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TOPICAL REPORT **VOLUME 3** DESIGN MANUALS

BRUSHLESS ROTATING ELECTRICAL GENERATORS FOR SPACE AUXILIARY POWER SYSTEMS

by

J. N. Ellis and F. A. Collins

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NO. NAS 3-2783

LEAR SIEGLER, INC.

POWER EQUIPMENT DIVISION

CLEVELAND 1, OHIO

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Space Power System Division
Solar and Chemical Power Branch

LEAR SIEGLER, INC.
Power Equipment Division
Cleveland, Ohio

TABLE OF CONTENTS

FIGURES

TABLES

Section A

Section B

Section CA or Section C

Section D

Section E

Section F

Section GA or Section G

Section HA or Section H

Section JA or Section J

Section KA or Section K

Section LA or Section L

Section MA or Section M

Section N

Section PA or Section P

Section RA or Section R

Section SA or Section S

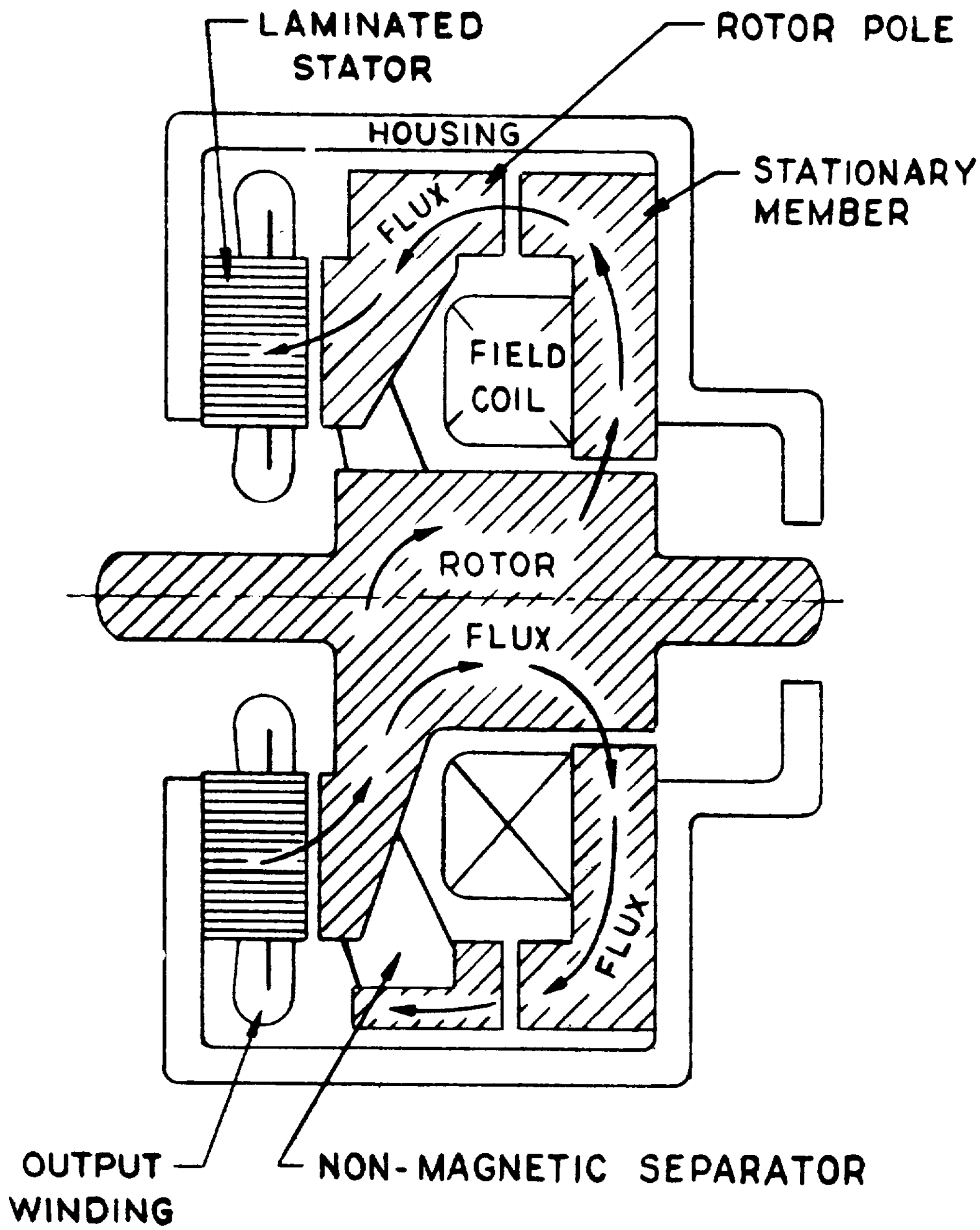
Section TA or Section T

DESIGN MANUAL FOR AXIAL AIR-GAP, STATIONARY-COIL, SALIENT-POLE, SYNCHRONOUS A-C GENERATOR

SECTION N

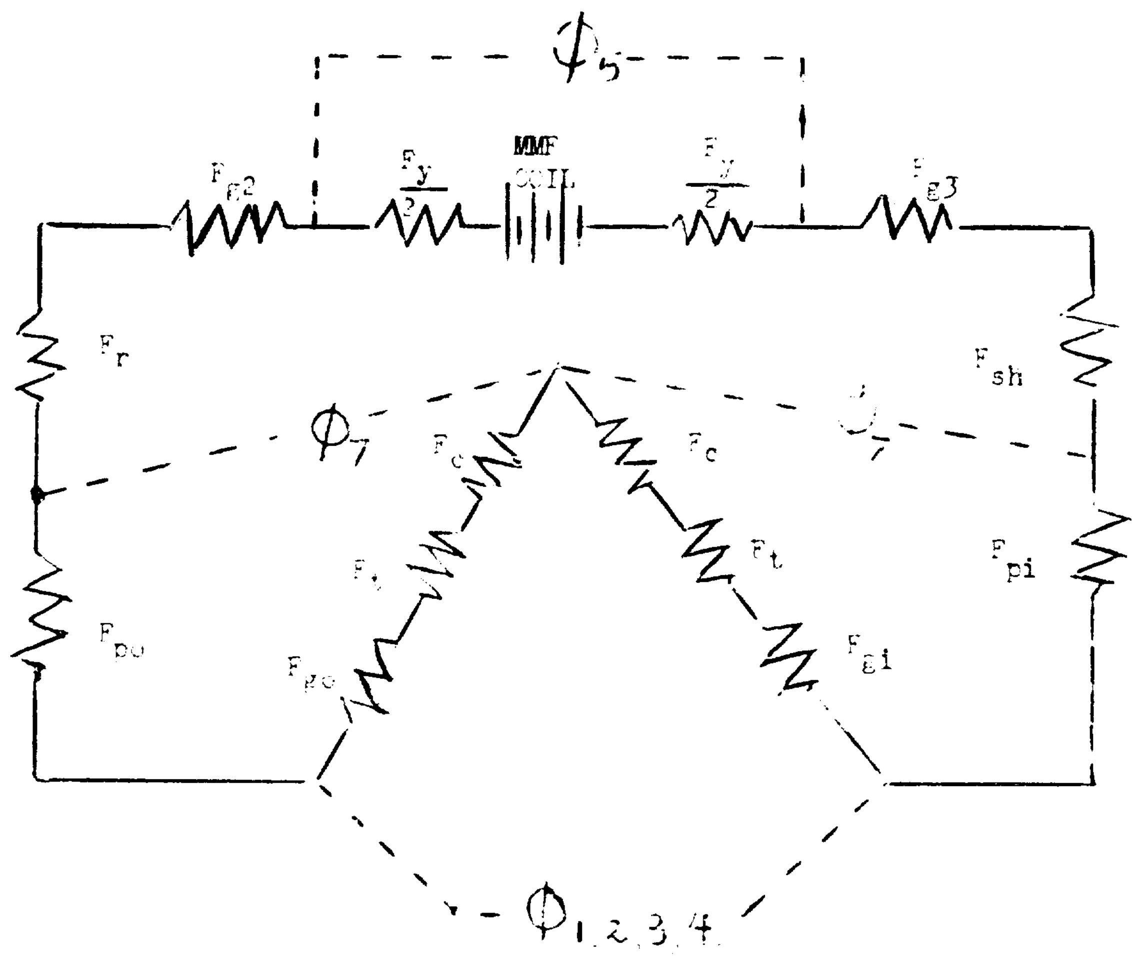
THE AXIAL AIR-GAP, LUNDELL-TYPE, A-C GENERATOR

The design manual presented here in section N, is a hand-calculation manual arranged for computer programming. To use this manual we suggest following the sequence indicated by the arrangement of the design sheet, Fig. N 3 The numbers in brackets on the design sheet give the item number of that particular calculation. The items in the design manual are given in the sequence indicated by their number.



DISK TYPE LUNDELL

FIGURE N 1



THE FLUX CIRCUIT FOR A SINGLE-STATOR, AXIAL-GAP, LUNDELL, A-C GENERATOR. THE LEAKAGE FLUXES ARE INDICATED BY DASHED LINES-----

FIGURE N 2

DISC-TYPE SYNCHRONOUS GENERATOR

STATOR

STATOR I.D.		(11)
STATOR O.D.		(12)
CORE LENGTH	(17)	(13)
DBS x 2		(24)
SLOTS		(23)
CARTER COEFF.		(67)
TYPE W'DG		(28)
THROW		(31)
SKEW & DIST FACT.	(42)	(43)
CHORD FACTOR		(44)
COND PER SLOT		(30)
TOTAL EFF. COND.		(45)
COND SIZE		(33)
COND AREA		(46)
CURRENT DENSITY		(47)
WDG. CONST.	(72) C_1	(71)
TOTAL FLUX		(88)
GAP AREA		(68)
GAP DENSITY		(95)
POLE CONST.		(73)
FLUX PER POLE		(92)
SHAFT FLUX		(111)
TOOTH PITCH	(27)	(26)
TOOTH DENSITY		(91)
CORE DENSITY		(94)
GRADE IRON		(18)
½ MEAN TURN		(49)
RES/PHASE @ °		(54)
EDDY FACT TOP		(55)
E.F. AVE	EFF. BOT.	(56)
DEMAG. FACT. C_m	(74) C_q	(75)
AMP COND. PER IN		(128)
REACT. FACTOR		(129)
COND. PERM.		(62)
END PERM.		(64)
LEAKAGE REACT.		(130)
AIR GAP PERM.		
REACT. OF ARM. X_{ad}	(131) X_{aq}	(132)
WT. OF COPPER		
WT. OF IRON		

ROTOR

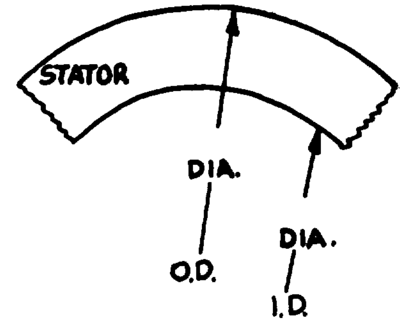
SINGLE GAP	(59)	g_2 (69)
ROTOR O.D.		I.D.
PERIPHERAL SPEED		(145)
POLE PITCH		α
POLE AREA-OUTER		(79)
POLE AREA-INNER		(79a)
ROTOR LEAKAGE		(102)
POLE DENSITY	(103)	(104b)
ROTOR IRON		(18)
DAMPER BARS Nº		
BAR SIZE		
BAR PITCH	h_o	b_o
FIELD COIL TURNS		(146)
COND. SIZE	(148)	(149)
COND AREA		(153)
MEAN TURN		(157)
RES @ °		(155)

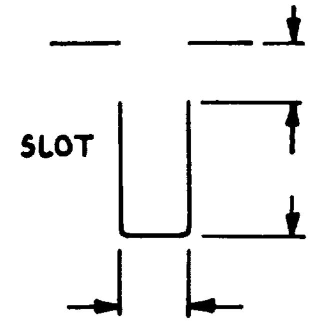
% LOAD			100	
P.F.				
AMPS			(237)	
VOLTS			(238)	
I^2R				
AMPS/IN.²				

FIELD SELF IND.		(161)
DAMP. LEAK XD_d		XD_q

REACTION-TIME CONSTANT

SYNCH. X_d	(133)	X_q (134)
UNSAT. TRANS.		(166)
SAT. TRANS.		(167)
SUBTRANS. X_c''	(168)	X_q'' (169)
NEG. SEQUENCE		(170)
ZERO SEQUENCE		(172)
OPEN CIR. TIME CON.		(176)
ARM. TIME CON.		(177)
TRANS. TIME CON.		(178)
SUBTRANS. TIME CON.		(179)





SATURATION

AIR GAP AT		(96)
STATOR AT	(97)	(98)
POLE AT		
NO LOAD AT		
RATED LOAD AT		(236)
OVERLOAD AT		
SHORT CIRCUIT AT		(180)

LOSSES-EFFICIENCY

% LOAD	0	100
F & W	(183)	(183)
STA. TEETH	(184)	(242)
STA. CORE	(185)	(185)
POLE FACE	(186)	(243)
DAMPER		
STA. I^2R		(245)
EDDY		(246)
FIELD I^2R	(182)	(241)
Σ LOSSES		
RATING		
RATING & LOSSES		
% LOSSES		
% EFF.		

W.O. ______ FOR FIGURE N3 COOLING ______

(2) KVA (9) % P.F. (4)/(3) VOLTS (8) AMPS (5) PHASE

(5a) CYCLES/SEC. ______ POLES (7) RPM BY ______

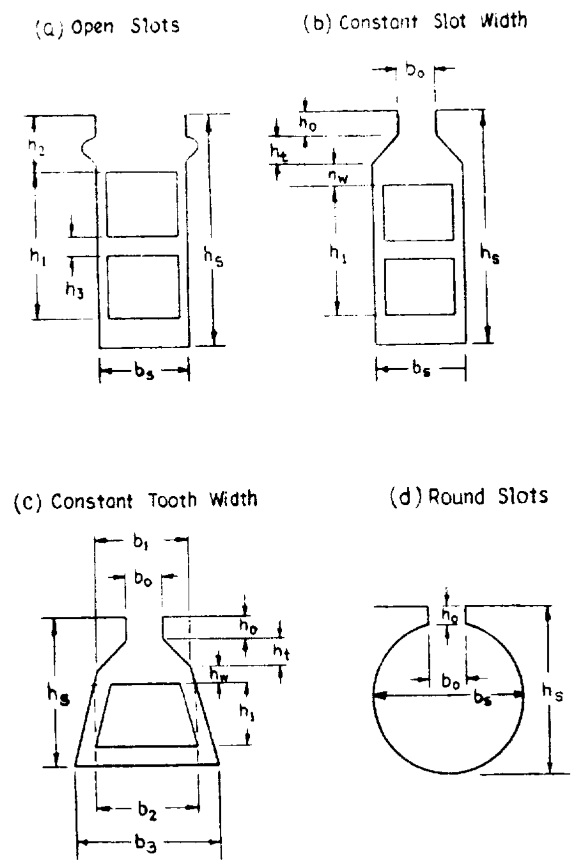
(1)	--	DESIGN NUMBER - To be used for filing purposes.
(2)	KVA	GENERATOR KVA
(3)	E	LINE VOLTS
(4)	E_{PH}	PHASE VOLTS - For 3 phase, delta connected generator $E_{PH} = (\text{Line Volts}) = (3)$ For 3 phase, wye connected generator $E_{PH} = \frac{(\text{Line Volts})}{\sqrt{3}} = \frac{(3)}{\sqrt{3}}$
(5)	m	PHASES - number of
(5a)	f	FREQUENCY - In cycles per second
(6)	P	POLES - Number of
(7)	RPM	SPEED - In revolutions per minute
(8)	I_{PH}	PHASE CURRENT - In amperes at rated load
(9)	PF	POWER FACTOR - Given in per unit
(9a)	K_c	ADJUSTMENT FACTOR - When PF = 0. to .95 set $K_c = 1$; when PF = .95 to 1. set $K_c = 1.05$

(10a)	d	STATOR EQUIVALENT DIAMETER
		$d = \sqrt{\frac{(O.D.)^2 + (I.D.)^2}{2}} = \sqrt{\frac{(12)^2 + (11)^2}{2}}$
(11)	I.D.	STATOR I.D. - The inside diameter of the stator toroid in inches.
(12)	O.D.	STATOR O.D. - The outside diameter of the stator toroid in inches
(13)	ℓ	GROSS CORE LENGTH - In inches
		$\ell = \frac{(O.D.)-(I.D.)}{2} = \frac{(12)-(11)}{2}$
(16)	K_i	STACKING FACTOR - This factor allows for the coating (core plating) on the punchings, and the looseness of the ribbon. Approximate values are giver in Table IV.

THICKNESS OF LAMINATIONS (INCHES)	GAGE	K_i
.C14	29	0.92
.018	26	0.93
.025	24	0.95
.028	23	0.97
.063	--	0.98
.125	--	0.99

TABLE IV

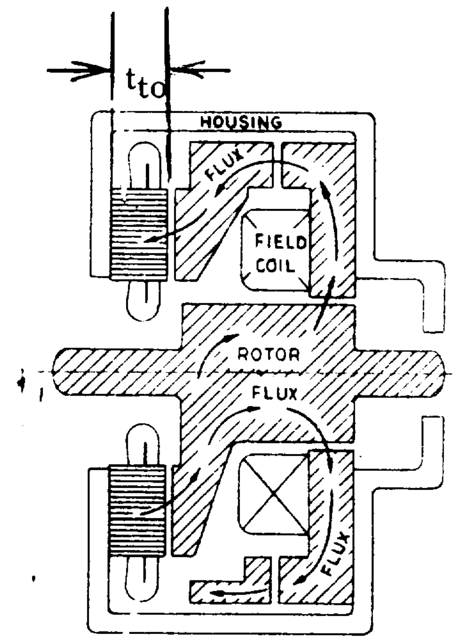
(17)	ℓ_s	SOLID CORE LENGTH - The solid length is the gross length times the stacking factor. $$\ell_s = (K_i) \times (\ell) = (16) \times (13)$$
(18)	--	MAGNETIZATION CURVES are to be available for stator, pole and yoke.
(19)	k	WATTS/LB - Core loss per lb of lamination material. Must be given at the density specified in (20).
(20)	B	DENSITY - This value must correspond to the density used in Item (19) to pick the watts/lb. The density that is usually used is 77.4 kilolines/in^2.
(21)		TYPE OF STATOR SLOT - Refer to Figure 1 for type of slot.
(22)	b_0, b_1, b_2, b_3, b_s, h_0, h_1, h_2, h_3, h_s, h_t, h_w	ALL SLOT DIMENSIONS - Given in inches per Figure 1. Note: For Type (c) slot $$b_s = \frac{(b_1) + (b_3)}{2} = \frac{(22) + (22)}{2}$$



(a) Open Slots
(b) Constant Slot Width
(c) Constant Tooth Width
(d) Round Slots
h2
h1
h3
hs
bs
bo
ho
ht
hw
b1
b2
b3

Fig 1

(23)	Q	STATOR SLOTS - number of
(24)	h_c	DEPTH BELOW SLOTS - The depth of the stator core below the slots. $h_c = t_{to} - h_s = (24) - (22)$ Where t_{to} is the total thickness of the stator

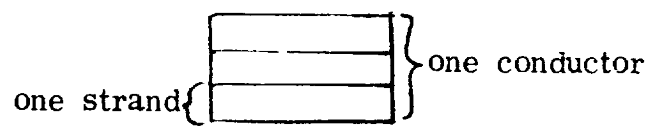


(25)	q	SLOTS PER POLE PER PHASE $q = \frac{(Q)}{(P)\ (m)} = \frac{(23)}{(6)\ (5)}$
(26)	Υ_s	STATOR SLOT PITCH (average) $\Upsilon_s = \frac{\pi\,(d)}{Q} = \frac{\pi(10a)}{(23)}$

(27)	$\tau_{s\ 1/3}$	STATOR SLOT PITCH - 1/3 distance up from narrowest section of tooth. $\tau_{s\ 1/3} = \tau_s = (26)$
(28)	--	TYPE OF WINDING - Record whether the connection is wye or delta
(29)	--	TYPE OF COIL - Record whether random wound or formed coils are used.

(30)	n_s	<u>CONDUCTORS PER SLOT</u> - The actual number of conductors per slot. For random wound coils use a space factor of 75% to 80%. Where space factor is the percent of the total slot area that is available for insulated conductors after **all** other insulation areas have been subtracted out.
(31)	Y	<u>THROW</u> - Number of slots spanned. For example, with a coil side in slot 1 and the other coil side in slot 10, the throw is 9.
(31a)		<u>PERCENT OF POLE PITCH SPANNED</u> - Ratio of the number of slots spanned to the number of slots in a pole pitch $= \frac{(Y)}{(m)(q)} = \frac{(31)}{(5)(25)}$
(32)	C	<u>PARALLEL PATHS</u>, no. of - Number of parallel circuits per phase
(33)	--	<u>STRAND DIA OR WIDTH</u> - In inches. For round wire, use strand diameter. For rectangular wire, use strand width.

(34) N_{ST} NUMBER OF STRANDS PER CONDUCTOR IN DEPTH - Applies to rectangular wire. In order to have a more flexible conductor and reduce eddy current loss a stranded conductor is often used. For example, when the space available for one conductor is .250 width x .250 depth, the actual conductor can be made up of 2 or 3 strands in depth as shown.



For the derivation of the eddy loss formula see the Appendix of the first quarterly report.

(35) d_b DIAMETER OF BENDER PIN in inches - This pin is used in forming coils

(36) ℓ_{e2} COIL EXTENSION BEYOND CORE in inches - Straight portion of coil that extends beyond stator core.

(37) h_{ST} HEIGHT OF UNINSULATED STRAND in inches

(38) h'_{st} DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH in inches.

(39) -- **STATOR COIL STRAND THICKNESS** in inches - For rectangular conductors only. For round wire use 0.

(40) τ_{SK} **SKEW** - Stator slot skew in inches at main air gap. To be measured at the stator O.D. as the deviation from a radial line at that point.

(41) τ_P **POLE PITCH** in inches at the median diameter

$$\tau_p = \frac{\pi (d)}{(P)} = \frac{\pi (10a)}{(6)}$$

(42) K_{SK} **SKEW FACTOR** - The skew factor is the ratio of the voltage induced in the coils to the voltage that would be induced if there were no skew

$$K_{SK} \frac{\sin\left[\frac{\pi(\tau_{SK})}{2(\tau_{P1})}\right]}{\frac{\pi(\tau_{SK})}{2(\tau_{P1})}}$$

τ_{p1} is the pole pitch at the outside diameter of the stator

τ_{SK} = item (40)

(43) K_d **DISTRIBUTION FACTOR** - The distribution factor is the ratio of the voltage induced in the coils to the voltage that would be induced in the coils if the winding were concentrated in a single slot. See Table F2 for compilation of distribution factors for the various harmonies.

$$K_d = \frac{\sin\left[\frac{(q)(\alpha_s)}{2}\right]}{(q)\sin\frac{(\alpha_s)}{2}} \quad \text{where } \alpha_s = \frac{180^\circ}{(mq)}$$

$$\therefore K_d = \frac{\sin\left[90^o/(m)\right]}{(q)\sin\left[90^o/(m)(q)\right]} = \frac{\sin\left[90^o/(5)\right]}{(25)\sin\left[90^o/(5)\times(25)\right]} \text{ For (25) = Integer}$$

or

$$K_d = \frac{\sin\left[N\alpha(m)/2\right]}{N\sin\left[\alpha(m)/2\right]} \text{ where } N \neq \text{Integer} = \frac{(Q)}{(m)(P)} \times \text{Integer \& } \alpha m = \frac{180^o}{N\times(m)}$$

$$\therefore K_d = \frac{\sin\left[90^o/(m)\right]}{N\sin\left[90^o/N(m)\right]} = \frac{\sin\left[90^o/(5)\right]}{N\sin\left[90^o/N\times(5)\right]} \text{ For (25) = Integer}$$

(44) K_P PITCH FACTOR - The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil. See Table 1 for compilation of the pitch factors for the various harmonics.

$$K_P = \sin\left[\frac{(Y)}{(m)(q)} \times 90^o\right] = \sin\left[\frac{(31)}{(5)(25)} \times 90^o\right]$$

(45) n_e TOTAL EFFECTIVE CONDUCTORS - The actual number of effective series conductors in the stator winding taking into account the pitch and skew factors but not allowing for the distribution factor.

$$n_e = \frac{(Q)(n_s)(K_P)(K_{SK})}{(C)} = \frac{(23)(30)(44)(42)}{(32)}$$

(46) a_c CONDUCTOR AREA OF STATOR WINDING in $(\text{inches})^2$ - The actual area of the conductor taking into account the corner radius on square and rectangular wire. See the following table for typical values of corner radii

If (39) = 0 then $a_c = .25\pi(\text{Dia})^2 = .25\pi(33)^2$

If (39) $\neq$ 0 then $a_c = (N_{ST})\left[(\text{strand width})(\text{strand depth}) - (.858\, r_c^{\,2})\right]$

$$= (34)\left[(33)(39) - \left\{.858\, r_c^{\,2}\right\}\right]$$

where $.858\, r_c^{\,2}$ is obtained from Table V below.

