\frac{1-s}{s}\right)$ is negative. By standard induction machine theory:

$$P_T = I_2^2 R_2' \left(\frac{1-s}{s}\right) \tag{63}$$

where P_T = turbine power input on the machine shaft, less windage and friction.

$$P_{RL} = I_2^2 R_2' \tag{64}$$

where P_{RL} = rotor loss

Equation (64) is of primary importance, since its results for different operating conditions can be compared with the rotor circuit power loss under conventional operation.

Similarly:

$$P_{SL} = I_1^2 R_1 \quad (65)$$

where P_{SL} = stator winding power loss.

The results of equation (65) can be compared directly with the stator winding loss for normal synchronous operation.

Hence, the proposed method:

A. permits calculation of the asynchronous operating characteristics of a round rotor synchronous machine with the field circuit open.

B. permits prediction of the thermal risks to the machine involved in asynchronous operation.

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