(39)	(33) .188	.189 (33) .75	(33) .751
.050	.000124	.000124	.000124
.072	.000210	.000124	.000124
.125	.000210	.00084	.000124
.165	.000840	.00084	.003350
.225	.001890	.00189	.003350
.438	--	.00335	.007540
.688	--	.00754	.01340
--	--	.03020	.03020

TABLE V

(47) S_S CURRENT DENSITY - Amperes per square inch of stator conductor

$$S_S = \frac{(I_{PH})}{(C)(a_C)} = \frac{(8)}{(32)(46)}$$

(48) L_E END EXTENSION LENGTH in inches

When (29) = 0 then:

$$L_E = \frac{.5 + K_T \pi (Y)\left[O.D.\right]}{Q} = .5 + \frac{\begin{bmatrix} 1.3 \text{ if } (6) = 2 \\ 1.5 \text{ if } (6) = 4 \\ 1.7 \text{ if } (6) > 4 \end{bmatrix} \pi (31) \left[(12)\right]}{(23)}$$

When (29) = 1. then:

$$L_E = 2\, \ell_{e2} + \pi\left[\frac{d_b}{2}\right] + Y\left[\frac{r_s^{\,2}}{r_s^{\,2} - b_s^{\,2}}\right]$$

$$= 2 \times (36) + \pi\left[\frac{(35)}{2}\right] + (31)\left[\frac{(26)^2}{(26)^2 - (22)^2}\right]$$

(49) ℓ_t **1/2 MEAN TURN** - The average length of one conductor in inches

$$\ell_t = (\ell) + (L_E) = (13) + (48)$$

(50) $X_s\,^oC$ **STATOR TEMP ^oC.** - Input temp at which F.L. losses will be calculated. No load losses and cold resistance will be calculated at 20^oC.

(51) ρ_s **RESISTIVITY OF STATOR WINDING** - In micro ohm-inches @ 20^oC. If tables are available using units other than that given above, use Table VI for conversion to ohm-inches.

ρ	ohm-cm	ohm-in	ohm-cir mil/ft
1 ohm-cm =	1.000	0.3937	6.015×10^6
1 ohm-in =	2.540	1.000	1.528×10^7
1 ohm-cir mil/ft =	1.662×10^{-7}	6.545×10^{-8}	1.000

TABLE VI
Conversion Factors for Electrical Resistivity

(52) $\rho_{S\,(hot)}$ **RESISTIVITY OF STATOR WINDING** - Hot at $X_s\,^oC$ in micro ohm-inches

$$\rho_{S(hot)} = (\rho_S)\left[\frac{(X_s\,^oC) + 234.5}{254.5}\right] = (51)\left[\frac{(50) + 234.5}{254.5}\right]$$

(53) R_{SPH} (cold) **STATOR RESISTANCE/PHASE** - Cold @ 20°C in ohms

$$R_{SPH(cold)} = \frac{(\rho_s)(n_s)(Q)(\ell_t) \times 10^{-6}}{(m)(a_c)(C)^2} = \frac{(51)(30)(23)(49)}{(5)(46)(32)^2} \times 10^{-6}$$

(54) R_{SPH} (hot) **STATOR RESISTANCE/PHASE** - Calculated @ X°C in ohms

$$R_{SPH(hot)} = \frac{(\rho_{s\ hot})(n_s)(Q)(\ell_t) \times 10^{-6}}{(m)(a_c)(C)^2} = \frac{(52)(30)(23)(49)}{(5)(46)(32)^2} \times 10^{-6}$$

(55) EF (top) **EDDY FACTOR TOP** - The eddy factor of the top coil. Calculate this value at the expected opera'ing temperature of the machine.

$$EF_{top} = 1 + \left\{ .584 + \left[\frac{N_{st}^2 - 1}{16}\right]\left[\frac{h'_{st}\ell}{h_{st}\ell_t}\right]^2 \right\} 3.35 \times 10^{-3} \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{S\ hot})\ x}\right]^2$$

$$= 1 + \left\{ .584 + \left[\frac{(34)^2 - 1}{16}\right]\left[\frac{(38)(13)}{(37)(49)}\right]^2 \right\} 3.35 \times 10^{-3} \left[\frac{(37)(30)(5a)(46)}{(22)(52)}\right]^2$$

(56) EF (bot) **EDDY FACTOR BOTTOM** - The eddy factor of the bottom coil at the expected operating temperature of the machine

$$EF_{(bot)} = (EF_{(top)}) - 1.677 \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{S\ hot})}\right]^2 \times 10^{-3}$$

$$= (55) - 1.677 \left[\frac{(37)(30)(5a)(46)}{(22)(52)}\right] 10^{-3}$$

(57)	b_{tm}	STATOR TOOTH WIDTH 1/2 way down tooth in inches - For slots type (a), (b), (d) and (e), Figure I $b_{tm} = (\tau_s) - (b_s) = (26) - (22)$ For slot type (c), Figure I $b_{tm} = (\tau_s) - (b_3) = (26) - (22)$
(58)	b_t	TOOTH WIDTH AT STATOR - Main air gap in inches For partially closed slot $b_t = \frac{\pi(d)}{(Q)} - b_0 = \frac{\pi(10a)}{(23)} - (22)$ For open slot $b_t = \frac{\pi(d)}{(Q)} - b_s = \frac{\pi(10a)}{(23)} - (22)$

(59)	g	MAIN AIR GAP - given in inches
(59a)	g_2	AUXILIARY AIR GAP (g_2) - given in inches
(59c)	g_3	AUXILIARY AIR GAP (g_3) - given in inches
(60)	C_X	REDUCTION FACTOR - Used in calculating conductor permeance and is dependent on the pitch and distribution factor. This factor can be obtained from Graph 1 with an assumed K_d of .955 or calculated as shown

$$C_X = \frac{(K_X)}{(K_P)^2\ (K_d)^2} = \frac{(61)}{(44)^2\ (43)^2}$$

(61)	K_X	FACTOR TO ACCOUNT FOR DIFFERENCE in phase current in coil sides in same slot.

For 60^o phase belt winding, i.e. when (42a) = 60

$$K_X = 1/4\left[\frac{3(y)}{(m)(q)} + 1\right] \text{ where } 2/3 \leqq (y)/(m)(q) \leqq 1.0$$

$$K_X = 1/4\left[\frac{3(31)}{(5)(25)} + 1\right] \text{ where } 2/3 \leqq (31a) \leqq 1.0$$

or

$$K_X = 1/4\left[\frac{6(y)}{(m)(q)} - 1\right] \text{ where } 1/2 \leqq (31a) \leqq 2/3$$

$$K_X = 1/4\left[\frac{6(31)}{(5)(25)} - 1\right] \text{ where } 1/2 \leqq (31a) \leqq 2/3$$

For 120° phase belt winding, i.e. when (42a) = 120

$K_X = .75$ when $2/3 \leq (y)/(m)(q)$

$K_X = .75$ when $2/3 \leq (31a)$

or

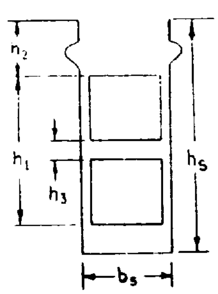
$$K_X = .05 \left[\frac{24(y)}{(m)(q)} - 1\right] \text{ where } 1/2 \leq \frac{(y)}{(m)(q)} \leq 2/3$$

$$K_X = .05 \left[\frac{24(31)}{(3)(25)} - 1\right] \text{ where } 1/2 \leq (31a) \leq 2/3$$

(62) | λ_i | CONDUCTOR PERMEANCE - The specific permeance for the portion of the stator current that is embedded in the iron. This permeance depends upon the configuration of the slot.

(a) For open slots

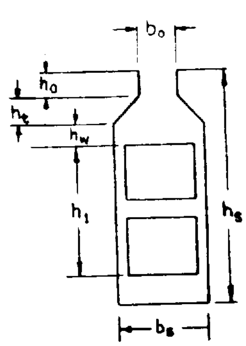
(a) Open Slots



$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)}\right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)}\right]$$

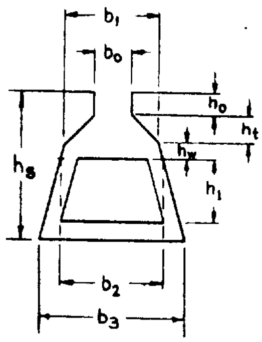
(b) Constant Slot Width



(b) For partially closed slots with constant slot width

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o) + (b_s)} + \frac{(h_w)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)}\right]$$

(c) Constant Tooth Width

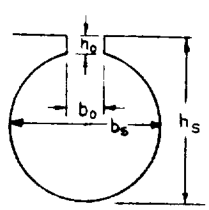


(c) For partially closed slots (tapered sides)

$$\lambda_i = (C_X)\,\frac{20}{(m)(q)}\left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o)+(b_1)} \right. +$$

$$\left. + \frac{2(h_w)}{(b_1 --(b_2)} + \frac{(h_1)}{3(b_2)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)}\right]$$

(d) Round Slots



(d) For round slots

$$\lambda_i = (C_X)\,\frac{20}{(m)(q)}\left[.62 + \frac{(h_o)}{(b_o)}\right]$$

$$\lambda_i = (60)\,\frac{20}{(5)(25)}\left[.62 + \frac{(22)}{(22)}\right]$$

(e) For open slots with a winding of one conductor per slot

$$\lambda_i = (C_X)\,\frac{20}{(m)(q)}\left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + .6 + \frac{(g)}{2(\tau_s)} + \frac{(\tau_s)}{4(g)}\right]$$

$$\lambda_i = (60)\,\frac{20}{(5)(25)}\left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + .6 + \frac{(59)}{2(26)} + \frac{(26)}{4(59)}\right]$$

(63)	K_E	<u>LEAKAGE REACTIVE FACTOR</u> for end turn
		$K_E = \frac{\text{Calculated value } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}}$ (For machines where (11) > 8")
		where L_E = (48) and abscisa of Graph 1 = $(\gamma)(\tau_s)$ = (31)(26)
		$K_E = \sqrt{\frac{\text{Calculated value of } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}}}$ (For machines where (11) < 8")
(64)	λ_E	<u>END WINDING PERMEANCE</u> - The specific permeance for the end extension portion of the stator winding
		$\lambda_E = \frac{6.28(K_E)}{(\ell)(K_d)^2}\left[\frac{\emptyset_E L_E}{2n}\right] = \frac{6.28(63)}{(13)(43)^2}\left[\frac{Q_E L_E}{2n}\right]$
		The term $\left[\frac{\emptyset_E L_E}{2n}\right]$ is obtained from Graph 1.
		The symbols used in this (term) do not apply to those of this design manual. Reference information for the symbol origin is included on Graph 1.

(65) --

WEIGHT OF COPPER - the weight of stator copper in lbs.

$$\#\text{'s copper} = .321(n_s)(Q)(a_c)(\ell_t) = .321(30)(23)(46)(49)$$

(66) --

WEIGHT OF STATOR IRON - in lbs.

$$\#\text{'s iron} = .283\left\{(b_{tm})(Q)(\ell_s)(h_s) + \pi(d)\quad(h_c)(\ell_s)\right\}$$

$$= .283\left\{(57)(23)(17)(22) + \pi(10a)\quad(24)(17)\right\}$$

(67) K_s

CARTER COEFFICIENT

$$K_s = \frac{(\tau_s)\left[5(g)+(b_s)\right]}{(\tau_s)\left[5(g)+(b_s)\right] - (b_s)^2} \quad \text{(For open slots)}$$

$$K_s = \frac{(26)\left[5(59)+(22)\right]}{(26)\left[5(59)+(22)\right] - (22)^2}$$

$$K_s = \frac{\tau_s\left[4.44(g)+.75(b_o)\right]}{\tau_s\left[4.44(g)+.75(b_o)\right] - (b_o)^2} \quad \text{(For partially closed slots)}$$

$$K_s = \frac{(26)\left[4.44(59)+.75(22)\right]}{(26)\left[4.44(59)+.75(22)\right] - (22)^2}$$

(68) A_g

MAIN AIR GAP AREA - The area of the gap surface at the stator bore

$$A_g = \frac{\pi}{4}\left[(O.D.)^2 - (I.D.)^2\right] = \frac{\pi}{4}\left[(12)^2 - (11)^2\right]$$

(69) g_e

EFFECTIVE AIR GAP (MAIN)

$$g_e = (K_s)(g) = (67)(59)$$

(70)	A_{g2}	AREA OF OUTER AUXILIARY AIR GAP (g_2) - Calculate from layout. This gap must be uniform circumferentially with no saturated sections if parasitic losses in the gap surfaces are to be prevented.
(70a)	A_{g3}	AREA OF THE INNER AUXILIARY GAP (g_3) - The same comment applies to g_3 as to g_2 above. Avoid discontinuity in the circumferential flux pattern.
(71)	C_1	THE RATIO OF MAXIMUM FUNDAMENTAL of the field form to the actual maximum of the field form. For pole heads with only one radius, C_1 is obtained from Curve #4. The abscissa is "pole embrace" (α) = (77). The graphical flux plotting method of determining C_1 is explained in the section titled "Derivations" in the Appendix.
(72)	C_W	WINDING CONSTANT - The ratio of the RMS line voltage for a full pitched winding to that which would be introduced in all the conductors in series if the density were uniform and equal to the Maximum value. $C_W = \frac{(E)(C_1)(K_d)}{\sqrt{2}(E_{PH})(m)} \quad \frac{(3)(71)(43)}{\sqrt{2}(4)(5)}$

Assuming $K_d = .955$, then $C_W = .225\ C_1$ for three phase delta machines and $C_W = .390\ C_1$ for three phase star machines.

(73)	C_P	<u>POLE CONSTANT</u> - The ratio of the average to the maximum value of the field form. C_P is obtained from Curve #4. Note the correction factor at the top of the curve.
(74)	C_M	<u>DEMAGNETIZING FACTOR</u> - direct axis.

$$C_M = \frac{(\alpha)\pi + \sin[(\alpha)\pi]}{4\sin[(\alpha)\pi/2]} = \frac{(77)\pi + \sin(77)}{4\sin[(77)\pi/2]}$$

(75)	C_q	<u>CROSS MAGNETIZING FACTOR</u> - quadrature ax:s

$$\left.\begin{aligned} C_q &= \frac{1/2\cos[(\alpha)\pi/2] + (\alpha)\pi - \sin[(\alpha)\pi]}{4\sin[(\alpha)\pi/2]} \\ &= \frac{1/2\cos[(77)\pi/2] + (77)\pi - \sin[(77)\pi]}{4\sin[(77)\pi/2]} \end{aligned}\right\}\text{valid for concentric poles.}$$

C_q can also be obtained from Curve 9.

(76)	--	<u>POLE DIMENSIONS LOCATIONS</u> per Figure N4a & N4b

b_{p1} = minimum width of pole (usually at tip) measured at the edge of the stator toroid.

b_{p2} = maximum width of pole (usually at entering edge) at edge of stator toroid.

b_p = average width of pole

$$b_p = \frac{b_{p1} + b_{p2}}{2}$$

(79) A_{po} **AREA OF POLE AT ENTERING EDGE OF STATOR TOROID**

(outer pole) - Obtain from layout.

(79a) A_{pi} **AREA OF POLE AT ENTERING EDGE OF STATOR TOROID**

(inner pole) - Obtain from layout.

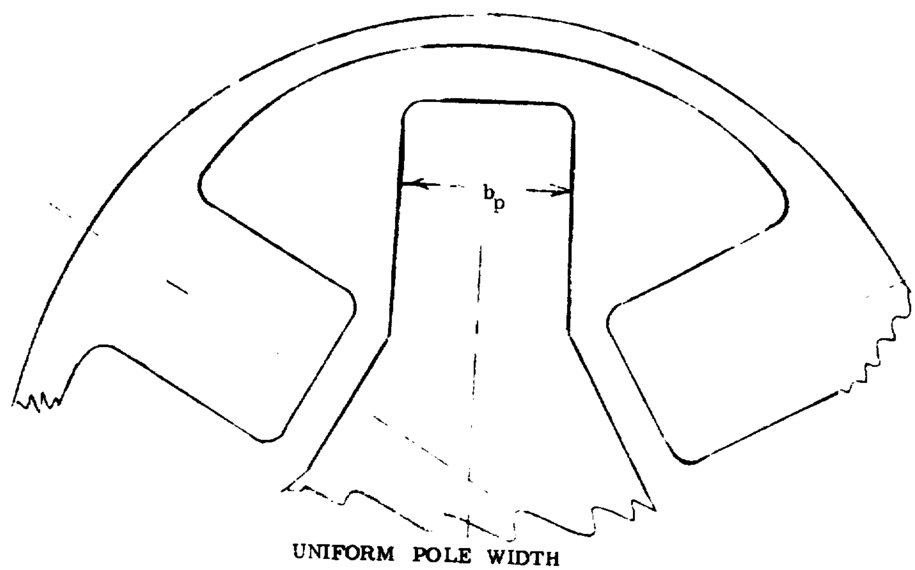


FIGURE N4a

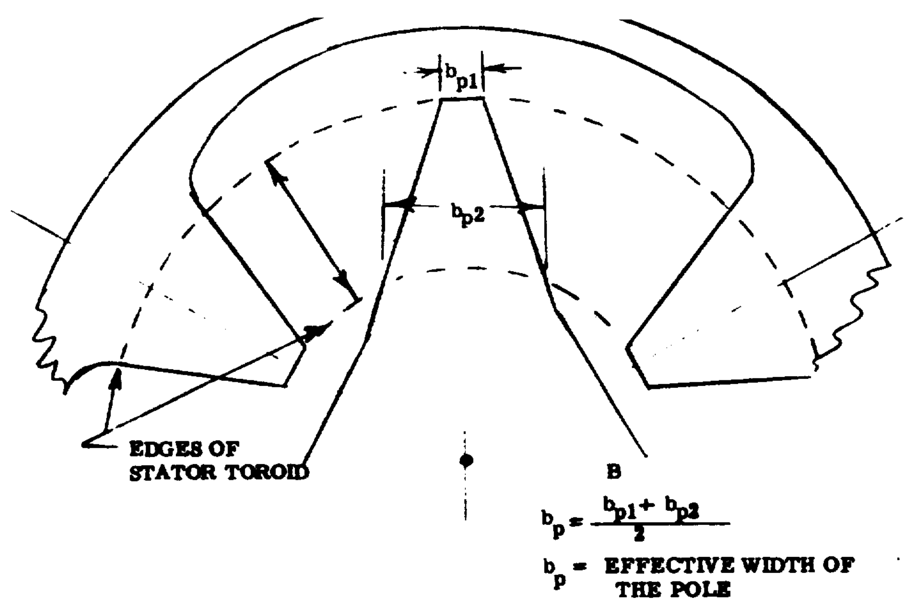


FIGURE N4b

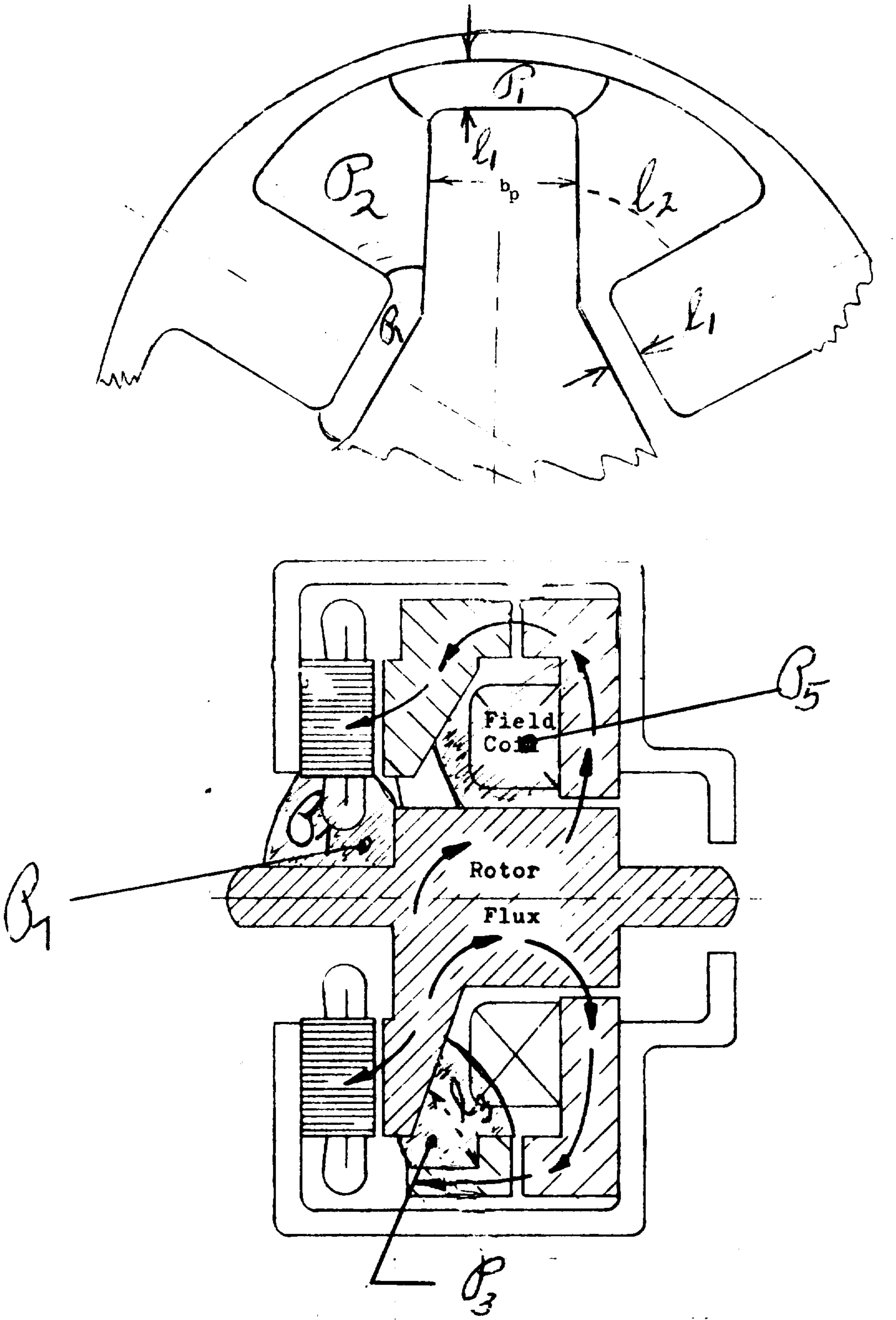


FIGURE N 5

(80)	P_1	POLE TIP TO ROTOR LEAKAGE PERMEANCE - Add the leakage permeance from the inside pole to the outer flux ring and the outside pole to the shaft section. PER FIGURE N 5
		$$P_1 = \left[\frac{\mu a_1}{\ell_1} + \frac{\mu a'_1}{\ell'_1}\right]\left[\frac{P}{2}\right]$$
(81)	P_2	SIDE LEAKAGE FROM POLE-TO-POLE
		$P_2 = \frac{\mu a}{\ell}$ PER FIGURE N 5
		a = area of leakage path between poles x poles
		ℓ = median length of leakage path between a pair of poles
(82)	P_3	LEAKAGE PERMEANCE FROM UNDERSIDE OF POLE TO ROTOR.
		Add the leakage permeance from inner pole to outer flux ring and from outer pole to shaft. Multiply this sum by $\frac{P}{2}$ PER FIG FIGURE N 5
		$$P_3 = \left[\frac{\mu a_3}{\ell_3} \quad \frac{\mu a'_3}{\ell'_3}\right]\frac{P}{2}$$
(83)	P_4	LEAKAGE PERMEANCE FROM UNDERSIDE OF POLE TO UNDERSIDE OF POLE -
		$P_4 = \left[\frac{\mu a_4}{\ell_4}\right](P)$ PER FIGURE N 6

P_4 <u>LEAKAGE PERMEANCE FROM UNDERSIDE OF POLE TO UNDERSIDE OF POLE</u> -

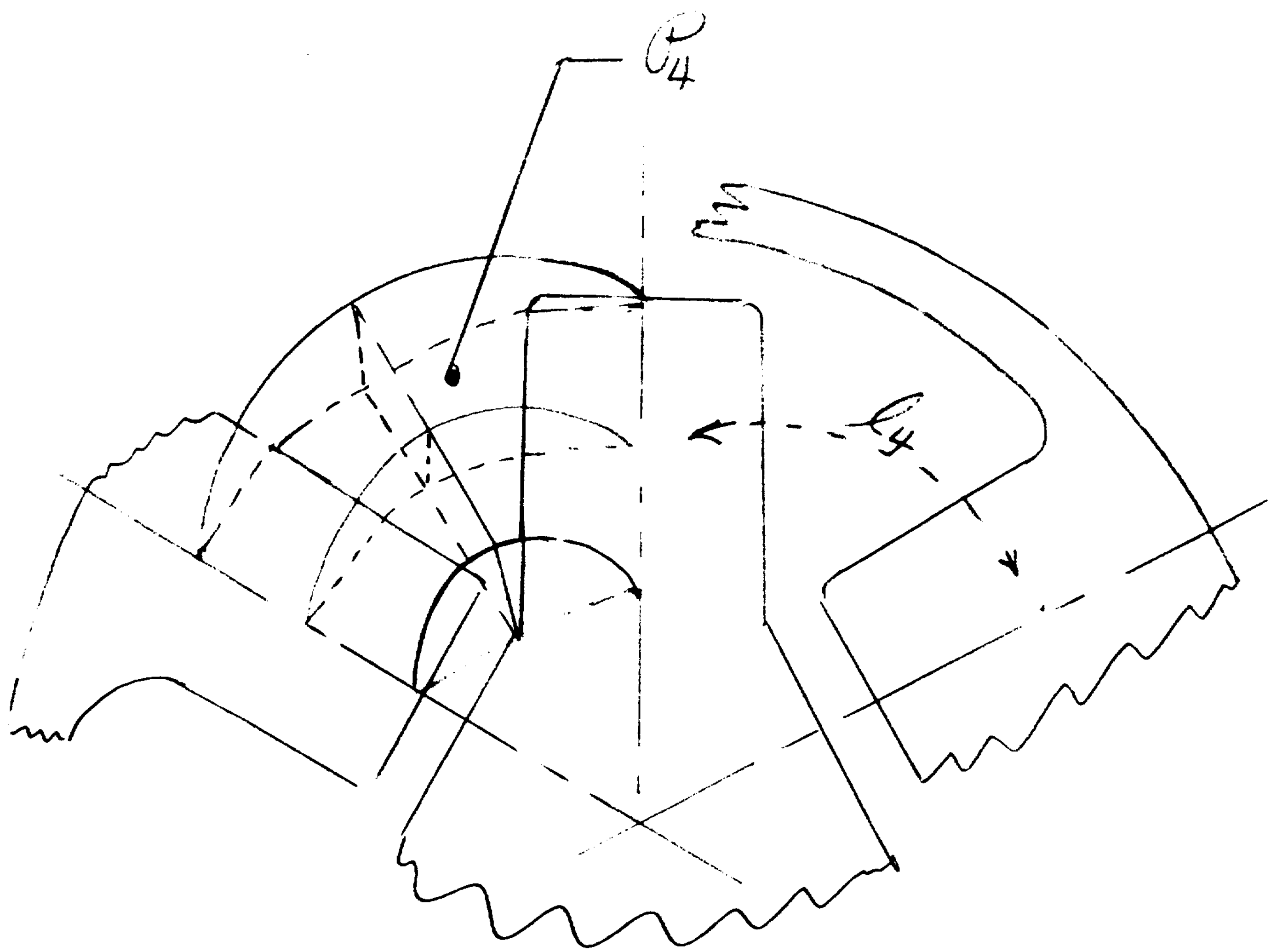


FIGURE N 6

(84)	P_5	LEAKAGE PERMEANCE THROUGH FIELD COIL

$$P_5 = \frac{\mu a_5}{\ell_5} \quad \text{PER FIGURE N 5}$$

Where $a_5 = \pi (d_c)(b_c)$ inches^2

Where b_c = width of field coil

Where d_c = field coil diameter

$$= \frac{\text{Coil O.D.} + \text{Coil I.D.}}{2} \text{ inches}$$

Where $\ell_5 = \frac{\text{Coil O.D.} - \text{Coil I.D.}}{2}$ inches

$\mu = 3.19$

(86)	P_7	STATOR TO FLUX RING AND SHAFT LEAKAGE PER FIGURE N5
(88)	$\emptyset_T$	TOTAL FLUX in Kilolines

$$\emptyset_T = \frac{6(E)10^6}{(C_W)(n_e)(RPM)} = \frac{6(3)10^6}{(72)(45)(\ 7)}$$

(89)	$\emptyset_{\ell 7}$	LEAKAGE FLUX FROM STATOR TO SHAFT AND OUTER FLUX RING

$$\emptyset_{\ell 7} = \frac{P_7 \left[2(F_T) + 2(F_c) + (F_{g2}) + (F_{g3}) + (F_{po}) + (F_{pi})\right] \times 10^{-3}}{2}$$

$$= (86)\left[2(97) + 2(98) + (123) + (120) + (104) + (104b)\right] \times 10^{-3}$$

(91) B_t **TOOTH DENSITY** in Kilolines/in^2 - The flux density in the stator tooth at 1/3 of the distance from the minimum section.

$$B_t = \frac{\phi_T}{(Q)(\ell_s)(b_{t\ 1/3})} = \frac{(88)}{(23)(17)(57a)}$$

(92) ϕ_P **FLUX PER POLE** in Kilolines

$$\phi_P = \frac{(\phi_T)(C_P)}{(P)} = \frac{(88)(73)}{(6)}$$

(94) B_c **CORE DENSITY** in Kilolines/in^2 - The flux density in the stator core

$$B_c = \frac{(\phi_P)}{2(h_c)(\ell_s)} = \frac{(92)}{2(24)(17)}$$

(95) B_g **GAP DENSITY** in Kilolines/in^2 - The maximum flux density in the air gap

$$B_g = \frac{(\phi_T)}{(A_g)} = \frac{(88)}{(68)}$$

(96) F_g **AIR GAP AMPERE TURNS** - The field ampere turns per pole required to force flux across the air gap when operating at no load with rated voltage.

$$F_g = \frac{(B_g)(g_e)}{3.19} \times 10^3 = \frac{(95)(69)}{3.19} \times 10^3$$

(97)	F_T	**STATOR TOOTH AMPERE TURNS**
		$F_T = (h_s)\left[\text{NI/inch at density } (B_t)\right]$
		$= (22)\left[\text{look up on stator magnetization curve given in (18) at density (91)}\right.$
(98)	F_c	**STATOR CORE AMPERE TURNS**
		$F_c = \frac{\pi(d)}{4(P)}\left[\text{NI/inch at density } (B\ c)\right]$
		$F_c = \frac{\pi(10a)}{4(6)}\left[\text{Look up on stator magnetization curve at density (94)}\right]$
(100)	ϕ_ℓ	**LEAKAGE FLUX** - at no load
		$\phi_\ell = \left[(P_1)+(P_2)+(P_3)+(P_4)\right]\left[2(F_T)+2(F_c)+(F_{g2})+(F_{g3})\right]\times10^{-3}$
		$= \left[(80)+(81)+(82)+(83)\right]\left[2(97)+2(98)+(123)+(120)\right]\times10^{-3}$
(102)	ϕ_{pt}	**TOTAL FLUX PER POLE** - at no load
		$\phi_{pt} = \phi_p + \frac{\phi_\ell}{P} = (92) + \frac{(100)}{(6)}$
(103)	B_{po}	**FLUX DENSITY IN OUTER POLE (NL)**
		$B_{po} = \frac{(\phi_{pt})}{(a_{po})} = \frac{(102)}{(79)}$

(104)	F_{po}	**AMPERE TURN DROP THROUGH OUTER POLE @ N. L.**
		$F_{po} = (\ell_{po}) \left[\text{NI/inch at density } (B_{po}) \right]$
		$= (104) \left[\text{Look up on pole magnetization curve at density (103).} \right]$
		Where ℓ_{po} = length of outer pole.
(104a)	B_{pi}	**FLUX DENSITY IN INNER POLE @ N. L.**
		$B_{pi} = \frac{\phi_{pt}}{A_{pi}} = \frac{(102)}{(79a)}$
(104b)	F_{pi}	**AMPERE TURN DROP THROUGH THE INNER POLE @ N. L.**
		$F_{pi} = (\ell_{pi}) \left[\text{NI/inch at density } (B_{pi}) \right]$
		$= (104b) \left[\text{Look up on pole magnetization curve at density (104a)} \right]$
		Where (ℓ_{pi}) = length of inner pole
(104c)	ϕ_r	**FLUX IN ROTATING OUTER FLUX RING AT NO LOAD**
		$\phi_r = \phi_{g2} = \phi_{g3} = \phi_{sh}$
		= (108) = (118a) = (111)

(104d)	B_r	FLUX DENSITY IN ROTATING OUTER RING at no load

$$B_r = \frac{(\phi_r)}{(A_r)} = \frac{(104c)}{(104d)}$$

Where A_r = ring cross-section area adjacent to the outer pole (P_o)

(104e)	F_r	AMPERE TURN DROP IN RING at no load.

$$F_r = (\ell_r) \left[\text{NI/inch at density } (B_r) \right]$$

$$= (104e) \left[\begin{array}{l} \text{Look up on ring magnetization curve} \\ \text{at density (104d)} \end{array} \right]$$

Where ℓ_r = length of ring

(108)	ϕ_{g2}	FLUX IN AUXILIARY GAP at no load

$$\phi_{g2} = \phi_{g3} = \phi_r = \phi_{sh} = \phi_{pt} \frac{(P)}{2} + \phi_{\ell 7}$$

$$= (102) \frac{(6)}{2} + (89)$$

(111)	ϕ_{sh}	FLUX IN SHAFT at no load

$$\phi_{sh} = \phi_{g2} = \phi_r = \phi_{g3}$$

$$= (108) = (104c) = (118a)$$

(112)	A_{sh}	AREA OF SHAFT (cross-sectional to flux)
(113)	B_{sh}	FLUX DENSITY IN SHAFT at no load $B_{sh} = \frac{\phi_{sh}}{A_{sh}} = \frac{(111)}{(112)}$
(114)	F_{sh}	AMPERE TURN DROP IN SHAFT at no load $F_{sh} = \ell_{sh} \left[\text{NI/inch at density } (B_{sh}) \right]$ $= (114) \left[\begin{array}{l} \text{Look up on shaft magnetization curve} \\ \text{at density (113)} \end{array} \right]$ Where ℓ_{sh} = effective length of shaft
(118)	$\phi_{\ell 5}$	LEAKAGE FLUX ACROSS THE FIELD COIL in Kilolines $\phi_{\ell 5} = (P_5) \left[(F_{g2}) + (F_{g3}) + 2(F_t) + 2(F_c) + (F_{po}) + (F_{pi}) + (F_r) + (F_{sh}) \right] \times 10^{-3}$ $= (84) \left[(123) + (120) + 2(97) + 2(98) + (104) + (104b) + (104e) + (114) \right] \times 10^{-3}$
(118a)	ϕ_{g3}	FLUX IN AUXILIARY GAP g_3 $\phi_{g3} = \phi_{g2} = (108)$
(119)	B_{g3}	FLUX DENSITY IN AUXILIARY GAP g_3 $B_{g3} = \frac{(\phi_{g3})}{(A_{g3})} = \frac{(118a)}{(70a)}$

(120)	F_{g3}	AMPERE TURN DROP ACROSS THE AUXILIARY AIR GAP g_3
		$F_{g3} = \frac{(B_{g3})}{3.19}(g_3) \times 10^3 = \frac{(119)}{3.19}(59c) \times 10^3$
(122)	B_{g2}	FLUX DENSITY IN AUXILIARY AIR GAP
		$B_{g2} = \frac{(\emptyset_{g2})}{(A_{g2})} = \frac{(108)}{(70)}$
(123)	F_{g2}	AMPERE TURN DROP ACROSS AUXILIARY GAP (g_2)
		$F_{g2} = \frac{(B_{g2})(g_2)}{3.19} \times 10^3 = \frac{(122)(59a)}{3.19} \times 10^3$
(126a)	$\emptyset_y$	FLUX IN YOKE
(126b)	B_y	YOKE DENSITY
		$B_y = \frac{(\emptyset_y)}{(A_y)} = \frac{(126a)}{(126b)}$
		Where a_y = yoke cross-sectional area
(126c)	F_y	AMPERE TURN DROP IN YOKE at no load
		$F_y = \ell_y \left[\text{NI/inch at density } (B_y) \right]$
		$= (126c) \left[\begin{array}{l} \text{Look up on yoke magnetization curve} \\ \text{at density } (126b) \end{array} \right]$
		Where ℓ_y = length of yoke

(127)	F_{NL}	TOTAL AMPERE TURNS at no load
		$F_{NL} = \left[2(F_c)+2(F_T)+(F_{po})+(F_{pi})+(F_r)+(F_{sh})+(F_{g2})+(F_{g3})+(F_y)\right]$
		$= 2(98)+2(97)+(104)+(104b)+(104e)+(114)+(123)+(120)+(126c)$
(127a)	I_{FNL}	FIELD CURRENT - at no load
		$I_{FNL} = (F_{NL})/(N_F) = 127)/(146)$
(127b)	E_{FNL}	FIELD VOLTS - at no load. This calculation is made with cold field resistance at 20^oC for no load condition.
		$E_F = (I_{FNL})(R_{f\ cold}) = (127a)(154)$
(127c)	S_F	CURRENT DENSITY - at no load. Amperes per square inch of field conductor.
		$S_F = (I_{FNL})/(a_{cf}) = (127a)/(153)$
(128)	A	AMPERE CONDUCTORS per inch - The effective ampere conductors per inch of stator periphery. This factor indicates the "specific loading" of the machine. Its value will increase with the rating and size of the machine and also will increase with the number of poles. It will decrease with increases in voltage or frequency. A is generally higher in single phase machines than in polyphase ones.
		$A = \frac{(I_{PH})(n_s)(K_P)}{(C)\ (\Upsilon_s)} = \frac{(8)(30)(44)}{(32)(26)}$

(129) X **REACTANCE FACTOR** - The reactance factor is the quantity by which the specific permeance must be multiplied to give percent reactance. It is the percent reactance for unit specific permeance, or the percent of normal voltage induced by a fundamental flux per pole per inch numerically equal to the fundamental armature ampere turns at rated current. Specific permeance is defined as the average flux per pole per inch of core length produced by unit ampere turns per pole.

$$X = \frac{100(A)(K_d)}{\sqrt{2}\,(C_1)(B_g) \times 10^3} = \frac{100\,(128)(43)}{\sqrt{2}\,(71)\,(95) \times 10^3}$$

(130) X_ℓ **LEAKAGE REACTANCE** - The leakage reactance of the stator for steady state conditions. When (5) = 3, calculate as follows:

$$X_\ell = X\left[(\lambda_i) + (\lambda_E)\right] = (79)\left[(62) + (64)\right]$$

In the case of two phase machines a component due to belt leakage must be included in the stator leakage reactance. This component is due to the harmonics caused by the concentration of the MMF into a small number of phase belts per pole and is negligible for three phase machines. When (5) = 2, calculate as follows:

$$\lambda_B = \frac{0.1(d)}{(P)(g_e)}\left[\frac{\sin\left[\frac{3(y)}{(m)(q)}\right]90^\circ}{(K_p)}\right] = \frac{0.1(11)}{(6)(69)}\left[\frac{\sin\left[\frac{3(31)}{(5)(25)}\right]90^\circ}{(44)}\right]$$

$X_\ell = X\left[(\lambda_i) + (\lambda_E) + (\lambda_B)\right]$ where $\lambda_B = 0$ for 3 phase machines.

$$X_\ell = (79)\left[(62) + (64) + (130)\right]$$

(131) X_{ad} REACTANCE - direct axis - This is the fictitious reactance due to armature reaction in the direct axis.

$$X_{ad} = \frac{.9(n_e)(I_{ph})(C_m)(K_d)}{P\left[2(F_{g})+(F_{g2})+(F_{g3})\right]} \times 100$$

$$X_{ad} = \frac{.9(45)(8)(74)(43)}{6\left[2(96)+(123)+(120)\right]} \times 100$$

(132) X_{aq} REACTANCE - Quadrature axis - This is the fictitious reactance due to armature reaction in the quadrature axis.

$$X_{aq} = \frac{(C_q)(X_{ad})}{(C_m)(C_1)}$$

$$X_{aq} = \frac{(75)(131)}{(74)(71)}$$

(133) X_d SYNCHRONOUS REACTANCE - direct axis - the steady state short circuit reactance in the direct axis.

$$X_d = (X_\ell) + (X_{ad}) = (130) + (131)$$

(134) X_q SYNCHRONOUS REACTANCE - quadrature axis - The steady state short circuit reactance in the quadrature axis.

$$X_q = (X_\ell) + (X_{aq}) = (130) + (132)$$

(145)	V_r	PERIPHERAL SPEED - The velocity of the rotor surface in feet per minute $$V_r = \frac{\pi (d_r)(RPM)}{12} = \frac{\pi (11a)(7)}{12}$$
(146)	N_F	NUMBER OF FIELD TURNS
(147)	ℓ_{tF}	MEAN LENGTH OF FIELD TURN
(148)	--	FIELD CONDUCTOR DIA OR WIDTH in inches
(149)	--	FIELD CONDUCTOR THICKNESS in inches - Set this item = 0. for round conductor.

(150) $X_f{}^oC$ — FIELD TEMP IN ^oC - Input temp at which full load field loss is to be calculated.

(151) ρ_f — RESISTIVITY of field conductor @ 20^oC in micro ohm-inches. Refer to table given in item (51) for conversion factors.

(152) ρ_f (hot) — RESISTIVITY of field conductor at $X_f{}^oC$

$$\rho_{f\ (hot)} = \rho_f \left[\frac{(X_f{}^oC) + 234.5}{254.5}\right] = (104) \left[\frac{(150) + 234.5}{254.5}\right]$$

(153) a_{cf} — CONDUCTOR AREA OF FIELD WINDING - Calculate same as stator conductor area (46) except substitute

(149) for (39)

(148) for (33)

(154) R_f (cold) — COLD FIELD RESISTANCE @ 20^oC

$$R_{f\ (cold)} = (\rho_f) \frac{(N_f)\ (\ell_{tf})}{(a_{cf})} = (151) \frac{(146)\ (147)}{(153)}$$

(155) R_f (hot) — HOT FIELD RESISTANCE - Calculated at $X_f{}^oC$ (103)

$$R_{f\ (hot)} = (\rho_{f\ hot}) \frac{(N_f)\ (\ell_{tf})}{(a_{cf})} = (152) \frac{(146)\ (147)}{(153)}$$

(156) -- — WEIGHT OF FIELD COIL in lbs.

$$\#\text{'s of copper} = .321(N_f)(\ell_{tf})(a_{cf})$$

$$= .321(146)(6)(147)(153)$$

(160) X'_F THE EFFECTIVE FIELD LEAKAGE REACTANCE - The reactance which added to the stator leakage reactance gives the transient reactance X'_{du}.

When unit fundamental armature ampere turns are suddenly applied on the direct axis, an initial field current (I_f) will be induced. The value of this initial field current will be just enough to make the net flux interlinking the field because of the field current and the armature current zero. The field ampere turns will equal the armature ampere turns.

$$X_F = X_{ad}\left[1 - \frac{\frac{C_1}{C_m}}{2C_p + \frac{4}{\pi}\frac{\lambda_F}{\lambda_a}}\right]$$

$$X_F = (131)\left[1 - \frac{\frac{(71)}{(74)}}{2(73) + \frac{4}{\pi}\frac{(160)}{(160)}}\right]$$

Where: $\lambda_a = \frac{6.38(d)}{P(g_e')} = \frac{6.38(11)}{(6)\ (160)}$

$$\lambda_F = \frac{P_e}{P(\ell)} = \frac{(160a)}{(6)(13)}$$

$$g'_e = (g_e)\left[\frac{2(F_g) + (F_{g2}) + (F_{g3})}{2(F_g)}\right]$$

$$= (69)\left[\frac{2(96) + (123) + (120)}{2(96)}\right]$$

(160a)	P_e	$$P_e = \frac{\phi_{g2} \text{ @ NL}}{(I_{fNL})(N_F) \text{ @ NL}}$$ $$P_e = \frac{(108)}{(127a)(146)}$$
(161)	L_F	FIELD INDUCTANCE $$L_F = (N_F)^2 \, P_e \, 10^{-8}$$ $$= (146)^2 \, (160a) \times 10^{-8}$$
(161a)	λ_F	SPECIFIC PERMEANCE OF FIELD $$\lambda_F = P_1 + P_2 + P_3 + P_4 + P_5$$ $$= (80) + (81) + (82) + (83) + (84)$$

(166)	X'_{du}	UNSATURATED TRANSIENT REACTANCE

$$X'_{du} = (X_\ell) + (X'_f) = (130) + (160)$$

(167)	X'_d	SATURATED TRANSIENT REACTANCE

$$X'_d = .88(X'_{du}) = .88(166)$$

(168)	X''_d	SUBTRANSIENT REACTANCE in direct axis

$$X''_d = (X'_d) = (167)$$

(169)	X''_q	SUBTRANSIENT REACTANCE in quadrature axis

$$X''_q = (X_q) = (134)$$

(170)	X_2	NEGATIVE SEQUENCE REACTANCE - The reactance due to the field which rotates at synchronous speed in a direction opposite to that of the rotor.

$$X_2 = .5\left[X''_d + X''_q\right] = .5\left[(168) + (169)\right]$$

(172)	X_0	ZERO SEQUENCE REACTANCE - The reactance drop across any one phase (star connected) for unit current in eac of the phases. The machine must be star connected for otherwise no zero sequence current can flow and the term then has no significance.

If (28) = 0, then $X_0 = 0$

If (28) $\neq$ 0, then

$$X_o = X\left\{\frac{(K_{xo})}{(K_{x1})}\left[(\lambda_i) + (\lambda_{Bo})\right] + \frac{1.667\left[(h_1) + 3(h_3)\right]}{(m)(q)(K_p)^2(K_d)^2(b_s)} + .2(\lambda_E)\right.$$

$$= (79)\left\{\frac{(173)}{(174)}\left[(62) + (123c)\right] + \frac{1.667\left[(22) + 3(22)\right]}{(5)(25)(44)^2(43)^2(22)}\right.$$

(173) | K_{xo}

If (30) = 1 Then $K_{xo} = 1$

If (30) ≠ 1 Then $K_{xo} = \frac{3(\gamma)}{(m)(q)} - 2$

$$= \frac{3(31)}{(5)(25)} - 2$$

(174) | K_{x1}

If (30) = 1 Then $K_{x1} = 1$

If (30) ≠ 1 Then:

$$K_{x1} = \left[\frac{3(\gamma)}{4(m)(q)} + \frac{1}{4}\right] = \left[\frac{3(31)}{4(5)(25)} + \frac{1}{4}\right] \quad \text{If } (31a) \geq .667$$

$$K_{x1} = \left[\frac{3(\gamma)}{4(m)(q)} - \frac{1}{4}\right] = \left[\frac{3(31)}{4(5)(25)} - \frac{1}{4}\right] \quad \text{If } (31a) < .667$$

(175) | λ_{Bo}

$$\lambda_{Bo} = \frac{(K_{xo})}{(K_p)^2}\left[.07(\lambda_a)\right] = \frac{(173)}{(44)^2}\left[.07(175)\right]$$

WHERE $\lambda_a = \frac{6.38(d)}{P(g_e)} = \frac{6.38(10a)}{(6)(69)}$

(176) | T'_{do}

<u>OPEN CIRCUIT TIME CONSTANT</u> - The time constant of the field winding with the stator open circuited and with negligible external resistance and inductance in the field circuit. Field Resistance at room temperature (20^oC) is used in this calculation.

$$T'_{do} = \frac{L_F}{R_F} = \frac{(161)}{(154)}$$

(177) T_a — **ARMATURE TIME CONSTANT** - Time constant of the D.C. component. In this calculation stator resistance at room temperature (20°C) is used.

$$T_a = \frac{X_2}{200\pi(f)(r_a)} = \frac{(170)}{200\pi(5a)(177)}$$

Where $r_a = \frac{(m)(I_{PH})^2(R_{SPH\ cold})}{\text{Rated KVA} \times 10^3} = \frac{(5)(8)^2(53)}{(2)\times 10^3}$

(178) T'_d — **TRANSIENT TIME CONSTANT** - The time constant of the transient reactance component of the alternating wave.

$$T'_d = \frac{(X'_d)}{(X_d)}(T'_{do}) = \frac{(167)}{(133)}(176)$$

(179) T''_d — **SUBTRANSIENT TIME CONSTANT** - The time constant of the subtransient component of the alternating wave. This value has been determined empirically from tests on large machines. Use following values:

$T''_d = .035$ second at 60 cycle

$T''_d = .005$ second at 400 cycle

(180) F_{SC} — **SHORT CIRCUIT AMPERE TURNS** - The field ampere turns required to circulate rated stator current when the stator is short circuited.

$$F_{SC} = (X_d)(F_g) = (133)(96)$$

(181)	SCR	**SHORT CIRCUIT RATIO** - The ratio of the field current to produce rated voltage on open circuit to the field current required to produce rated current on short circuit. Since the voltage regulation depends on the leakage reactance and the armature reaction, it is closely related to the current which the machine produces under short circuit conditions and, therefore, is directly related to the SCR. $SCR = (F_{NL})/(F_{SC}) = (127)/(180)$
(182)	I^2R_F	**FIELD I^2R** - at no load. The copper loss in the field winding is calculated with cold field resistance at 20°C for no load condition. Field $I^2R = (I_{FNL})^2\ (R_{f\ cold}) = (127a)^2\ (154)$
(183)	F&W	**FRICTION & WINDAGE LOSS** - For this calculation use the information given in the Rotor Friction Analysis part of The Thermal Study of Section C.

(184) W_{TNL} STATOR TEETH LOSS - at no load. The no load loss (W_{TNL}) consists of eddy current and hysteresis losses in the iron. For a given frequency the no load tooth loss will vary as the square of the flux density.

$$W_{TNL} = .453(b_{tm})(Q)(\ell_s)(h_s)(K_Q)$$

$$= .453(57)(23)(17)(22)(184)$$

$$\text{Where } K_Q = (k)\left[\frac{(B_t)}{(B)}\right]^2 = (19)\left[\frac{(91)}{(20)}\right]^2$$

(185) W_c STATOR CORE LOSS - The stator core losses are due to eddy currents and hysteresis and do not change under load conditions. For a given frequency the core loss will vary as the square of the flux density (B_c).

$$W_c = \left[\pi\, d_{\cdot\cdot}\right](h_c)(\ell_s)(K_Q)$$

$$= \left[\pi(10a)\right](24)(17)(185)$$

$$\text{Where } K_Q = (k)\left[\frac{(B_c)}{(B)}\right]^2 = (19)\left[\frac{(94)}{(20)}\right]^2$$

(186) W_{NPL} POLE FACE LOSS - at no load. The pole surface losses are due to slot ripple caused by the stator slots. They depend upon the width of the stator slot opening, the air gap, and the stator slot ripple frequency. The no load pole face loss (W_{PNL}) can be obtained from Graph 2. Graph 2 is plotted on the bases of open

slots. In order to apply this curve to partially open slots, substitute b_o for b_s. For a better understanding of Graph 2, use the following sample:

K_1 as given on Graph 2 is derived empirically and depends on lamination material and thickness. Those values given on Graph 2 have been used with success. K_1 is an input and must be specified. See Item (187) for values of K_1.

K_2 is shown as being plotted as a function of $(B_G)^{2.5}$ Also note that upper scale is to be used. Another note in the lower right hand corner of graph indicates that for a solid line (_______), the factor is read from the left scale, and for a broken or dashed line (_____ _ _____ _), the right scale should be read. For example, find K_2 when B_G = 30 kilolines. First locate 30 on upper scale. Read down to the intersection of solid line plot of $K_2 = f(B_G)^{2.5}$. At this intersection read the left scale for K_2. $K_2 = .28$. Also refer to Item (188) for K_2 calculations.

K_3 is shown as a solid line plot as a function of $(F_{SLT})^{1.65}$. The note on this plot indicates that the upper scale X 10 should be used. Note F_{SLT} = slot frequency. For an example, find K_3 when F_{SLT} = 1000. Use upper scale X 10 to locate 1000. Read down to intersection of solid line plot of $K_3 = f(F_{SLT})^{1.65}$. At this intersection read the left scale for K_3. $K_3 = 1.35$. Also refer to Item (189) for K_3 calculations.

For K_4 use same procedure as outlined above except use lower scale. Do not confuse the dashed line in this plot with the note to use the right scale. The note does not apply in this case. Read left scale. Also refer to Item (190) for K_4 calculations.

For K_5 use bottom scale and substitute b_o for b_s when using partially closed slot. Read left scale when using solid plot. Use right scale when using dashed plot. Also refer to Item (191) for K_5 calculations.

For K_6 use the scale attached for C_1 and read K_6 from left scale. Also refer to Item (192) for K_6 calculations.

The above factors (K_2), (K_3), (K_4), (K_5), (K_6) can also be calculated as shown in (188), (189), (190), (191), (192) respectively.

$$W_{PNL} = \pi(d)(\ell)(K_1)(K_2)(K_3)(K_4)(K_5)(K_6)$$

$$= \pi(11)(13)(187)(188)(189)(190)(191)(192)$$

(187) | K_1 | K_1 is derived empirically and depends on lamination material and thickness. The values used successfully for K_1 are shown on Graph 2. They are:

K_1 = 1.17 for .028 lam thickness, low carbon steel

= 1.75 for .063 lam thickness, low carbon steel

= 3.5 for .125 lam thickness, low carbon steel

= 7.0 for solid core

K_1 is an input and must be specified on input sheet.

(188) K_2 — K_2 can be obtained from Graph 2 (see Item (186) for explanation of Graph 2) or it can be calculated as follows:

$$K_2 = f(B_G) = 6.1 \times 10^{-5} (B_G)^{2.5}$$

$$= 6.1 \times 10^{-5} (95)^{2.5}$$

(189) K_3 — K_3 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

$$K_3 = f(F_{SLT}) = 1.5147 \times 10^{-5} (F_{SLT})^{1.65}$$

$$= 1.5147 \times 10^{-5} (189)^{1.65}$$

Where $F_{SLT} = \frac{(RPM)}{60} (Q)$

$$= \frac{(7)}{60} (23)$$

(190) K_4 — K_4 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

For $\gamma_s \leq .9$

$$K_4 = f(\gamma_s) = .81(\gamma_s)^{1.285}$$

$$= .81(26)^{1.285}$$

For $.9 \leqq \tau_s \leqq 2.0$

$K_4 = f(\tau_s) = .79(\tau_s)^{1.145}$

$= .79(26)^{1.145}$

For $\tau_s > 2.0$

$K_4 = f(\tau_s) = .92(\tau_s)^{.79}$

$= .92(26)^{.79}$

(191)	K_5	K_5 can be obtained from Graph 2 (see item 186 for explanation of Graph 2) or it can be calculated as follows:

For $(b_s)/(g) = 1.7$

$K_5 = f(b_s/g) = .3 \left[(b_s)/(g)\right]^{2.31}$

$= .3 \left[(22)/(59)\right]^{2.31}$

NOTE: For partially open slots substitute b_o for b_s in equations shown.

For $1.7 < (b_s)/(g) \leqq 3$

$K_5 = f(b_s)/(g) = .35 \left[(b_s)/(g)\right]^{2}$

$= .35 \left[(22)/(59)\right]^{2}$

For $3 < (b_s)/(g) \leqq 5$

$K_5 = f(b_s)/(g) = .625 \left[(b_s)/(g)\right]^{1.4}$

$= .625 \left[(22)/(59)\right]^{1.4}$

For $(b_s)/(g) > 5$

$$K_5 = f\ (b_s)\ /(g) = 1.38\left[(b_s)\ /\ (g)\right]^{.965}$$

$$= 1.38\left[(22)/(59)\right]^{.965}$$

(192) | K_6 | K_6 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

$$K_6 = f(C_1) = 10\left[.9323(C_1) - 1.60596\right]$$

$$= 10\left[.9323(71) - 1.60596\right]$$

(194) | I^2R | <u>STATOR I^2R</u> - at no load. This item = 0. Refer to Item (245) for 100% load stator I^2R.

(195) | -- | <u>EDDY LOSS</u> - at no load. This item = 0. Refer to Item (246) for 100% load eddy loss.

(196) | -- | <u>TOTAL LOSSES</u> - at no load. Sum of all losses.

Total losses = (Field I^2R) + (F&W) + (Stator Teeth Loss) + (Stator Core Loss) + (Pole Face Loss)

= (182) + (183) + (184) + (185) + (186)

NOTE: The output sheet shows the next items to be: (Rating), (Rating + Losses), (% Losses), (% Efficiency). These items do not apply to the no load calculation since the rating is zero. Refer to Items (248), (249), (250), (251) for these calculations under load.

The no load calculations should all be repeated now for 100% load.

(196a) $\phi_{\ell\ell}$ ROTOR **LEAKAGE FLUX PER POLE** at 100% load

$$\phi_{\ell\ell} = \phi_{\ell}\left\{\frac{(e_d)(F_g) + \left[1 + \cos(\theta)\right](F_T) + (F_C)}{(F_g) + (F_T) + (F_C)}\right\}$$

$$= (100)\left\{\frac{(198)(96) + \left[1 + \cos(198a)\right](97) + (98)}{(96) + (97) + (98)}\right.$$

(198) e_d Where $e_d = \cos\epsilon + (X_d)\sin\Psi$

$$= \cos(198a) + (83)\sin(198b)$$

(198a) θ Where $\theta = \cos^{-1}\left[(\text{Power Factor})\right]$

$$= \cos^{-1}\left[(9)\right]$$

Where $\Psi = \tan^{-1}\left[\frac{\sin(\theta) + (X_q)/(100)}{\cos(\theta)}\right]$

$$= \tan^{-1}\left[\frac{\sin(198a) + (134)/(100)}{\cos(198a)}\right]$$

Where $\epsilon = \Psi - \theta = (198a) - (198a)$

(207) ϕ_{7L} **STATOR TO ROTOR FLUX LEAKAGE** at full load

$$\phi_{7L} = \frac{P_7\left[2(F_C) + 2(F_T)\left[1 + \cos(\theta)\right] + (F_{g2L}) + (F_{g3L}) + (F_{p0L}) + (F_{piL})\right]}{2} \times 10^{-3}$$

$$= \frac{(86)\left[2(98) + 2(97)\left[(1 + \cos(198a)\right] + (225) + (231) + (222a) + (222c)\right]}{2} \times 10^{-3}$$

(213) ϕ_{PL} **FLUX PER POLE** at 100% load

For P. F. 0 to .95

$$\phi_{PL} = (\phi_P)\left[(e_d) - \frac{.93(X_{ad})}{100}\sin(\Psi)\right]$$

$$= (92)\left[(198) - \frac{.93(131)}{100}\sin(198a)\right]$$

For P.F. .95 to 1.0

$$\phi_{PL} = (\phi_P)(K_c) = (92)(9a)$$

(213a) ϕ_{PTL} TOTAL FLUX PER POLE at 100% load

$$\phi_{PTL} = \phi_{PL} + \frac{\phi_{ll}}{P} = (213) + \frac{(196a)}{(6)}$$

(221) ϕ_{g2L} AUXILIARY GAP (g_2) FLUX

$$\phi_{g2L} = (\phi_{g3L}) = (\phi_{rL}) = (\phi_{shL}) = (\phi_{pL})\frac{P}{2} + (\phi_{7L})$$

$$= (213)\frac{(6)}{2} + (207)$$

(222) B_{poL} FLUX DENSITY IN OUTER POLE at full load

$$B_{po} = \frac{\phi_{PTL}}{A_{po}} = \frac{(213a)}{(79)}$$

(222a) F_{poL} AMPERE TURN DROP THROUGH OUTER POLE at full load

$F_{poL} = (\ell_{po})$ [NI/inch at density (B_{poL})]

$= (104)$ [Look up on pole magnetization curve at density (222)]

(222b) B_{piL} FLUX DENSITY IN INNER POLE at full load

$$B_{piL} = \frac{\phi_{PTL}}{A_{pi}} = \frac{(213a)}{(79a)}$$

(222c)	F_{piL}	<u>AMPERE TURN DROP THROUGH INNER POLE</u> at full load
		$F_{piL} = \ell_{pi} \left[\text{NI/inch at density } (B_{piL}) \right]$
		$= (104b) \left[\begin{array}{l} \text{Look up on pole magnetization curve at} \\ \text{density (222b)} \end{array} \right]$
(222d)	B_{rL}	<u>FLUX DENSITY IN ROTATING OUTER RING</u> at no load
		$B_{rL} = \frac{\phi_{rL}}{A_r} = \frac{(221)}{(104d)}$
(222e)	F_{rL}	<u>AMPERE TURN DROP IN RING</u> at full load
		$F_{rL} = (\ell_r) \left[\text{NI/inch at density } (B_r) \right]$
		$= (104e) \left[\begin{array}{l} \text{Look up on ring magnetization curve at} \\ \text{density (222d)} \end{array} \right]$
(224)	B_{g2L}	<u>FLUX DENSITY IN AUXILIARY GAP</u> under load
		$B_{g2L} = \frac{\phi_{g2L}}{A_{g2}} = \frac{(221)}{(70)}$
(225)	F_{g2L}	<u>AMPERE TURN DROP IN AUXILIARY GAP (g_2)</u>
		$F_{g2L} = \frac{(B_{g2L})}{3.19} (g_2) \times 10^3$
		$= \frac{(224)}{3.19} (59a) \times 10^3$

(226) ϕ_{5L} LEAKAGE ACROSS FIELD COIL

$$\phi_{5L} = P_5 \left[2(F_c)+2(F_T)\left[1+\cos(\theta)\right](F_{g2L})+(F_{g3})+(F_{poL})+(F_{piL}) +(F_{rL})+(F_{shL})+(F_{yL})\right] \times 10^{-3}$$

$$= (84)\left[2(98)+2(97)\left[1+\cos(198a)\right]+(225)+(231)+(222a)+(222c) +(222e)+(233)+(229c)\right] \times 10^{-3}$$

(229a) ϕ_{yL} FLUX IN YOKE BACK OF COIL at full load

(229b) B_{yL} FLUX DENSITY IN YOKE BACK OF COIL at full load

$$B_y = \frac{(\phi_{yL})}{(A_y)} = \frac{(229a)}{(126b)}$$

(229c) F_{yL} AMPERE TURN DROP IN YOKE at full load

$$F_{yL} = l_y \left[\text{NI/inch at density } (B_{yL})\right]$$

$$= (123c)\left[\begin{array}{l}\text{Look up on yoke magnetization curve}\\ \text{at density (229b)}\end{array}\right]$$

(230) B_{g3L} GAP DENSITY IN AUXILIARY GAP (g_3) at full load

$$B_{g3L} = \frac{(\phi_{g3L})}{(A_{g3})} = \frac{(221)}{(70a)}$$

(231) F_{g3L} AMPERE TURN DROP ACROSS GAP at full load

$$F_{g3} = \frac{(B_{g3L})}{3.19}(g_3) \times 10^3$$

$$= \frac{(230)}{3.19}(59c) \times 10^3$$

(232)	B_{shL}	SHAFT DENSITY at full load $$B_{shL} = \frac{(\emptyset shL)}{(A_{sh})} = \frac{(221)}{(112)}$$
(233)	F_{shL}	SHAFT AMPERE TURN DROP $$F_{shL} = (\ell_{sh}) \left[\text{NI/inch at density } (B_{sh}) \right]$$ $$= (114) \left[\begin{array}{l} \text{Look up on shaft magnetization curve} \\ \text{at density (232)} \end{array} \right]$$
(236)	F_{FL}	TOTAL AMPERE TURNS at full load $$F_{FL} = 2(F_c)+2(F_T)\left[1+\cos(\theta)\right] +(F_{g2L})+(F_{g3L})+(F_{poL})+(F_{piL}) +(F_{rL})+(F_{shL})+(F_{yL})$$ $$= 2(98)+2(97)\left[1+\cos(198a)\right]+(225)+(231)+(222a)+(222c) +(222e)+(233)+(229c)$$

(237)	I_{FFL}	FIELD CURRENT at 100% load $I_{FFL} = (F_{FL})/(N_F) = (236)/(146)$
(239)	--	CURRENT DENSITY at 100% load Current Density = $(I_{FFL})/(a_{cf}) = (237)/(153)$
(238)	E_{FFL}	FIELD VOLTS at 100% load - This calculation is made with ho field resistance at expected temperature at 100% load. Field Volts = $(I_{FFL})(R_{f\ hot}) = (237)(155)$
(241)	I^2R_{FL}	FIELD I^2R at 100% load - The copper loss in the field winding is calculated with hot field resistance at expected temperature for 100% load condition. Field $I^2R = (I_{FFL})^2(R_{f\ hot}) = (237)^2(155)$
(242)	W_{TFL}	STATOR TEETH LOSS at 100% load - The stator tooth loss under load increases over that of no load because of the parasitic fluxes caused by the ripple due to the rotor damper bar slot openings. $W_{TFL} = \left\{ 2 \left[.27 \left(\frac{X_d}{100}\right) \frac{(\%\ Load)}{100} \right]^{1.8} + 1 \right\} (W_{TNL})$ $= \left\{ 2 \left[.27 \left(\frac{133}{100}\right) 1 \right]^{1.8} + 1 \right\} (148)$

(243) W_{PFL} **POLE FACE LOSS** at 100% load

$$W_{PFL} = \left\{ \left[\frac{(K_{sc})(I_{PH}) \frac{(\%\ Load)}{100} (n_s)}{(C)(F_g)} \right]^2 + 1 \right\} (W_{PNL})$$

$$= \left\{ \left[\frac{(243)(8)\ 1\ (30)}{(32)(96)} \right]^2 + 1 \right\} (186)$$

(K_{sc}) is obtained from Graph 3

(245) I^2R_L **STATOR I^2R** at 100% load - The copper loss based on the D.C resistance of the winding. Calculate at the maximum expected operating temperature.

$$I^2R = (m)(I_{PH})^2\ (R_{SPH}\ hot) \frac{(\%\ Load)}{100}$$

$$= (5)(8)^2\ (54)\ 1$$

(246) -- **EDDY LOSS** - Stator I^2R loss due to skin effect

$$\text{Eddy Loss} = \left[\frac{(EF\ top) + (EF\ bot)}{2} - 1 \right] (\text{Stator } I^2R)$$

$$= \left[\frac{(55) + (56)}{2} - 1 \right] (245)$$

(247) -- **TOTAL LOSSES** at 100% load - sum of all losses at 100% load

Total Losses = (Field I^2R) + (F&W) + (Stator Teeth Loss)
+ (Stator Core Loss) + (Pole Face Loss)
+ (Stator I^2R) + (Eddy Loss)

= (241) + (183) + (242) + (185) + (243) + (245) + (246)

(248) -- **RATING IN KILOWATTS** at 100% load

$$\text{Rating} = 3(E_{PH})(I_{PH}) \times (\text{P.F.}) \times 10^{-3}$$

$$= 3(4)(8) \times (9) \times 10^{-3}$$

(249) -- **RATING PLUS LOSSES** $= (248) + (247) \times 10^{-3}$

(250) -- **% LOSSES** $= \dfrac{\text{Losses} \times (100) \times 10^{-3}}{\text{Rating Plus Losses}}$

$$= \frac{(247) \times 10^{-3} \times 10^{2}}{(249)}$$

(251) -- **% EFFICIENCY** = 100% - % Losses

= 100% - (250)

These items can be recalculated for any load condition by simply inserting the values that correspond to the % load being calculated.

Values for F&W (183) and W_C (Stator Core Loss) (185) do not change with load.

DESIGN MANUAL FOR
HOMOPOLAR INDUCTOR A-C GENERATOR

SECTION P

INPUT AUXILIARY DATA SHEET

Auxiliary information taken from the design manuals to be used in conjunction with input sheets for convenience.

A. All dimensions for lengths, widths, and diameters are to be given in inches.

B. Resistivity inputs, Items (141) and (151) are to be given in micro-ohm-inches.

The following items along with an explanation of each are tabulated here for convenience. For complete explanation of each item number, refer to design manuals.

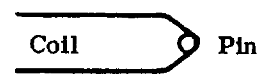
Item No.	Explanation
(9)	Power factor to be given in per unit. For example for 90% P.F., insert .90.
(9a)	Adjustment Factor - For P.F. $<$ .95 insert 1.0 For P.F. $>$ .95 insert 1.05
(10)	Optional Load Point -- Where load data output is required at a point other than those given as standard on the input sheet. Example: For load data output at 155% load, insert 1.55.
(14)	Number of radial ducts in stator.
(15)	Width of radial ducts used in Item (14).
(18)	Magnetization curve of material used to be submitted as defined in Item (18).
(19)	Watts/Lb. to be taken from a core loss curve at the density given in Item (20) (Stator).
(20)	Density in kilolines/in^2. This value must correspond to density used to pick Item (19) usually use 77.4 KL/in^2.
(21)	Type of slot - For open slot Type A, insert 1.0. For partially open slot Type B with constant slot width, insert 2.0. For partially open slot Type C with constant tooth width, insert 3.0. For round slot Type D, insert 4.0. For additional information, refer to figure adjacent to input sheet which shows a picture of each slot.
(22)	For stator slot dimension - for dimensions that do not apply to the slot insert 0.0. Use Table below as guide for input.

Symbol	Item	Slot Type 1	2	3	4
b_o	(22)	0.0	*	*	*
b_1	↓	0.0	0.0	*	0.0
b_2		0.0	0.0	*	0.0
b_3		0.0	0.0	*	0.0
b_s		*	*	φ	*
h_o		0.0	*	*	*
h_1		*	*	*	0.0
h_2		*	0.0	0.0	0.0
h_3		*	*	0.0	0.0
h_s		*	*	*	*
h_t		0.0	*	*	0.0
h_w	↓	0.0	*	*	0.0

* = insert actual value.

$$\varphi = b_s = \frac{b_1 + b_3}{2}$$

Item No.	Explanation
(28)	Type of winding - for wye connected winding insert 1.0.
	for delta connected winding insert 0.0.
(29)	Type of coil - for formed wound (rect. wire), insert 1.0.
	for random wound (round wire) insert 0.0.
(30)	Slots spanned - Example - for slot span of 1-10, insert 9.0.
(33)	For round wire insert diameter. For rectangular wire insert wire width.
(34)	Strands per conductor in depth only.
(34a)	Total strands per conductor in depth and width.
(35)	Diameter of coil head forming pin. Insert .25 for stator O.D. $<$ 8 inches;
	Insert .50 for stator O.D. $>$ 8 in.
(37)	Use vertical height of strand for round wire, insert 0.0.
(38)	Distance between centerline of strands in depth.
(39)	Stator strand thickness -- use narrowest dimension of the two dimensions given for a rectangular wire. For round wire insert 0.0.
(40)	Stator slot skew in inches.
(42a)	Phase belt angle - for 60° phase belt, insert 60°.
	for 120° phase belt, insert 120°.
(48)	See explanation of items (71), (72), (73), (74) and (75). Same applies here.
(87)	When no load saturation output data is required at various voltages, insert 1.0.
	When no load saturation information is not required, insert 0.0.
(137)	Damper bar thickness -- use damper bar slot height for rectangular bar. For round bar insert 0.0.
(138)	Number of damper bars per pole.
(140)	Damper bar pitch in inches.
(148)	For round wire insert diameter. For rectangular wire insert wire width.
(149)	For rectangular wire insert wire thickness. For round wire insert 0.0.
(187)	Pole face loss factor. For rotor lamination thickness .028 in. or less, insert 1.17.
	For rotor lamination thickness .029 in. to .063 in. insert 1.75.
	For rotor lamination thickness .064 in. to .125 insert 3.5.
	For solid rotor insert 7.0.
(71) (72) (73) (74) (75)	If the values of these constants are available, insert the actual number. If they are not available, insert 0.0 and the computer will calculate the values and record them on the output.



HOMOPOLAR COMPUTER DESIGN (INPUT)

MODEL ______________________ EWO ______________ DESIGN NO(1) ______________

PARAMETERS	(2)	KVA	GENERATOR KVA	
	(3)	E	LINE VOLTS	
	(4)	E_{ph}	PHASE VOLTS	
	(5)	m	PHASES	
	(5a)	f	FREQUENCY	
	(6)	p	POLES	
	(7)	RPM	RPM	
	(8)	I_{ph}	PHASE CURRENT	
	(9)	PF	POWER FACTOR	
	(9a)	K_c	ADJ. FACTOR	
	(10)		OPTIONAL LOAD POINT	
STATOR STACK	(11)	d	STATOR I.D.	
	(12)	D	STATOR O.D.	
	(13)	ℓ	GROSS CORE LENGTH	
	(14)	n_v	NO. OF DUCTS	
	(15)	b_v	WIDTH OF DUCT	
	(16)	K_i	STACKING FACTOR (STATOR)	
	(19)	k	WATTS/LB.	
	(20)	B	DENSITY	
STATOR SLOT	(21)		TYPE OF SLOT	
	(22)	b_o	SLOT OPENING	
	(22)	b_1	SLOT WIDTH TOP	
	(22)	b_2		
	(22)	b_3		
	(22)	b_s	SLOT WIDTH	
	(22)	h_o		
	(22)	h_1		
	(22)	h_2		
	(22)	h_3		
	(22)	h_s	SLOT DEPTH	
	(22)	h_t		
	(22)	h_w		
	(23)	Q	NO. OF SLOTS	
STATOR WINDING	(28)		TYPE OF WDG.	
	(29)		TYPE OF COIL	
	(30)	n_s	CONDUCTORS/SLOT	
	(31)	y	SLOTS SPANNED	
	(32)	c	PARALLEL CIRCUITS	
	(33)		STRAND DIA. OR WIDTH	
	(34)	N	STRANDS/CONDUCTOR	
	(34a)	N'_{st}	STRANDS/CONDUCTOR	
	(39)		STATOR STRAND T'KNS	
	(35)	d_p	DIA. OF PIN	
	(36)	ℓ_{e2}	COIL EXT. STR. PORT	
	(37)	h_{st}	UNINS. STRD. HT.	
	(38)	h'_{st}	DIST. BTWN. CL OF STD.	
	(42a)		PHASE BELT/ANGLE	
	(40)	τ_{sk}	STATOR SLOT SKEW	
	(50)	X_s °C	STATOR TEMP °C	
	(51)	ρ_s	RES'TVY STA. COND. @ 20° C	
GAP	(59)	g_{min}	MINIMUM AIR GAP	
	(59a)	g_{max}	MAXIMUM AIR GAP	

	FUND/MAX OF FIELD FLUX	(71)	C_1	CONSTANTS
	WINDING CONSTANT	(72)	C_w	
	POLE CONST.	(73)	C_p	
	END EXTENSION ONE TURN	(48)	LE	
	DEMAGNETIZATION FACTOR	(74)	C_m	
	CROSS MAGNETIZING FACTOR	(75)	C_q	
	POLE WIDTH	(76)	b_p	ROTOR STACK
	POLE LENGTH	(76)	ℓ_p	
	POLE HEIGHT	(76)	h_p	
	POLE HEIGHT (EFFECTIVE)	(76)	h'_p	
	POLE EMBRACE	(77)	α	
	ROTOR DIAMETER	(11a)	d_r	
	STACKING FACTOR (ROTOR)	(16)	K_i	
	WEIGHT OF ROTOR IRON	(157)	(-)	
	POLE FACE LOSS FACTOR	(187)	(K_1)	
	WIDTH OF SLOT OPENING	(135)	b_{bo}	DAMPER BAR
	HEIGHT OF SLOT OPENING	(135)	h_{bo}	
	DAMPER BAR DIA. OR WIDTH	(136)	( )	
	RECTANGULAR BAR THICKNESS	(137)	h_{bl}	
	RECTANGULAR SLOT WIDTH	(135)	b_{bl}	
	NO. OF DAMPER BARS	(138)	n_b	
	DAMPER BAR LENGTH	(139)	ℓ_b	
	DAMPER BAR PITCH	(140)	τ_b	
	RESISTIVITY OF DAMP. BAR @ 20°	(141)	ρ_D	
	DAMPER BAR TEMP °C	(142)	X_D °C	
	SHAFT DIAMETER	(78a)	D_{sh}	SHAFT
	SHAFT I.D.	(78a)	d_{sh}	
	SHAFT EXT. DIAMETER	(78a)	d'_{sh}	
	LENGTH OF SHAFT	(78a)	ℓ_{sh}	
	TYPE OF YOKE	(78)		YOKE
	YOKE THICKNESS	(78)	t_y	
	YOKE THICKNESS	(78)	t_{ye}	
	YOKE THICKNESS	(78)	t_{yr}	
	YOKE I.D.	(78)	d_{yc}	
	FIELD COIL INSIDE DIA.	(78)	d_{coil}	FIELD
	FIELD COIL OUTSIDE DIA.	(78)	D_{coil}	
	FIELD COIL WIDTH	(78)	b_{coil}	
	NO. OF FIELD TURNS	(146a)	NF	
	MEAN LENGTH OF FLD. TURN	(147)	ℓ_{tr}	
	FLD. COND. DIA. OR WIDTH	(148)		
	FLD. COND. THICKNESS	(149)		
	FLD. TEMP IN °C	(150)	X_f °C	
	RESISTIVITY OF FLD. COND. @ 20°	(151)	ρ_f	
	NO LOAD SAT.	(87)		
	~~FRICTION & WINDAGE~~	(183)	(F&W)	
	LEAKAGE PERMEANCE	(80c)	P_m	PERMEANCE
	LEAKAGE PERMEANCE	(84a)	P_5	
	LEAKAGE PERMEANCE	(85a)	P_6	
	LEAKAGE PERMEANCE	(86a)	P_7	
	STATOR LAM MTR'L	(18)		MATR'L
	ROTOR LAM. MTR'L	(18)		
	YOKE MTR'L	(18)		

DESIGNER ______________________

DATE ______________________

REV. B

STATOR SLOT	POLE

SUMMARY OF DESIGN CALCULATIONS – HOMOPOLAR INDUCTOR (OUTPUT)

MODEL ______________________ EWO ____________ DESIGN NO. ________________

STATOR	(17) (ℓ_s)	SOLID CORE LENGTH			CARTER COEFFICIENT	(67) (K_s)	GAP
	(24) (h_c)	DEPTH BELOW SLOT			AIR GAP AREA PER STATOR	(68) (–)	
	(26) (τ_s)	SLOT PITCH			AIR GAP PERM	(70_c) (λ_a)	
	(27) (τ_s1/3)	SLOT PITCH 1/3 DIST. UP			EFFECTIVE AIR GAP	(69) (g_e)	
	(42) (K_{sk})	SKEW FACTOR			FUND/MAX OF FLD. FLUX	(71) (C_1)	CONSTANTS
	(43) (K_d)	DIST. FACTOR			WINDING CONST.	(72) (C_w)	
	(44) (K_p)	PITCH FACTOR			POLE CONST.	(73) (C_p)	
	(45) (η_e)	EFF. CONDUCTORS			END. EXT. ONE TURN	(48) (LE)	
	(46) (a_c)	COND. AREA			DEMAGNETIZING FACTOR	(74) (C_M)	
	(47) (S_s)	CURRENT DENSITY (STA.)			CROSS MAGNETIZING FACTOR	(75) (C_q)	
	(49) (ℓ_t)	1/2 MEAN TURN LENGTH			AMP COND/IN	(128) (A)	REACTANCE
	(53) (R_{ph})	COLD STA. RES. @ 20° C			REACTANCE FACTOR	(129) (X)	
	(54) (R_{sph})	HOT STA. RES @ X° C			LEAKAGE REACTANCE	(130) (X_ℓ)	
	(55) (EF_{top})	EDDY FACTOR TOP			REACTANCE OF	(131) (X_{ad})	
	(56) (EF_{bot})	EDDY FACTOR BOT			ARMATURE REACTION	(132) (X_{aq})	
	(62) (λ_1)	STATOR COND. PERM.			SYN REACT DIRECT AXIS	(133) (X_d)	
	(64) (λ_E)	END PERM.			SYN REACT QUAD AXIS	(134) (X_q)	
	(65) ( )	WT. OF STA COPPER			FIELD LEAKAGE REACT	(160) (X_f)	
	(66) ( )	WT. OF STA IRON			FIELD SELF INDUCTANCE	(161) (L_f)	
PERMEANCE	(80c) (P_m)	LEAKAGE PERMEANCE			DAMPER	(163) (X_{Dd})	
	(84a) (P_5)	LEAKAGE PERMEANCE			LEAKAGE REACT	(165) (X_{Dq})	
	(85a) (P_6)	LEAKAGE PERMEANCE			UNSAT. TRANS. REACT	(166) (X'_{du})	
	(86a) (P_7)	LEAKAGE PERMEANCE			SAT. TRANS. REACT	(167) (X'_d)	
ROTOR	(153) (a_{CF})	FLD. COND. AREA			SUB. TRANS. REACT DIRECT AX.	(168) (X''_d)	
	(154) (R_F)	COLD FLD RES @ 20° C			SUB. TRANS. REACT QUAD AX.	(169) (X''_q)	
	(155) (R_F)	HOT FLD RES @ X° C			NEG SEQUENCE REACT	(170) (X_2)	
	(156) ( )	WT. OF FLD. COPPER			ZERO SEQUENCE REACT	(172) (X_o)	
	(157) ( )	WT. OF ROTOR IRON			TOTAL FLUX	(88) (ϕ_t)	MAGNETIZATION
	(145) (V_r)	PERIPHERAL SPEED			FLUX PER POLE	(92) (ϕ_p)	
					GAP DENSITY	(95) (B_g)	
TIME CONSTANTS	(176) (T_{do})	OPEN CIR. TIME CONST.			TOOTH DENSITY	(91) (B_t)	
	(177) (T_a)	ARM TIME CONST.			CORE DENSITY	(94) (B_c)	
	(178) (T'_d)	TRANS TIME CONST.			TOOTH AMPERE TURNS	(97) (F_t)	
	(179) (T''_d)	SUB TRANS TIME CONST.			CORE AMPERE TURNS	(98) (F_c)	
	(180) (F_{sc})	SHORT CIR. NI			GAP AMPERE TURNS	(96) (F_g)	

	PERCENT LOAD	0		100	150	200	OPTIONAL
VARIABLE LOAD	(ϕ_m) (91a) LEAKAGE FLUX		ϕ_{ml} (202e)				
	(F_{gm})(96a) GAP AMPERE TURNS		F_{gl} (203)				
	(B_p) (104b) POLE DENSITY		B_{pl} (213b)				
	(B_t) (91c) TOOTH DENSITY		B_{tl} (205)				
	(B_{sh}) (113) SHAFT DENSITY		B_{shl} (215a)				
	(B_c) (94) CORE DENSITY		B_{cl} (200g)				
	(B_{yc}) (125a) COIL YOKE DENSITY		B_{ycl} (228a)				
	(F_{nl}) (127) TOTAL NI		(F_{fl}) (236)				
	(I_{fnl}) (127a) FIELD AMPS		(I_{ffl}) (237)				
	(SF) (127c) CUR.DENS.(FLD.)		(S_{fl}) (239)				
	(E_F) (127b) FIELD VOLTS		(E_{ffl}) (238)				
	(I^2R_r)(182) FIELD LOSS		(I^2R_r)(241)				
	(F&W) (183) F&W LOSS		(F&W) (183)				
	(W_{rnl}) (184) STA TOOTH LOSS		(W_{ml}) (242)				
	(W_c) (185) STA CORE LOSS		(W_c) (185)				
	(W_{pnl}) (186) POLE FACE LOSS		(W_{pfl}) (243)				
	(W_{dnl}) (193) DAMPER LOSS		(W_{dfl}) (244)				
	(I^2R_s)(194) STATOR CU LOSS		(I^2R_s) (245)				
	(–) (195) EDDY LOSS		(–) (246)				
	(–) (196) TOTAL LOSSES		(–) (247)				
	(–) (–) RATING (KW)		(–) (248)				
	(–) (–) PERCENT EFF.		(–) (251)				

 DESIGNER ______________ DATE ____________ REV. A

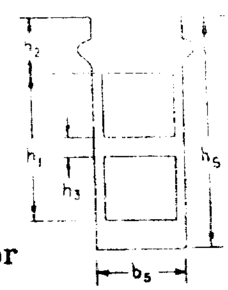
HOMOPOLAR

NO LOAD SATURATION OUTPUT SHEET

ITEMS / VOLTS	(3) (E) VOLTS (104b) (B_p) POLE DENSITY	(96a) (F_{gm}) AIR GAP A.T. (106a) (F_p) POLE A.T.	(94) (B_c) CORE DENSITY (113) (B_{SH}) SHAFT DENSITY	(98) (F_c) CORE A.T. (114) (F_{SH}) SHAFT A.T.	(91) (B_t) TOOTH DENSITY (125a) (B_{YC}) YOKE DENSITY	(97) (F_t) TOOTH A.T. (127) (F_{nl}) TOTAL A.T. (N.L.)
80%						
90%						
100%						
110%						
120%						
130%						
140%						
150%						
160%						

REV. A

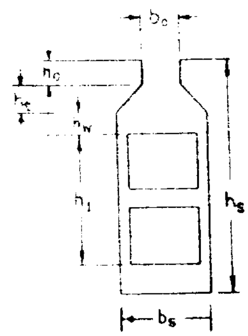
(a) Open Slots



TYPE 1

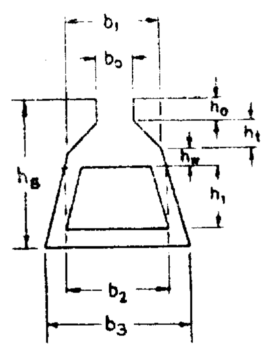
(Type 5 is an open slot with 1 conductor per slot)

(b) Constant Slot Width



TYPE 2

(c) Constant Tooth Width

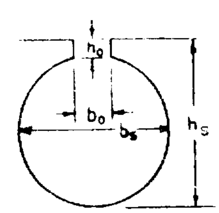


TYPE 3

b_s for type 3 is

$$b_s = \left(\frac{b_1 + b_3}{2}\right)$$

(d) Round Slots



TYPE 4

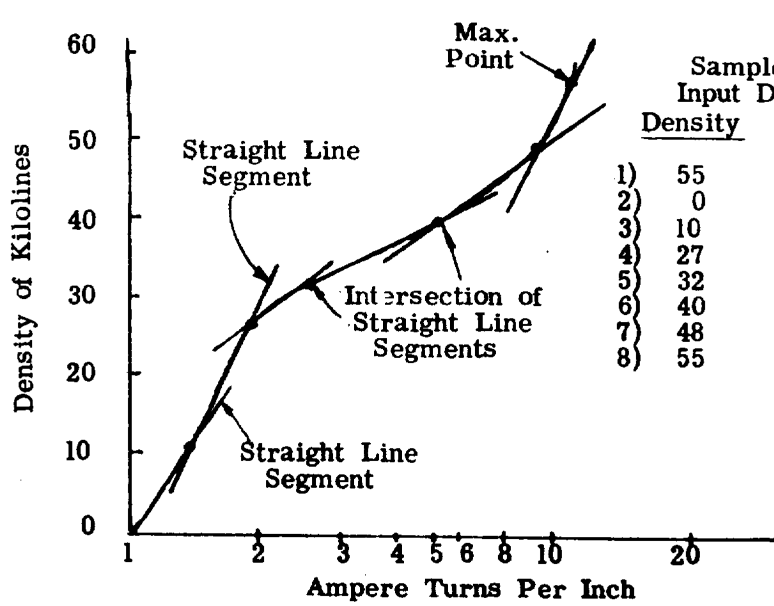
(1)	--	DESIGN NUMBER
(2)	KVA	GENERATOR KVA
(3)	E	LINE VOLTS
(4)	E_{PH}	PHASE VOLTS
(5)	m	PHASES
(5a)	f	FREQUENCY
(6)	P	POLES
(7)	RPM	SPEED
(8)	I_{PH}	PHASE CURRENT
(9)	P. F.	POWER FACTOR
(9a)	K_c	ADJUSTMENT FACTOR
(10)	--	LOAD POINTS
(11)	d	STATOR PUNCHING I.D.
(11a)	d_r	ROTOR O.D.
(12)	D	PUNCHING O.D.
(13)	ℓ	GROSS STATOR CORE LENGTH
(14)	n_v	RADIAL DUCTS
(15)	b_v	RADIAL DUCT WIDTH
(16)	K_i	STACKING FACTOR
(17)	ℓ_s	SOLID CORE LENGTH

(18) **MATERIAL** - This input is used in selecting the proper magnetization curves for stator;

yoke; pole, and shaft; when different materials are used. Separate spaces are provided on the input sheet for each section mentioned above. Where curves are available on card decks, used the proper identifying code. Where card decks are not available submit data in the following manner:

The magnetization curve must be available on semi-log paper. Typical curves are shown in this manual on Curves F15 & F16 Draw straight line segments through the curve starting with zero density. Record the coordinates of the points where the straight line segments intersect. Submit these coordinates as input data for the magnetization curve. The maximum density point must be submitted first.

Refer to Figure below for complete sample



Sample Input Data

	Density	NI
1)	55	—
2)	0	0
3)	10	1.5
4)	27	1.9
5)	32	2.5
6)	40	4.9
7)	48	9.0
8)	55	12.0

(19)	k	WATTS/LB
(20)	B	DENSITY
(21)		TYPE OF STATOR SLOT
(22)		ALL SLOT DIMENSIONS
(23)	Q	STATOR SLOTS
(24)	h_c	DEPTH BELOW SLOTS
(25)	q	SLOTS PER POLE PER PHASE
(26)	τ_s	STATOR SLOT PITCH
(27)	$\tau_s 1/3$	STATOR SLOT PITCH
(28)	--	TYPE OF WINDING
(29)	--	TYPE OF COIL
(30)	n_s	CONDUCTORS PER SLOT
(31)	γ	THROW
(31a)		PER UNIT OF POLE PITCH SPANNED
(32)	C	PARALLEL PATHS
(33)	--	STRAND DIA. OR WIDTH
(34)	N_{ST}	NUMBER OF STRANDS PER CONDUCTOR IN DEPTH
(34a)	N'_{ST}	NUMBER OF STRANDS PER CONDUCTOR
(35)	d_b	DIAMETER OF BENDER PIN
(36)	ℓ_{e2}	COIL EXTENSION BEYOND CORE
(37)	h_{ST}	HEIGHT OF UNINSULATED STRAND
(38)	h'_{ST}	DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH

(39)	--	STATOR COIL STRAND THICKNESS
(40)	τ_{SK}	SKEW
(41)	τ_P	POLE PITCH
(42)	K_{SK}	SKEW FACTOR
(42a)		PHASE BELT ANGLE
(43)	K_d	DISTRIBUTION FACTOR
(44)	K_p	PITCH FACTOR
(45)	n_e	TOTAL EFFECTIVE CONDUCTORS
(46)	a_c	CONDUCTOR AREA OF STATOR WINDING
(47)	S_S	CURRENT DENSITY
(48)	L_E	END EXTENSION LENGTH
(49)	ℓ_t	1/2 MEAN TURN PER STATOR
(50)	$X_s\ {}^oC$	STATOR TEMP ^oC
(51)	ρ_s	RESISTIVITY OF STATOR WINDING
(52)	$\rho_{s\,(hot)}$	RESISTIVITY OF STATOR WINDING
(53)	R_{SPH} (cold)	STATOR RESISTANCE/PHASE

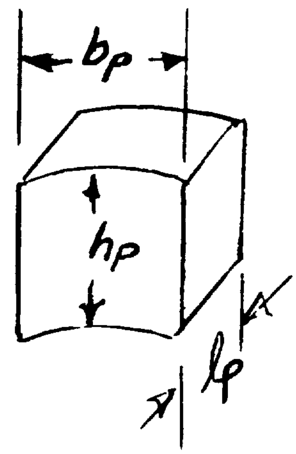
$$R_{SPH\,(cold)} = \frac{2(\rho_s)(n_s)(Q)(\ell_t) \times 10^{-6}}{(m)(a_c)(C)^2}$$

$$= \frac{2(51)(30)(23)(49) \times 10^{-6}}{(5)(46)(32)^2}$$

(54)	R_{SPH} (hot)	STATOR RESISTANCE/PHASE $$R_{SPH\,(hot)} = \frac{2(\rho_{s(hot)})(\eta_s)(Q)(\ell_t) \times 10^{-6}}{(m)(a_c)(c)^2}$$ $$= \frac{2(52)(30)(23)(49)(10^{-6})}{(5)(46)(32)^2}$$
(55)	EF (top)	EDDY FACTOR TOP
(56)	EF (bot)	EDDY FACTOR BOTTOM
(57)	b_{tm}	STATOR TOOTH WIDTH
(57a)	$b_{t\,1/3}$	STATOR TOOTH WIDTH
(58)	b_t	TOOTH WIDTH AT STATOR I.D. IN INCHES
(59)	g	MAIN AIR GAP IN INCHES
(60)	C_X	REDUCTION FACTOR
(61)	K_X	FACTOR USED IN CALCULATING (60)
(62)	λ_i	CONDUCTOR PERMEANCE
(63)	K_E	LEAKAGE REACTIVE FACTOR
(64)	λ_E	END WINDING PERMEANCE
(65)	--	WEIGHT OF COPPER
(66)	--	WEIGHT OF STATOR IRON
(67)	K_s	CARTER COEFFICIENT
(68)	A_g	MAIN AIR GAP AREA
(69)	g_e	EFFECTIVE AIR GAP

(70c)	λ_a	AIR GAP PERMEANCE
(71)	C_1	THE RATIO OF MAXIMUM FUNDAMENTAL of the field form to the actual maximum of the field form.
(72)	C_W	WINDING CONSTANT
(73)	C_P	POLE CONSTANT
(74)	C_M	DEMAGNETIZING FACTOR
(75)	C_q	CROSS MAGNETIZING FACTOR
(76)	--	**POLE DIMENSIONS LOCATIONS**

Where:



l_p length of pole (one end only)

b_p width of pole

h_p height of pole at center

h'_p effective height when rotor is tapered

all dimensions in inches

(77)	α	**POLE EMBRACE**
(77a)	--	The permeance paths for the leakage fluxes in the homopolar inductor are designated P_m, P_5, P_6, P_7 and the leakage fluxes that leak through the above permeance paths carry the same subscript.

The leakage fluxes are shown on the following schematic drawing of a homopolar inductor and also on the schematic drawing showing the mmf drops in the flux circuit.

This computer program is set up to handle the permeance calculations two ways:

1) P_m, P_5, P_6, P_7 can be calculated by the computer. For this case, insert <u>0.</u> on the input sheet.

2) P_m, P_5, P_6, P_7 can be calculated by the designer. For this case, insert the actual calculated value on the input sheet.

Permeance calculations P_1 through P_7 are all based on the equation -

$$P = \frac{\mu \text{ (area)}}{\ell}$$

where μ = 3.19

Area = cross sectional area perpendicular to flux

ℓ = length of path

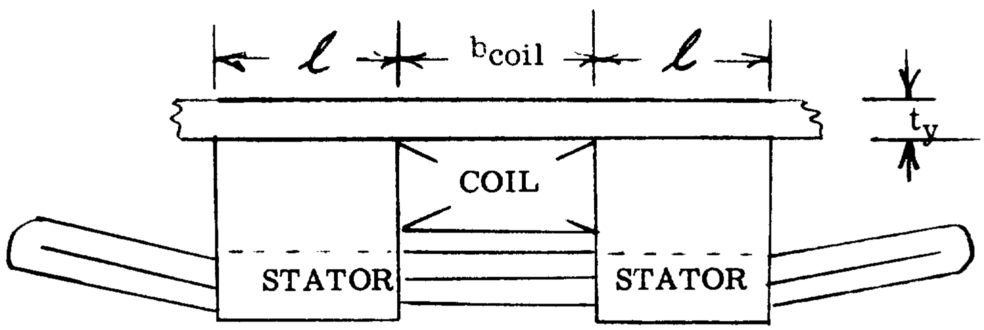
(78)

YOKE AND COIL DIMENSIONS FOR THREE TYPES OF HOMOPOLAR INDUCTOR CONSTRUCTION

There are three common types of housing or yoke construction and each must be calculated differently.

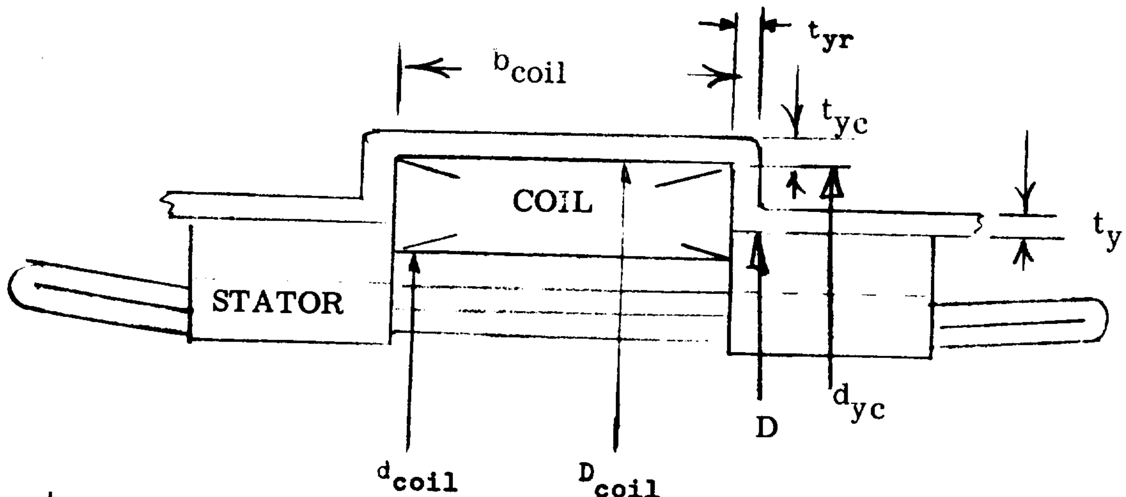
Type I

The first type of housing is straight and of uniform thickness



The coil is located axially between the stator stacks and radially between the output winding and the housing or yoke $\ell_y = (b_{coil} + 2/3\ell)$ assuming that the effective length of the yoke for the flux density calculated is 1/3 of the stack length.

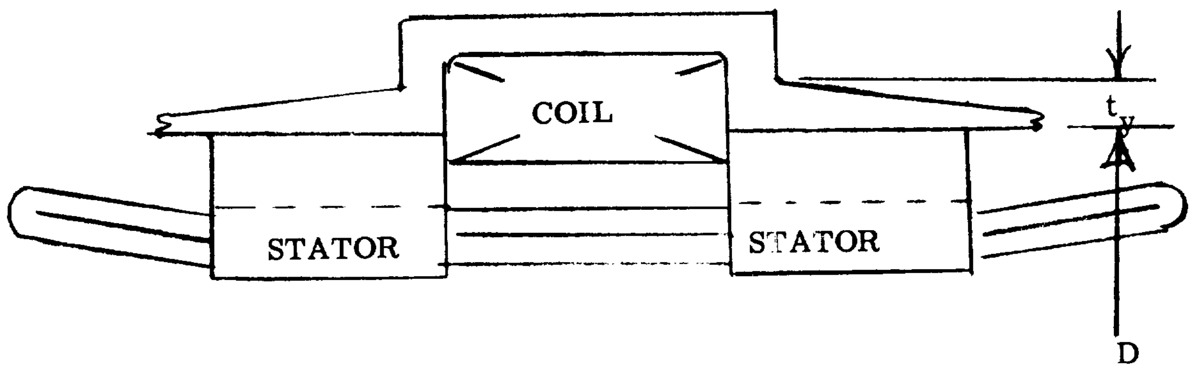
Type II



In the second type of housing, the excitation coil is so located that the housing or yoke must be jogged out to accommodate it.

Type III

In the third configuration, the housing is tapered over the stator and the yoke density is approximately uniform over most of the stator stack length. The yoke length in this case can be taken as 3/4 over each stack.



b_{coil} = coil width

t_{yr} = yoke thickness

t_{yc} = yoke thickness

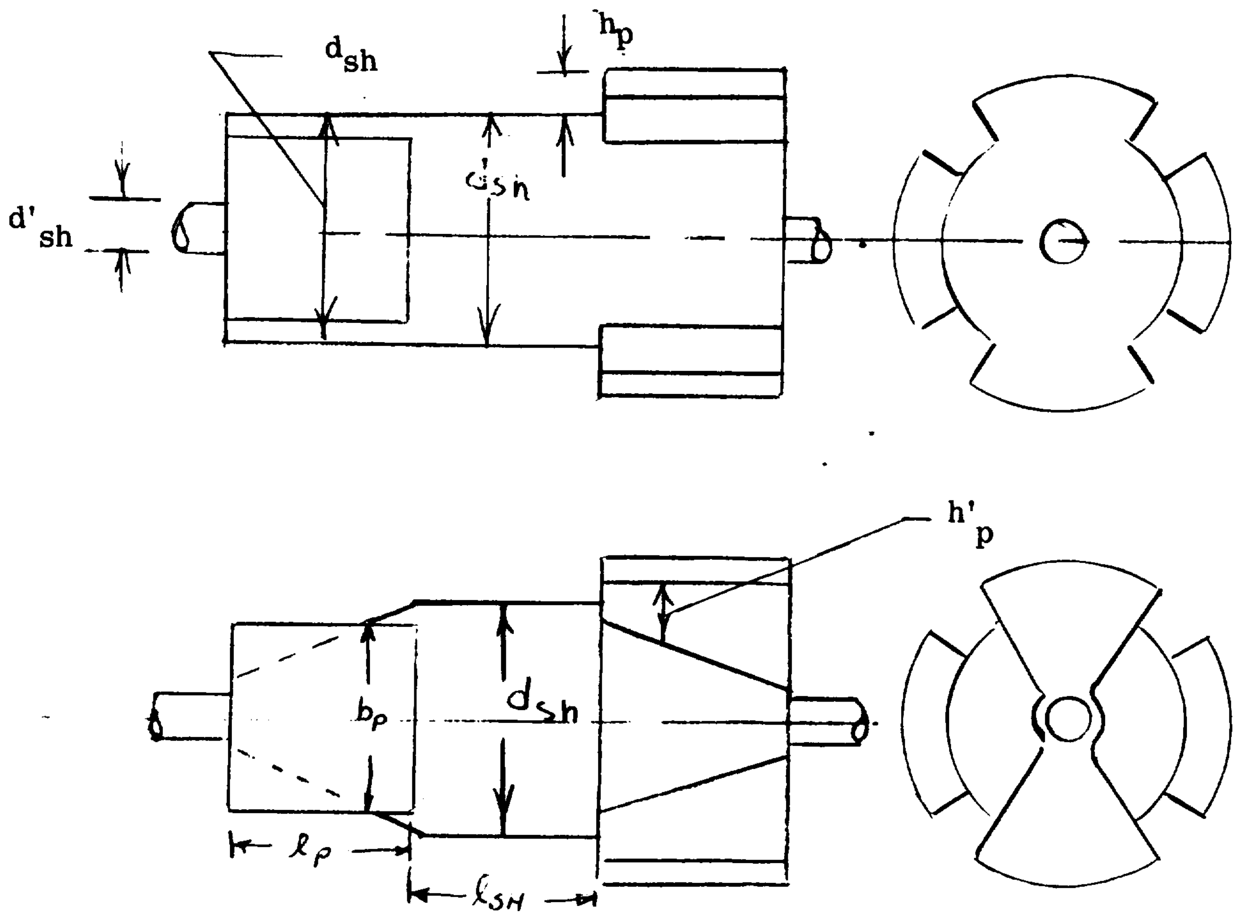
t_y = yoke thickness

d_{yc} = yoke ID

d_{coil} = field coil inside dia.

D_{coil} = field coil outside dia.

(78a) SHAFT DIMENSIONS

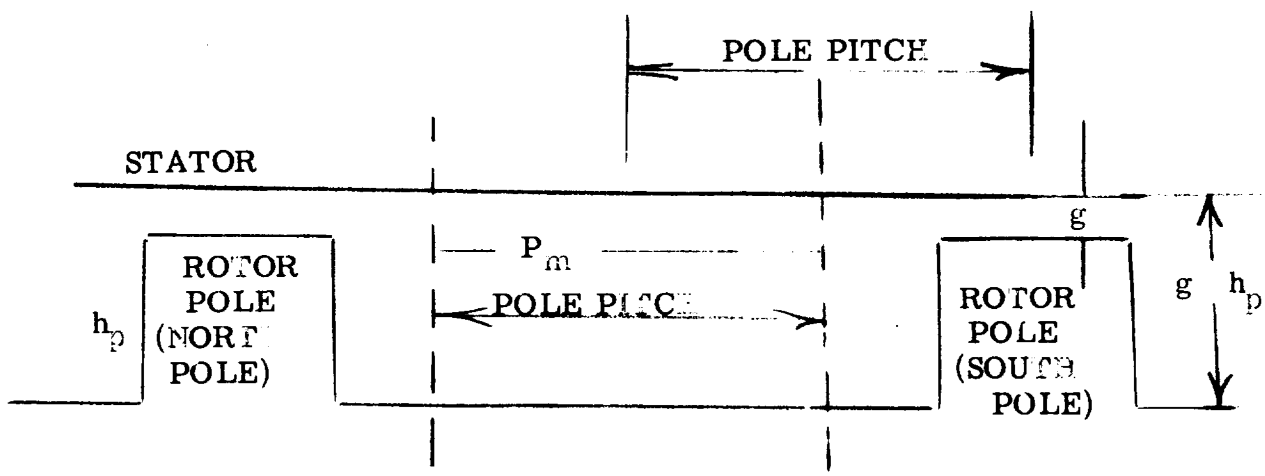


(79) a_p **POLE AREA** - The effective cross sectional area of the pole.

$$a_p = (b_p)(\ell_p)(K_i) = (76)(76)(16)$$

$K_i = 1.0$ FOR SOLID ROTOR

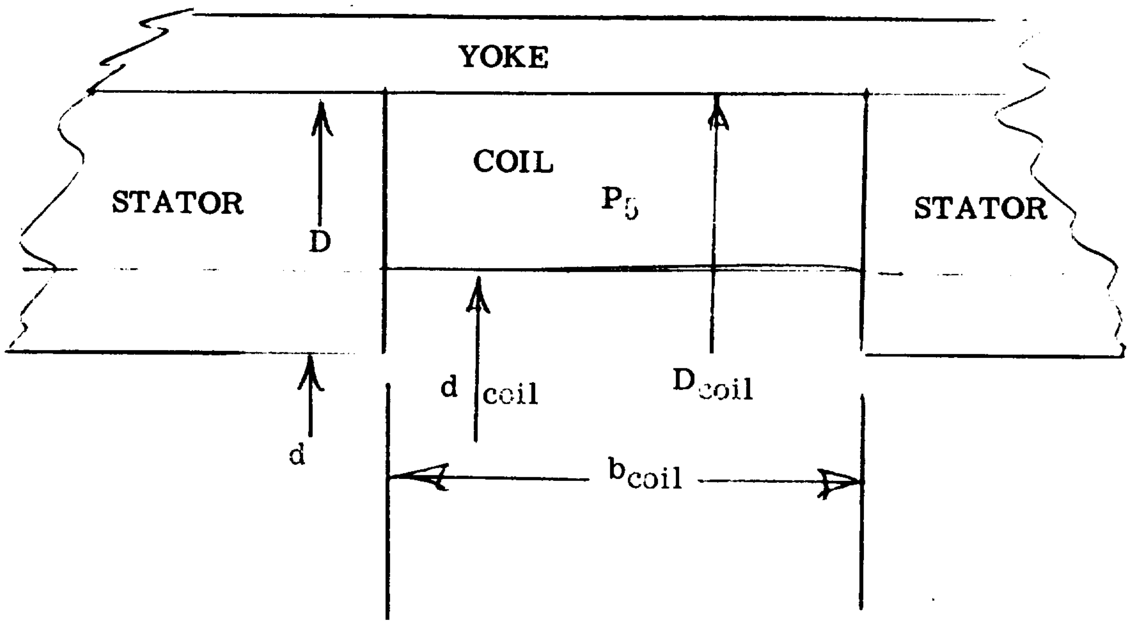
(80c) P_m LEAKAGE PERMEANCE FROM ROTOR TO STATOR BETWEEN ROTOR LOBES OR ROTOR TEETH



$$P_m = \frac{3.19(\pi)(d_r)(\ell)}{P(h'_p + g)} \qquad \frac{10(11a)(13)}{(6)[(76) + (59)]}$$

Use effective pole height (h'_p) when the rotor is tapered and the actual height (h_p) when the rotor is straight.

(84a) | P_5 | LEAKAGE PERMEANCE - across the field coil



$$P_5 = 3.19 \frac{\left[\frac{D_{coil} - d_{coil}}{2}\right] \left[\frac{D_{coil} + d_{coil}}{2}\right] \pi \ \frac{2}{3}}{b_{coil}}$$

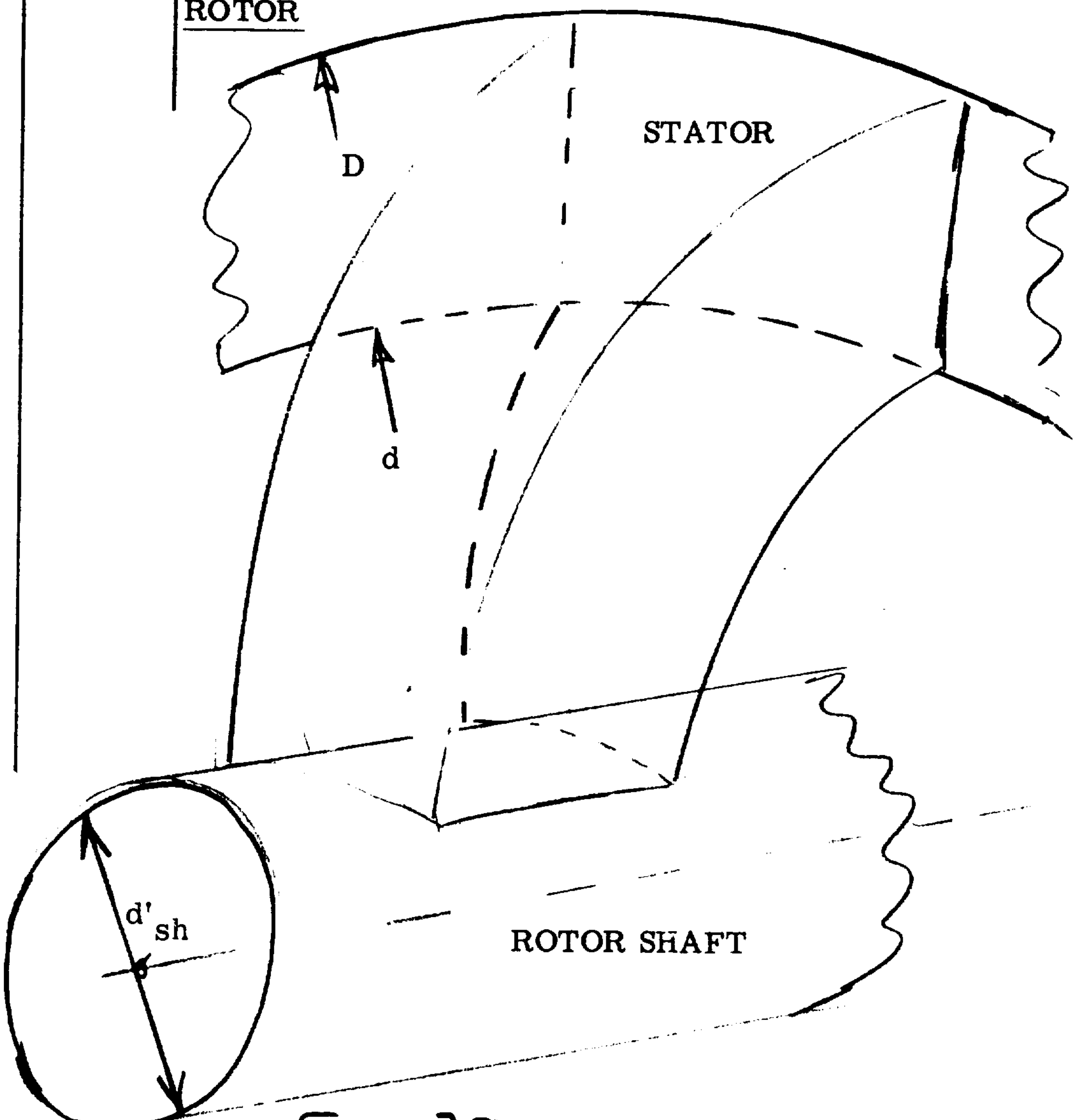
$$= \frac{6.7}{4} \ \frac{[(78) - (78)]\ [(78) + (78)]}{(78)}$$

(85a) | P_6 | LEAKAGE PERMEANCE FROM STATOR TO STATOR

$$P_6 = 3.19 \frac{\left[\frac{d_{coil} - d}{2}\right]\left[\frac{d_{coil} + d}{2}\right] \pi}{b_{coil}}$$

$$= \frac{10}{4} \ \frac{[(78) - (11)]\ [(78) + (11)]}{(78)}$$

(86a) | P_7 | LEAKAGE PERMEANCE FROM STATOR TO SHAFT AND ROTOR



$$P_7 = \pi \frac{\left[\frac{d + d'_{sh}}{2}\right]\left[\frac{D - d}{2}\right] \frac{3.19}{2}}{\frac{1}{2}\left[D - d_{sh}\right]}$$

$$= \frac{3.19(\pi)}{4} \frac{\left[(11) + (78_a)\right]\left[(12) - (11)\right]}{\left[(12) - (78_a)\right]}$$

(87)	--	NO LOAD SATURATION CALCULATIONS - The next calculations deal with no load saturation. When the no load saturation data is required at various voltages, insert 1. on input sheet for "No Load Sat." The computer will then calculate the complete no load saturation curve 80, 90, 100, 110, 120, 130, 140, 150 and 160% of rated volts. When complete saturation data is not necessary, insert 0. on input sheet and the computer will calculate data for rated voltage.
(88)	ϕ_T	TOTAL FLUX in Kilolines
(91)	B_t	TOOTH DENSITY in Kilolines/in^2
(91a)	ϕ_m	Leakage flux from rotor to stator between the rotor lobes (poles or teeth). $\phi_m = (P_m)(F_g) \times 10^{-3} = (80c)(96)(10^{-3})$
(91b)	A_T	Area of the teeth of one stator at a point 1/3 the length of the tooth out from the bore. $A_T = Q \ell_s b_{t\,1/3} = (23)(17)(57a)$

(91c) B'_T

The flux density in the stator teeth in Kilolines/in^2, at no-load rated voltage.

$$B_T = \frac{(\emptyset_T) + (\emptyset_m)(P)}{(A_T)} \quad \frac{(88) + (91a)(6)}{(91b)}$$

(92) $\emptyset_P$

FLUX PER POLE in Kilolines

(94) B_c

The flux density in the core in Kilolines/in^2 at no-load rated voltage.

$$B_c = \frac{(\emptyset_P) + (\emptyset_m)}{(A_c)} = \frac{(92) + (91a)}{(94a)}$$

(94a) A_c)

EFFECTIVE AREA OF THE CORE

$$A_c = \frac{(D - 2hc)\ \pi\, \ell_s}{P} = \frac{\left[(12)-2(24)\right]\ \pi\ (17)}{(6)}$$

(95) B_g

GAP DENSITY in Kilolines/in^2 - The maximum flux density in the air gap.

$$B_g = \frac{(\phi_T)}{\pi\,(d)\,(\ell)} = \frac{(88)}{\pi(11)(13)}$$

(96) F_g

AIR GAP AMPERE TURNS - The field ampere turns per pole required to force the useful flux across the air gap when operating at no load with rated voltage.

$$F_g = \frac{(B_g)(g_e)\ 10^3}{3.19} = \frac{(95)(69)\ 10^3}{3.19}$$

(96a)	$F_g + m$	Total air-gap ampere-turn drop across the single air-gap at no-load, rated voltage.

$$F_g + m = F_g + \frac{(P)(\emptyset_m)(g_e) \times 10^{3}}{3.19\ (A_g)}$$

$$= (96) + \frac{(6)(91a)(69) \times 10^{3}}{3.19\ (68)}$$

(97)	F_T	STATOR TOOTH AMPERE TURNS

$$F_T = h_s \left[\text{NI/in at density} (B_t') \right]$$

$$= (22) \left[\begin{array}{l} \text{Look-up on stator magnetization curve given} \\ \text{in (18) at density (91c)} \end{array} \right]$$

(98)	F_c	STATOR CORE AMPERE TURNS

$$F_c = h_c \left[\text{NI/in @ } B_c \right]$$

$$= (24) \left[\text{NI/in @ (94)} \right]$$

(99)	$\emptyset_7$	The flux leaking through leakage permeance path P_7 at no-load, rated volts. The leakage flux from the outer end of the stator to the shaft and rotor.

$$\emptyset_7 = P_7 \left[(F_g + m) \right] \times 10^{-3} = (86a)(96a) \times 10^{-3}$$

(104b)	B_p	Pole Flux Density at NL. $B_p = \frac{\phi_p + \phi_m}{a_p} = \frac{(92) + (91a)}{(79)}$
(106a)	F_p	Ampere turns drop in pole at no-load. $= h_p \left[NI/in \text{ at } (B_p) \right]$ $= (76) \left[NI/in \text{ at } (104b) \right]$
(112)	A_{SH}	The cross-section area of the portion of the rotor shaft connecting the two pole-carrying sections. $A_{SH} = \left[(D_{SH})^2 \frac{\pi}{4} \right] - \left[(d_{SH})^2 \frac{\pi}{4} \right]$ $= \left[(78a)^2 \frac{\pi}{4} \right] - \left[(78a)^2 \frac{\pi}{4} \right]$
(112a)	ϕ_{SH}	The total flux in the shaft, in kilolines, when operating at no load, rated volts. $\phi_{SH} = \frac{P}{2} \phi_p + P\phi_m + \phi_7$ $= \frac{(6)}{2} (92) + (6)(91a) + (99)$
(113)	B_{SH}	The flux density in the shaft, in Kilolines/in^2 at no-load rated volts. $B_{sh} = \frac{(\phi_{SH})}{(A_{SH})} = \frac{(112a)}{(112)}$

(114)	F_{SH}	The ampere-turn drop in the shaft at no load. $= \ell_{SH}\left[NI/in\ @\ B_{SH}\right] = (78)\left[NI/in\ @\ (113)\right]$
(118a)	$\emptyset_5$	The flux leaking through permeance path P_5 at no-load. This is the flux leaking across the field coil. $\emptyset_5 = P_5\left[2(F_g + m)\right] \times 10^{-3} = (84a)\left[2(96a)\right] \times 10^{-3}$
(121a)	$\emptyset_6$	The flux leaking from stator to stator through permeance path P_6. $\emptyset_6 = P_6\left[2(F_g + m)\right] \times 10^{-3} = (85a)\left[2(96a)\right] \times 10^{-3}$
(124a)	A_y	The area of the yoke over the exciting coil, and connecting the two stators. Shown in item 78 as Type 1. Also the area of the yoke portion over the stator in Types 2 and 3. $A_y = t_y\ (D + t_y)\pi\ in^2$ $= (78)\left[(12) + (78)\right]\pi$
(124b)	A_{yc}	The area of the portion of the yoke that is outside the field coil in generator types 2 and 3. $A_{yc} = (d_{yc} + t_{yc})\pi\ t_{yc}\ in^2$ $= \left[(78) + (78)\right]\pi\ (78)$

(124c)	A_{yr}	The area of the portion of the yoke that is radial and at the sides of the coil in types 2 and 3.
		$A_{yr} = t_{yr} \left[D + 2t_y \right] \pi$
		$= (78) \left[(12) + 2(78) \right] \pi$
(125a)	B_{yc}	For Type 1 - The flux density in the yoke @ No-load
		$B_{yc} = \dfrac{\phi_{SH} + \phi_5 + \phi_6}{A_y} = \dfrac{(112a) + (118a) + (121a)}{(124a)}$
		For Types 2 and 3 - The flux density in the yoke outside the field coil.
		$B_{yc} = \dfrac{\phi_{SH} + \phi_6 + \phi_5}{A_{yc}}$
		$= \dfrac{(112a) + (121a) + (118a)}{(124b)}$
(125b)	F_{yc}	Type 1 - The ampere-turn drop in the yoke @ no-load.
		$F_{yc} = (b_{coil} + 2/3 \ell) \left[NI/in \text{ @ } B_{yc} \right]$
		$= \left[(78) + \frac{2}{3}(13) \right] \left[NI/in \text{ @ } (125a) \right]$
		Types 2 and 3 - The ampere turn drop in the yoke section outside the field coil.
		$F_{yc} = b_{coil} \left[NI/in \text{ @ } B_{yc} \right]$
		$= (78) \left[NI/in \text{ @ } (125a) \right]$

(125c)	B_{yr}	Types 2 and 3 - The flux density in the radial portion of the yoke at the sides of the coil in types 2 and 3.

$$B_{yr} = \frac{\emptyset_{SH} + (\emptyset_5) + (\emptyset_6)}{(A_{yr})}$$

$$= \frac{(112a) + (118a) + (121a)}{(124c)}$$

(125d)	F_{yr}	Ampere turn drop in the radial section of the yoke.

$$F_{yr} = \left[d_{yc} - D\right] \text{ NI/in } @ (B_{yr})$$

$$\left[(78) - (12)\right]\left[\text{NI/in } @ \text{ } (125c)\right]$$

The length used here is an approximation and the F_{yr} should be so negligible as to be unnecessary to calculate. The calculation is included to insure an adequate area of iron in this section.

(126a)	B_y	Types 2 and 3 - The flux density in the yoke outside the stator.

$$B_y = \frac{\emptyset_{SH} + \emptyset_6}{A_y} = \frac{(112a) + (121a)}{(124a)}$$

(126b)	F_y	The ampere-turn drop in the yoke section over the stators in types 2 and 3.

Type 2 $F_y = 2/3\ell\left[\text{NI/in } @ \text{ } (B_y)\right]$

$$= 2/3 \text{ } (13) \left[\text{NI/in } @ \text{ } (126a)\right]$$

Type 3 $F_y = 4/3\ell\left[\text{NI } @ \text{ } (B_y)\right]$

$$= 4/3 \text{ } (13) \left[\text{NI/in } @ \text{ } (126a)\right]$$

(127)	F_{NL}	The total ampere turns required to produce rated volts at no-load.
		$F_{NL} = 2\left[(F_{g+m}) + (F_T) + (F_c) + (F_p)\right] + (F_{SH}) + (F_y) + (F_{yc}) + (F_{y1}$
		$= 2\left[(96a) + (97) + (98) + (106a)\right]$
		$+ (114) + (126b) + (125b) + (125d)$
(127a)	I_{FNL}	The field current at no-load.
		$I_{FNL} = \dfrac{F_{NL}}{N_F} = \dfrac{(127)}{(146)}$
(127b)	E_F	The field volts at no-load
		$= (I_{FNL})\,(R_{f\ cold}) = (127a)\,(154)$
(127c)	S_F	Current density at no-load.
		$S_F = \dfrac{I_{FNL}}{A_{CF}} = \dfrac{(127a)}{(153)}$
(128)	A	<u>AMPERE CONDUCTORS</u> per inch
(129)	X	<u>REACTANCE FACTOR</u>
(130)	X_ℓ	<u>LEAKAGE REACTANCE</u> - The leakage reactance of the stator for steady state conditions. When (5) = 3, calculate as follows:
		$X_\ell = 2(X)\left[(\lambda_i + (\lambda_E)\right] = 2(129)\left[(62) + (64)\right]$

In the case of two phase machines a component due to the belt leakage must be included in the stator leakage reactance. This component is due to the harmonics caused by the concentration of the MMF into a small number of phase belts per pole and is negligible for three phase machines. When (5) - 2, calculate as follows:

$$\lambda_B = \frac{0.1(d)}{(P)(g_e)}\left[\frac{\sin\left[\frac{3(y)}{(m)(q)}\right]90^o}{(K_p)}\right] = \frac{0.1(11)}{(6)(69)}\left[\frac{\sin\left[\frac{3(31)}{(5)(25)}\right]90^o}{(44)}\right]$$

$X_\ell = 2X\left[(\lambda_1) + (\lambda_E) + (\lambda_B)\right]$ **where $\lambda_B = 0$ for 3 phase machines.**

$X_\ell = 2(79)\left[(62) +)64) + (80)\right]$

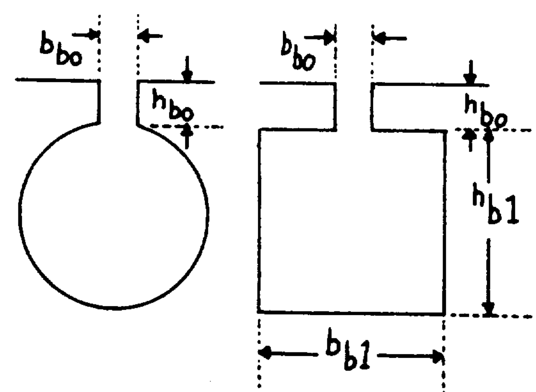
(131) X_{ad} **<u>REACTANCE</u> - direct axis**

(132) X_{aq} **<u>REACTANCE</u> - quadrature axis**

(133) X_d **<u>SYNCHRONOUS REACTANCE</u> - direct axis**

(134) X_q **<u>SYNCHRONOUS REACTANCE</u> - quadrature axis**

(135) -- <u>DAMPER SLOT DIMENSIONS</u>



b_{bo} - width of slot opening

h_{bo} - height of slot opening

h_D - diameter of round slot

h_{b1} - **height of bar section of slot**

b_{b1} - **width of rectangular slot**

(136)	--	DAMPER BAR DIA OR WIDTH in inches
(137)	h_{bl}	DAMPER BAR THICKNESS in inches - Damper bar thickness considered equal to damper bar slot height (h_b) per Item (135). Set this item = 0 for round bar.
(138)	n_b	NUMBER OF DAMPER BARS PER POLE
(139)	ℓ_b	DAMPER BAR LENGTH in inches
(140)	τ_b	DAMPER BAR PITCH in inches
(141)	ρ_D	RESISTIVITY of damper bar @ 20°C in ohm-inches
(142)	$X_D{}^\circ C$	DAMPER BAR TEMP °C - Input temp at which damper losses are to be calculated.
(143)	ρ_D (hot)	RESISTIVITY of damper bar @ $X_D{}^\circ C$
(144)	a_{cd}	CONDUCTOR AREA OF DAMPER BAR - Calculate same as stator conductor area
(145)	V_r	PERIPHERAL SPEED - The velocity of the rotor surface in feet per minute
(146)	N_F	NUMBER OF FIELD TURNS PER COIL
(147)	ℓ_{tF}	MEAN LENGTH OF FIELD TURN
(148)	--	FIELD CONDUCTOR DIA OR WIDTH in inches
(149)	--	FIELD CONDUCTOR THICKNESS in inches - Set this item = for round conductor.

(150)	$X_f{}^oC$	FIELD TEMP IN ^oC - Input temp at which full load field loss is to be calculated.
(151)	ρ_f	RESISTIVITY of field conductor @ 20^oC in micro ohm-inches. Refer to table given in Item (51) for conversion factors.
(152)	ρ_f (hot)	RESISTIVITY of field conductor at $X_f{}^oC$
(153)	a_{cf}	CONDUCTOR AREA OF FIELD WINDING - Calculate same as stator conductor area
(154)	R_f (cold)	COLD FIELD RESISTANCE @ 20^oC per coil $R_{f(cold)} = (\rho_f)\frac{(N_F)(\ell_{tf}) \times 10^{-6}}{(a_{cf})} = \frac{(151)(146)(147a) \times 10^{-6}}{(153)}$
(155)	R_f (hot)	HOT FIELD RESISTANCE - Calculated at $X_f{}^oC$ $R_{f(hot)} = (\rho_{f\,hot})\frac{(N_f)(\ell_{tf}) \times 10^{-6}}{(a_{cf})} = \frac{(152)(146)(147a) \times 10^{-6}}{(153)}$
(156)	--	WEIGHT OF FIELD COPPER in lbs. #'s of copper $= .321\ (N_f)(\ell_{tf})(a_{cf})$ $= .321\ (146)(147a)(153)$
(157)	--	WEIGHT OF ROTOR IRON - Because of the large number of different pole shapes, one standard formula cannot be used for calculating rotor iron weight. Therefore, the computer will not calculate rotor iron weight.

(158)	λ_b	**PERMEANCE OF DAMPER BAR** - The permeance of that portion of the damper bar that is embedded in pole iron.
(159)	λ_{pt}	**PERMEANCE OF END PORTION OF DAMPER BARS**
(160)	X_F	**FIELD LEAKAGE REACTANCE**

$$X_F = X_{ad}\left[1 - \frac{C_1/C_m}{2C_p + \frac{4}{\pi}\,\frac{\lambda F}{\lambda a}}\right]$$

$$= (131)\left[1 - \frac{(71)/(74)}{2(73) + \frac{4}{\pi}\,\frac{(161\,F)}{(70c)}}\right]$$

(161)	L_F	**FIELD SELF-INDUCTANCE**

$$L_F = (N_F)^2\left[\frac{P}{4}\, C_p\, \lambda_a\, \frac{\pi}{2}\, \ell_p + \lambda_F\right]10^{-8}$$

$$= (146)^2\left[\frac{(6)}{4}\,(73)\,(70c)\,\frac{\pi}{2}\,(13) + (161\,F)\right]10^{-8}$$

(161 F)	λ_F	**FIELD LEAKAGE PERMEANCE**

$$\lambda_F = \left[P_5 + P_6 + \frac{P_4}{2} + P_m\,\frac{P}{4}\right]\frac{1}{\ell}$$

$$= \left[(84a) + (85a) + \frac{(83)}{2} + (80c)\,\frac{(6)}{4}\right]\frac{1}{(13)}$$

(162)	λ_{D_d}	**LEAKAGE PERMEANCE OF DAMPER BAR IN DIRECT AXIS**
(163)	X_{D_d}	**DAMPER LEAKAGE REACTANCE IN DIRECT AXIS**

(164)	λ_{Dq}	LEAKAGE PERMEANCE OF DAMPER BARS IN QUADRATURE AXIS
(165)	X_{Dq}	DAMPER LEAKAGE REACTANCE IN THE QUADRATURE AXIS
(166)	X'_{Du}	UNSATURATED TRANSIENT REACTANCE
(167)	X'_d	SATURATED TRANSIENT REACTANCE
(168)	X''_d	SUBTRANSIENT REACTANCE, DIRECT AXIS
(169)	X''_q	SUBTRANSIENT REACTANCE QUADRATURE AXIS
(170)	X_2	NEGATIVE SEQUENCE REACTANCE
(172)	X_o	ZERO SEQUENCE REACTANCE
(176)	T'_{do}	OPEN CIRCUIT TIME CONSTANT
(177)	T_a	ARMATURE TIME CONSTANT
(178)	T'_d	TRANSIENT TIME CONSTANT
(179)	T''_d	SUBTRANSIENT TIME CONSTANT
(180)	F_{SC}	SHORT-CIRCUIT AMPERE TURNS $F_{SC} = 2(X_d)(F_g)(10^{-2}) = 2(83)(96)\ 10^{-2}$
(181)	SCR	SHORT CIRCUIT RATIO
(182)	I^2R_F	FIELD I^2R - at no load. The copper loss in the field winding is calculated with cold field resistance at 20^o C for no load condition. Field $I^2R = (I_{FNL})^2\ (R_{f\ cold}) = (127a)^2\ (154)$

(183)	F&W	FRICTION & WINDAGE LOSS - The best results are obtained by using existing data. For ratioing purposes, the loss can be assumed to vary approximately as the 5/2 power of the rotor diameter and as the 3/2 power of the RPM. When no existing data is available, the following calculation can be used for an approximate answer. Insert 0. when computer is to calculate F & W. Insert actual F&W when available. Use same value for all load conditions.

$$F\&W - 2.52 \times 10^{-6} (d_r)^{2.5} (\ell_\rho) (RPM)^{1.5}$$

$$- 2.52 \times 10^{-6} (11a)^{2.5} (76) (7)^{1.5}$$

For gases or fluids other than standard air, the fluid density and viscosity must be considered. The formula above can be modified by the factors.

$$\left(\frac{\rho}{.0765}\right)^{.8} \left(\frac{u}{.0435}\right)^{.2}$$

where ρ - density - Lbs FT^{-3}

u - viscosity LBS FT^{-1} HR^{-1}

.0765 - density std. air

.0435 - viscosity Std. air

(184)	W_{TNL}	STATOR TEETH LOSS - at no load.
(185)	W_c	STATOR CORE LOSS
(186)	W_{NPL}	POLE FACE LOSS - at no load.
(187)	K_1	
(188)	K_2	
(189)	K_3	
(190)	K_4	
(191)	K_5	
(192)	K_6	
(193)	W_{DNL}	DAMPER LOSS - at no load.
(196)	--	TOTAL LOSSES - at no load. Sum of all losses. Total losses = (Rotor I^2R) + (F&W) + (Stator Teeth Loss) + (Stator Core Loss) + (Pole Face Loss) + (Damper Loss) = (182) + (183) + (184) + (185) + (186) + (193)
(198)	e_d	LOAD SATURATION $e_d = \cos \xi + \frac{(X_d)}{100} \sin \psi$ $= \cos (198a) + \frac{(133)}{100} \sin (198a)$

(198a)	θ	$\theta = \cos^{-1}$ (Power Factor) $\theta = \cos^{-1}$ (9) $\psi = \tan^{-1}\left[\frac{\sin(\theta) + (X_q)/(100)}{\cos(\theta)}\right]$ $\psi = \tan^{-1}\left[\frac{\sin(198a) + (134)/(100)}{\cos(198a)}\right]$ $\epsilon = \psi - \theta = (198a) - (198a)$
(198b)	F_{dm}	Demagnetizing ampere-turns at full load. $F_{dm} = \frac{.45\,(N_e)(I_{ph})(C_m)(K_d)}{(P)}$ $= \frac{.45\,(45)(8)(74)(43)}{(6)}$
(198c)	ϕ'_{mL}	First approximation of the leakage flux from the shaft to the stator between the rotor lobes or poles (or teeth). $\phi'_{mL} = P_m\left[F_{dm} + F_g\, e_d\right] \times 10^{-3}$ $= (80c)\left[(198b) + (96)(198)\right] \times 10^{-3}$
(199)	F'_{gL}	First approximation of the ampere turns drop across the main air-gap at full load. $F'_{gL} = F_g\, e_d + \frac{(P)(\phi'_{mL})(g_e) \times 10^{+3}}{3.19(A_g)}$ $= (96)(198) + \frac{(6)(198c)(69) \times 10^{+3}}{3.19\,(68)}$

(200)	F'_{TL}	Tooth ampere-turn drop under load (1st approximation) $F'_{TL} = F_T \left[1 + \cos(\theta)\right]$ $(97) \left[1 + \cos\ (198a)\right]$
(200a)	$\emptyset'_{PL}$	The first approximation of the flux per pole at full load. $\emptyset'_{PL} = \emptyset_P \left[e_d - .93 \frac{Xad}{100} \sin \Psi\right]$ $(92) \left[(198) - \frac{.93\ (131)\ \sin\ (198a)}{100}\right]$
(200b)	B'_{PL}	The first approximation of the flux density in the pole at full load. $B'_{PL} = \frac{\emptyset'_{PL} + \emptyset_m}{A_{pole}} = \frac{(200a) + (91a)}{(79)}$
(200c)	F'_{PL}	The first approximation of the ampere turns drop in the pole at full load. $F'_{PL} = h_p \left[NI/in\ @ B'_{PL}\right]$ $= (76) \left[NI/in\ @\ (200b)\right]$
(200d)	$\emptyset'_{5L}$	First approximation of the leakage flux through P_5 at full load. $\emptyset'_{5L} = P_5 \left[2\ F'_{gL} + 2\ F'_{TL} + 2\ F'_{PL}\right] \times 10^{-3}$ $= (84a) \left[2\ \ (199) + (200) + (200c)\right] \times 10^{-3}$

(200e)	ϕ'_{6L}	First approximation of the leakage flux through P_6 at full-load. $\phi'_{6L} = P_6 \left[2\ F'_{gL} + 2\ F'_{TL} + 2\ F'_{PL} \right] \times 10^{-3}$ $= (85a) \left[2\ \ (199) + (200) + (200c) \right] \times 10^{-3}$
(200f)	ϕ_{CL}	Flux in the core at full load. $\phi_{CL} = \phi_{PL} + \frac{\phi_{5L} + \phi_{6L}}{P}$ $(213.) = \frac{(226a) + (220a)}{(6)}$
(200g)	B_{CL}	Flux density in the core at full load. $B_{CL} = \frac{\phi_{CL}}{A_C} = \frac{(200f)}{(94a)}$
(201)	F_{CL}	Ampere-turn drop in the core @full load. $F_{CL} = (h_c)$ NI/in @ B_{CL} $= (24)$ NI/in @ (200g)
(202)	ϕ'_{7L}	First approximation of the leakage flux through P_7 at full load. $\phi'_{7L} = P_7 \left[F'_{gL} + F'_{TL} + F'_{PL} \right] \times 10^{-3}$ $= (86a) \left[(199) + (200) + (200c) \right] \times 10^{-3}$

(202b)	ϕ'_{SHL}	First approximation of the shaft flux at full load. $\phi'_{SHL} = \phi'_{PL} \frac{P}{2} + P\, \phi_{mL} + \phi'_{7L}$ $= (200a) \frac{(6)}{2} + (6)(198c) + (202)$
(202c)	B'_{SHL}	First approximation of shaft density @ full load. $B'_{SHL} = \frac{\phi'_{SHL}}{A_{SH}} = \frac{(202b)}{(112)}$
(202d)	F'_{SHL}	First approximation of ampere turn drop in shaft at full load. $F'_{SHL} = \ell_{SH} \left[NI/in \ @ B'_{SHL} \right]$ $= (78a) \left[NI/in \ @ \ (202c) \right]$
(202e)	ϕ_{mL}	The final value of ϕ_{mL} at full load. $\phi_{mL} = P_m \left[F_{dm} + F'_{gL} \right] \times 10^{-3}$ $= (80c) \left[(198b) + (199) \right] \times 10^{-3}$

(203)	F_{gL}	Final ampere turns across the air-gap.
		$$F_{gL} = (F_g)(e_d) + \frac{(P)(\emptyset_{mL})(g_e) \times 10^{3}}{(A_g)\, 3.19}$$
		$$= (96)(198) + \frac{(6)(202e)(69) \times 10^{3}}{3.19(68)}$$
(205)	B_{TL}	Flux density in teeth at full load.
		$$B_{TL} = \emptyset_T + \frac{(P)(\emptyset_{mL})}{(A_T)}$$
		$$= (88) + \frac{(6)(202e)}{(91b)}$$
(206)	F_{TL}	Ampere-turn drop across the stator teeth at full load.
		$$F_{TL} = h_s \left[NI/in\ @ B_{TL} \right]$$
		$$= (22) \left[NI/in\ @ (205) \right]$$
(207a)	$\emptyset_{7L}$	Final value $\emptyset_7$ @ full load.
		$$\emptyset_{7L} = P_7 \left[F_{TL} + F_{gL} + F_{PL} \right] \times 10^{-3}$$
		$$= (86a) \left[(206) + (203) + (213L) \right] \times 10^{-3}$$

(213)	ϕ_{PL}	The final value of ϕ_{PL} at full load. $\phi_{PL} = (\phi'_{PL}) + \phi_{mL}$ $\phi_{PL} = (200a) + (202e)$
(213b)	B_{PL}	The pole flux density at full load (final value). $B_{PL} = \frac{\phi_{PL}}{A_P} = \frac{(213)}{(79)}$
(213L)	F_{PL}	The final value of the flux drop in the pole at full load. $F_{PL} = h_p \left[NI/in\ @ B_{PL} \right]$ $= (76) \left[NI/in\ @ (213b) \right]$
(214a)	ϕ_{SHL}	Final value @full load. $\phi_{SHL} = \phi_{PL} \frac{(P)}{2} + \frac{P}{2} \phi_{ML} + \phi_{7L}$ $= (213) \frac{(6)}{2} + \frac{(6)}{2} (202e) + (207a)$
(215a)	B_{SHL}	Final value of shaft flux density @full load. $B_{SHL} = \frac{\phi_{SHL}}{A_{SH}} = \frac{(214a)}{(112)}$
(216a)	F_{SHL}	Final value ampere-turn drop in shaft @full load. $F_{SHL} = \ell_{SH} \left[(NI/in\ @ B_{SHL} \right]$ $= (78a) \left[NI/in\ @ (215a) \right]$

(220a)	ϕ_{6L}	Final value @full load. $\phi_{6L} = P_6 \left[2(F_{TL}) + 2(F_{gL}) + 2(F_{PL}) + (F_{SHL})\right] \times 10^{-3}$ $= (85a)\left[2(206) + 2(203) + 2(213L) + (216a)\right] \times 10^{-3}$
(226a)	ϕ_{5L}	Final value @full load. $\phi_{5L} = P_5 \left[2(F_{TL}) + 2(F_{gL}) + 2(F_{PL}) + (F_{SHL})\right] \times 10^{-3}$ $= (84a)\left[2(206) + 2(203) + 2(213L) + (216a)\right] \times 10^{-3}$
(228a)	B_{yCL}	Type 1 - The flux density in the yoke of the generator at full load. $B_{yCL} = \dfrac{\phi_{SHL} + \phi_{6L} + \phi_{5L}}{A_y}$ $= \dfrac{(214a) + (220a) + (226a)}{(124a)}$ Types 2 and 3. The flux density in the yoke outside the field coil. $B_{yCL} = \dfrac{\phi_{SHL} + \phi_{6L} + \phi_{5L}}{A_{yC}}$ $= \dfrac{(214a) + (220a) + (226a)}{(124b)}$

(228b)	F_{yCL}	Type 1 - The ampere drop in the yoke at full load. $F_{yCL} = \left[(b_{coil}) + 2/3(\ell)\right]\left[NI/in\ @B_{yCL}\right]$ $\left[(78) + \frac{2}{3}(13)\right]\left[NI/in\ @\ (228a)\right]$ Types 2 and 3. The ampere-turns drop in just the yoke section outboard of the coil. $F_{yCL} = b_{coil}\left[NI/in\ @B_{yCL}\right]$ $= (78)\left[NI/in\ @\ (228a)\right]$
(228c)	B_{yrL}	Types 2 and 3. The flux in the radial section of the yoke @full load. $B_{yrL} = \frac{\phi_{SHL} + \phi_{6L} + \phi_{5L}}{A_{yr}}$ $= \frac{(214a) + (220a) + (226a)}{(124c)}$
(228d)	F_{yrL}	Types 2 and 3. The ampere turn drop in the radial section of the yoke at full load. $F_{yrL} = \left[d_{yc} - D\right]\left[NI/in\ @(B_{yrL})\right]$ $= \left[(78) - (12)\right]\left[NI/in\ @\ (228c)\right]$

(229a)	B_{yL}	Types 2 and 3. The flux density in the yoke outside the stator. $$B_{yL} = \frac{\phi_{SHL} + \phi_{6L}}{A_y}$$ $$= \frac{(214a) + (220a)}{(124a)}$$
(229b)	F_{yL}	The ampere-turn drop in the yoke section over the stators in types 2 and 3. Type 2 = $F_{yL} = 2/3\ell \left[NI/in\ @(B_{yL})\right]$ $= 2/3(13)\ \left[NI/in\ @\ (229a)\right]$ Type 3 = $F_{yL} = 4/3\ell \left[NI/in\ @(B_{yL})\right]$ $= 4/3(13)\ \left[NI/in\ @(229a)\right]$
(236)	F_{FL}	The total ampere-turns required to supply rated load at rated volts. $$F_{FL} = 2\left[F_{gL} + F_{TL} + F_{CL} + F_{PL}\right] + F_{SHL} + F_{yL} + F_{yCL} + F_{yrL}$$ $$= 2\left[(203) + (206) + (201) + (213L)\right] + (216a) + (229b) + (228b) + (228d)$$
(237)	I_{FFL}	<u>FIELD CURRENT</u> at 100% load.
(238)	E_{FFL}	FIELD VOLTS at 100% load.

(239)	S_{FL}	CURRENT DENSITY IN FIELD at 100% load.
(241)	I^2R_F	FIELD I^2R at 100% load.
(242)	W_{TFL}	STATOR TEETH LOSS at 100% load.
(243)	W_{PFL}	POLE FACE LOSS at 100% load.
(244)	W_{DFL}	DAMPER LOSS at 100% load.
(245)	I^2R	STATOR I^2R at 100% load.
(246)	--	EDDY LOSS at 100% load.
(247)	--	TOTAL LOSSES at 100% load - sum of all losses at 100% load. Total Losses - (Field I^2R) + (F&W) + (Stator Teeth Loss) + (Stator Core Loss) + (Pole Face Loss) + (Stator I^2R) + (Eddy Loss) + (DAMPER LOSS) + (241) + (183) + (242) + (185) + (243) + (245) + (246) + (244)
(248)	--	RATING IN KW at 100% load
(249)	--	RATING & LOSSES
(250)	--	% LOSSES
(251)	--	% EFFICIENCY = 100% - % Losses

DESIGN MANUAL FOR PERMANENT-MAGNET SALIENT-POLE, A-C GENERATORS

SECTION R

INPUT AUXILIARY DATA SHEET

Auxiliary information taken from the design manuals to be used in conjunction with input sheets for convenience.

A. All dimensions for lengths, widths, and diameters are to be given in inches.

B. Resistivity inputs, Items (141) and (151) are to be given in micro-ohm-inches.

The following items along with an explanation of each are tabulated here for convenience. For complete explanation of each item number, refer to design manuals.

Item No.	Explanation
(9)	Power factor to be given in per unit. For example for 90% P. F., insert .90.
(9a)	Adjustment Factor - For P. F. $<$ .95 insert 1.0 For P. F. $>$ .95 insert 1.05
(10)	Optional Load Point -- Where load data output is required at a point other than those given as standard on the input sheet. Example: For load data output at 155% load, insert 1.55.
(14)	Number of radial ducts in stator.
(15)	Width of radial ducts used in Item (14).
(18)	Magnetization curve of material used to be submitted as defined in Item (18).
(19)	Watts/Lb. to be taken from a core loss curve at the density given in Item (20) (Stator).
(20)	Density in kilolines/in^2. This value must correspond to density used to pick Item (19) usually use 77.4 KL/in^2.
(21)	Type of slot - For open slot Type A, insert 1.0. For partially open slot Type B with constant slot width, insert 2.0. For partially open slot Type C with constant tooth width, insert 3.0. For round slot Type D, insert 4.0. For additional information, refer to figure adjacent to input sheet which shows a picture of each slot.
(22)	For stator slot dimension - for dimensions that do not apply to the slot insert 0.0. Use Table below as guide for input.

Symbol	Item	Slot Type 1	2	3	4
b_o	(22)	0.0	*	*	*
b_1	↓	0.0	0.0	*	0.0
b_2	↓	0.0	0.0	*	0.0
b_3	↓	0.0	0.0	*	0.0
b_s	↓	*	*	φ	*
h_o	↓	0.0	*	*	*
h_1	↓	*	*	*	0.0
h_2	↓	*	0.0	0.0	0.0
h_3	↓	*	*	0.0	0.0
h_s	↓	*	*	*	*
h_t	↓	0.0	*	*	0.0
h_w	↓	0.0	*	*	0.0

* = insert actual value.

$$\varphi = b_s = \frac{b_1 + b_3}{2}$$

Item No.   Explanation

(28) Type of winding - for wye connected winding insert 1.0.

for delta connected winding insert 0.0.

(29) Type of coil - for formed wound (rect. wire), insert 1.0.

for random wound (round wire) insert 0.0.

(30) Slots spanned - Example - for slot span of 1-10, insert 9.0.

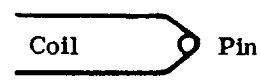
(33) For round wire insert diameter. For rectangular wire insert wire width.

(34) Strands per conductor in depth only.

(34a) Total strands per conductor in depth and width.

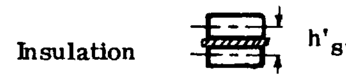
(35) Diameter of coil head forming pin. Insert .25 for stator O.D. < 8 inches;

Insert .50 for stator O.D. > 8 in.



(37) Use vertical height of strand for round wire, insert 0.0.

(38) Distance between centerline of strands in depth.



(39) Stator strand thickness -- use narrowest dimension of the two dimensions given for a rectangular wire. For round wire insert 0.0.

(40) Stator slot skew in inches.

(42a) Phase belt angle - for 60^{o} phase belt, insert 60^{o}.

for 120^{o} phase belt, insert 120^{o}.

(48) See explanation of items (71), (72), (73), (74) and (75). Same applies here.

(87) When no load saturation output data is required at various voltages, insert 1.0.

When no load saturation information is not required, insert 0.0.

(137) Damper bar thickness -- use damper bar slot height for rectangular bar. For round bar insert 0.0.

(138) Number of damper bars per pole.

(140) Damper bar pitch in inches.

(148) For round wire insert diameter. For rectangular wire insert wire width.

(149) For rectangular wire insert wire thickness. For round wire insert 0.0.

(187) Pole face loss factor. For rotor lamination thickness .028 in. or less, insert 1.17.

For rotor lamination thickness .029 in. to .063 in. insert 1.75.

For rotor lamination thickness .064 in. to .125 insert 3.5.

For solid rotor insert 7.0.

(71)
(72)
(73)
(74)
(75)

If the values of these constants are available, insert the actual number. If they are not available, insert 0.0 and the computer will calculate the values and record them on the output.

PERMANENT MAGNET GENERATOR **COMPUTER DESIGN (INPUT)**

MODEL NO. ______ EWO ______ DESIGN NO. (1) ______

PARAMETERS	(2)	KVA	GENERATOR KVA	
	(3)	E	LINE VOLTS	
	(4)	E_{ph}	PHASE VOLTS	
	(5)	m	PHASES	
	(5a)	f	FREQUENCY	
	(6)	p	POLES	
	(7)	RPM	RPM	
	(8)	I_{ph}	PHASE CURRENT	
	(9)	PF	POWER FACTOR	
STATOR STACK	(11)	d	STATOR I.D.	
	(12)	D	STATOR O.D.	
	(13)		GROSS CORE LENGTH	
	(14)	n_v	NO. OF DUCTS	
	(15)	b_v	WIDTH OF DUCT	
	(16)	K_1	STACKING FACTOR (STATOR)	
	(19)	k	WATTS/LB.	
	(20)	B	DENSITY	
STATOR SLOT	(21)		TYPE OF SLOT	
	(22)	b_o	SLOT OPENING	
	(22)	b_1	SLOT WIDTH TOP	
	(22)	b_2		
	(22)	b_3		
	(22)	b_s	SLOT WIDTH	
	(22)	h_o		
	(22)	h_1		
	(22)	h_2		
	(22)	h_3		
	(22)	h_s	SLOT DEPTH	
	(22)	h_t		
	(22)	h_w		
	(23)	Q	NO. OF SLOTS	
STATOR WINDING	(28)		TYPE OF WDG.	
	(29)		TYPE OF COIL	
	(30)	n_s	CONDUCTORS/SLOT	
	(31)	y	SLOTS SPANNED	
	(32)	c	PARALLEL CIRCUITS	
	(33)		STRAND DIA. OR WIDTH	
	(34)	N_{st}	STRANDS/CONDUCTOR	
	(34a)	N'_{st}	STRANDS/CONDUSTOR	
	(39)		STATOR STRAND T'KNS	
	(35)	d_b	DIA. OF PIN	
	(36)	e2	COIL EXT. STR. PORT	
	(37)	h_{st}	UNINS. STRD. HT.	
	(38)	h'_{st}	DIST. BTWN. C_L OF STD.	
	(42a)		PHASE BELT/ANGLE	
	(40)	sk	STATOR SLOT SKEW	
	(50)	X_s °C	STATOR TEMP °C	
	(51)	s	RES'TVY STA. COND. @ 20 °C	
GAP	(59)	g min	MINIMUM AIR GAP	
	(59a)	g max	MAXIMUM AIR GAP	

	FUND/MAX OF FIELD FLUX	(71)	C_1	CONSTANTS
	WINDING CONSTANT	(72)	C_w	
	POLE CONST.	(73)	C_p	
	END EXTENSION ONE TURN	(48)	LE	
	DEMAGNETIZATION FACTOR	(74)	C_m	
	CROSS MAGNETIZING FACTOR	(75)	C_q	
	POLE HEAD WIDTH	(76)	b_h	ROTOR STACK
	MAGNET WIDTH	(76)	b_p	
	POLE HEAD HEIGHT	(76)	h_h	
	MAGNET HEIGHT	(76)	h_f	
	MAGNET LENGTH	(76)	p	
	POLE HEAD LENGTH	(76)	n	
	POLE EMBRACE	(77)	α_c	
	ROTOR DIAMETER	(11a)	d_r	
	STACKING FACTOR(ROTOR)	(16)	K_1	
	WEIGHT OF ROTOR IRON	(157)	(–)	
	POLE FACE LOSS FACTOR	(187)	(K_1)	
	WIDTH OF SLOT OPENING	(135)	b_{bo}	DAMPER BAR
	HEIGHT OF SLOT OPENING	(135)	h_{bo}	
	DAMPER BAR DIA. OR WIDTH	(136)	( )	
	RECTANGULAR BAR THICKNESS	(137)	h_{bl}	
	RECTANGULAR SLOT WIDTH	(135)	b_{bl}	
	NO. OF DAMPER BARS	(138)	n_b	
	DAMPER BAR LENGTH	(139)	b	
	DAMPER BAR PITCH	(140)	b	
	RESISTIVITY OF DAMP. BAR @ 20 °	(141)	D	
	DAMPER BAR TEMP °C	(142)	X_o °C	
	FRICTION & WINDAGE	(183)	F & W	
	MAGNET RED FACTOR	(508)	C	
	MAGNET HYST. SLOPE	(519a)	h	
	MAGNET MATERIAL	(18)		MTR'L
	ROTOR HEAD LAM	(18)		
	STATOR LAM. MATERIAL	(18)		
	P_o / P_m CURVE DATA	( )		

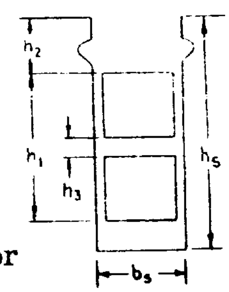
STATOR SLOT	POLE
DAMPER SLOT	REMARKS

DESIGNER ______

DATE ______

REV. A

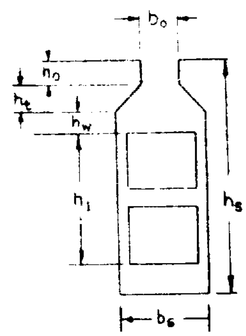
(a) Open Slots



TYPE 1

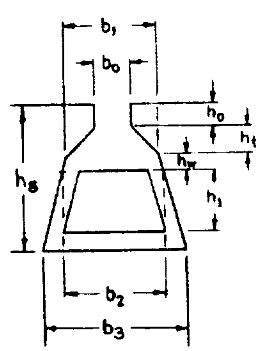
(Type 5 is an open slot with 1 conductor per slot)

(b) Constant Slot Width



TYPE 2

(c) Constant Tooth Width

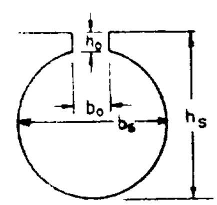


TYPE 3

b_s for type 3 is

$$b_s = \left(\frac{b_1 + b_3}{2}\right)$$

(d) Round Slots



TYPE 4

PERMANENT-MAGNET GENERATOR
SUMMARY OF DESIGN CALCULATIONS (OUTPUT)

MODEL ______________ EWO ________ DESIGN NO. ______________

STATOR	(17) (ℓ_s)	SOLID CORE LENGTH			CARTER COEFFICIENT	(67) (K_s)	GAP
	(24) (h_c)	DEPTH BELOW SLOT			AIR GAP AREA	(68) (–)	
	(26) (τ_s)	SLOT PITCH			AIR GAP PERM	(70a) (λ_a)	
	(27) (τ_s1/3)	SLOT PITCH 1/3 DIST. UP			EFFECTIVE AIR GAP	(69) (g_e)	
	(42) (K_{sk})	SKEW FACTOR			FUND/MAX OF FLD. FLUX	(71) (C_1)	CONSTANTS
	(43) (K_d)	DIST. FACTOR			WINDING CONST.	(72) (C_w)	
	(44) (K_p)	PITCH FACTOR			POLE CONST.	(73) (C_p)	
	(45) (ne)	EFF. CONDUCTORS			END. EXT. ONE TURN	(48) (L_E)	
	(46) (a_c)	COND. AREA			DEMAGNETIZING FACTOR	(74) (C_M)	
	(47) (S_s)	CURRENT DENSITY (STA.)			CROSS MAGNETIZING FACTOR	(75) (C_q)	
	(49) (ℓ_t)	1/2 MEAN TURN LENGTH			AMP COND/IN	(128) (A)	REACTANCE
	(53) (R_{ph})	COLD STA. RES. @ 20° C			REACTANCE FACTOR	(129) (X)	
	(54) (R_{ph})	HOT STA. RES. @ X C			LEAKAGE REACTANCE	(130) (X_a)	
	(55) (EFtop)	EDDY FACTOR TOP			SYN REACT DIRECT AXIS	(133) (X_d)	
	(56) (EFbot)	EDDY FACTOR BOT			DAMPER	(163) (X_{Dd})	
	(62) (λ_l)	STATOR COND. PERM.			LEAKAGE REACT	(165) (X_{Dq})	
	(64) (λ_e)	END PERM.			UNSAT. TRANS. REACT	(166) (X'_{du})	
	(65) ( )	WT. OF STA COPPER			SUB. TRANS. REACT DIRECT AX.	(168) (X''_d)	
	(66) ( )	WT. OF STA IRON			SUB. TRANS. REACT QUAD AX.	(169) (X''_q)	
	(41) (τ_p)	POLE PITCH			NEG. SEQUENCE REACT	(170) (X_2)	
	(509) P_i	PERMEANCE IN STATOR			ZERO SEQUENCE REACT	(172) (X_0)	
	(510) P_o	PERMEANCE OUT STATOR			TOTAL FLUX	(88) (Φ_t)	
	(507) P_m	PERMEANCE MAGNET			FLUX PER POLE	(92) (Φ_p)	
	(511) P_g	PERMEANCE AIR GAP			GAP DENSITY	(95) (B_g)	
	(157) ( )	WT. OF ROTOR IRON			TOOTH DENSITY	(91) (B_t)	
		WT. OF MAGNETS			CORE DENSITY	(94) (B_c)	
	(145) (V_r)	PERIPHERAL SPEED			SHORT CIRCUIT AMPS	(522) (I_{sc})	

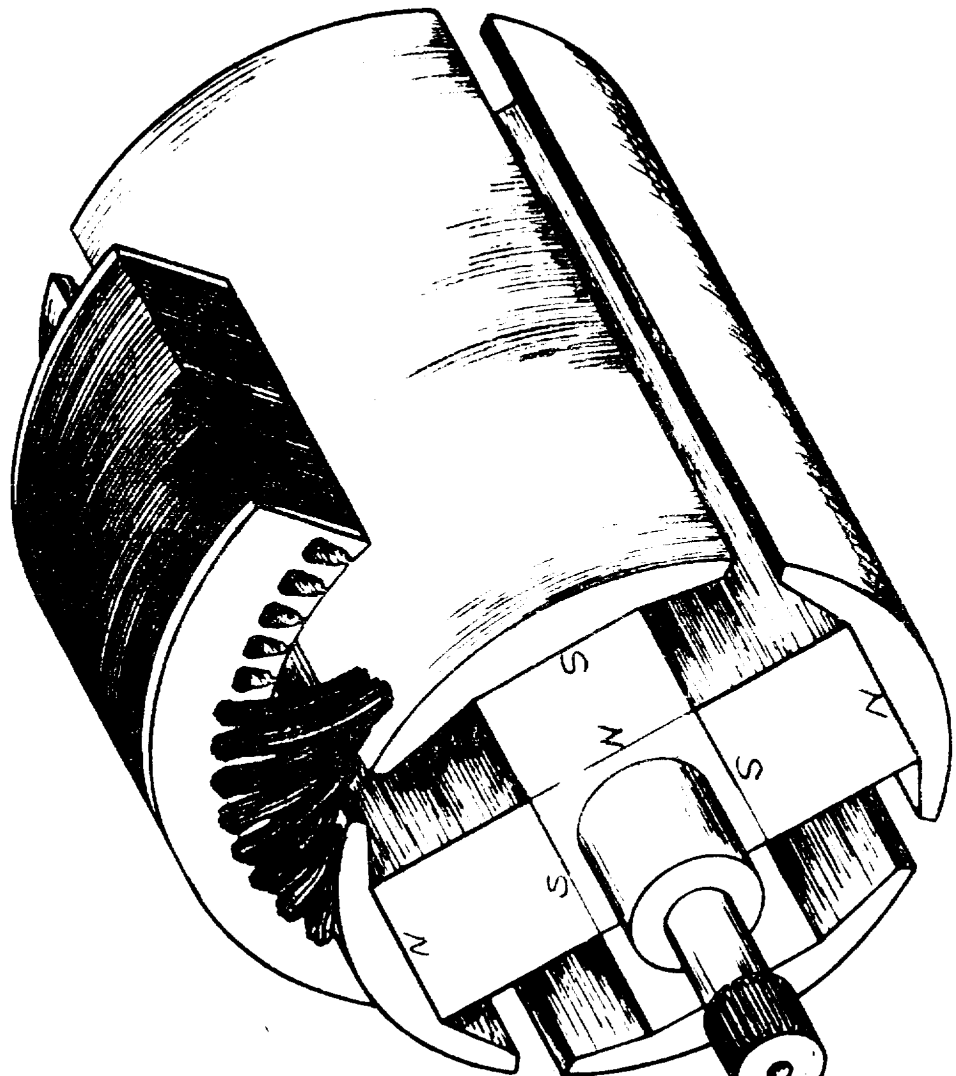
	(ϕ_{pt})	(102a) POLE FLUX					
	(B_p)	(103a) POLE DENSITY					
LOSSES @ NL	(F&W)	(183) F&W LOSS			(F&W) (183)		LOSSES @ FL
	(W_{tnl})	(184) STA TOOTH LOSS			(W_{TFL}) (242)		
	(W_c)	(185) STA CORE LOSS			(W_c) (185)		
	(W_{pnl})	(186) POLE FACE LOSS			(W_{pfl}) (243)		
	(W_{dnl})	(193) DAMPER LOSS			(W_{dfl}) (244)		
	(I^2R_s)	(194) STATOR CU LOSS			(I^2R_s) (245)		
	(–)	(195) EDDY LOSS			(–) (246)		
	(–)	(196) TOTAL LOSSES			(–) (247)		
	(–)	(–) RATING (KW)			(–) (248)		
	(–)	(–) RATING & LOSSES			(–) (249)		
	(–)	(–) PERCENT LOSSES			(–) (250)		
	(–)	(–) PERCENT EFF.			(–) (251)		

VOLT AMPERE CHARACTERISTIC	VOLTS @ 0 LOAD AMPS	
	VOLTS @ 1/4 LOAD AMPS	
	VOLTS @ 1/2 LOAD AMPS	
	VOLTS @ 3/4 LOAD AMPS	
	VOLTS @ 4/4 LOAD AMPS	
	VOLTS @ 5/4 LOAD AMPS	
	VOLTS @ 3/2 LOAD AMPS	

DESIGN MANUAL
FOR
PERMANENT MAGNET, A. C. GENERATORS

INTRODUCTION

The calculation procedure given here is for only one configuration of permanent magnet generators. It is the classical design with definite poles consisting of blocks of magnet material. The pole heads are designed to support the magnets and are usually wider than the magnet blocks. Sometimes the pole heads are designed to provide high out-of-stator flux leakage and thereby cause the magnet material to stay magnetized at a high level of flux density even when air-stabilized.

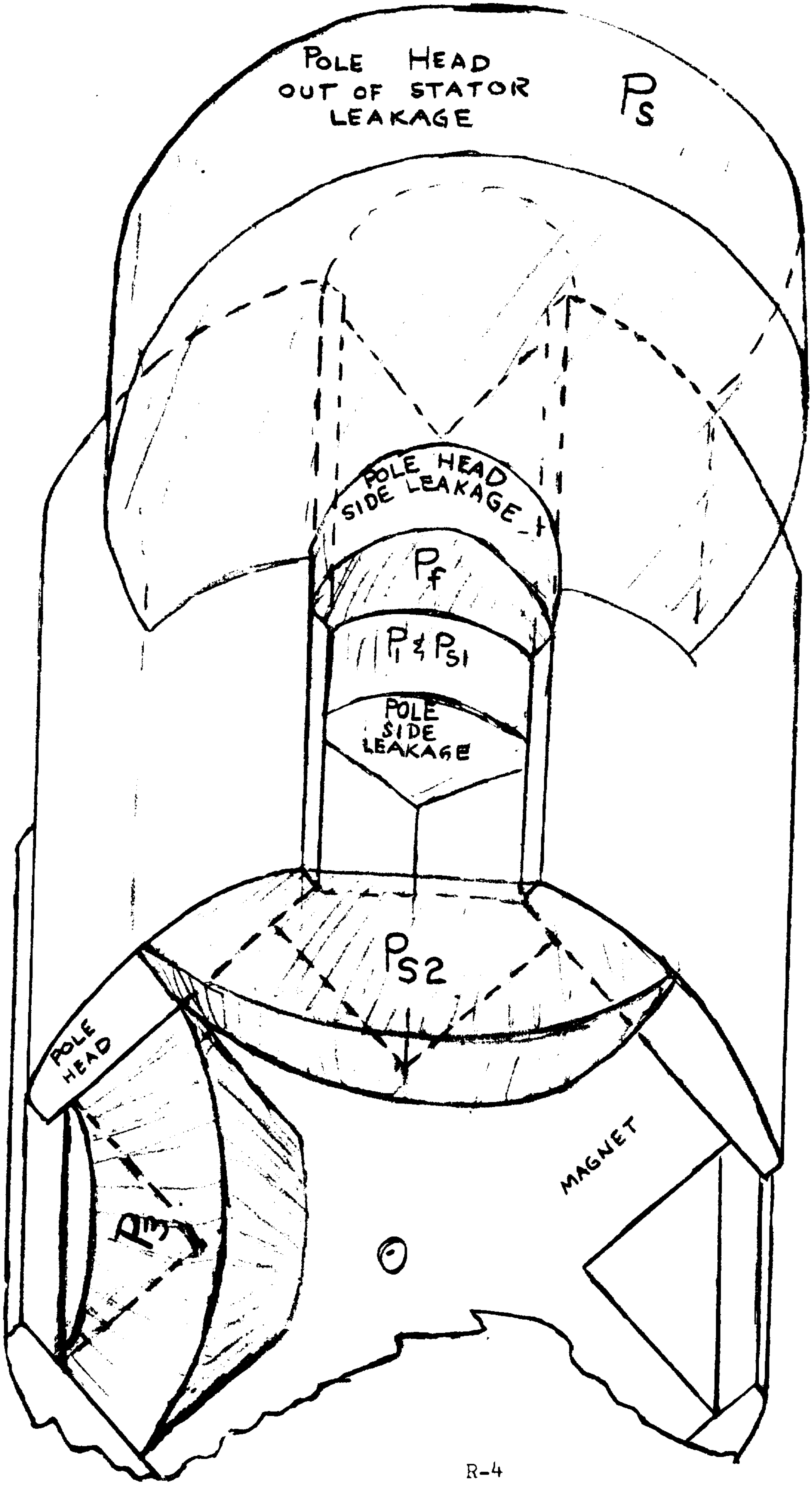


PERMANENT MAGNET GENERATOR

FIGURE R-1

The following sketch illustrates the leakage fluxes that are calculated in determining the performance of the permanent magnet generators covered by this design manual. The formulae and the designations for the permeance calculations are taken from Strauss "Synchronous Machines with Rotating Permanent Magnet Fields" Trans. AIEE 1952 Part II, pp. 887-893. Formulae from Roter's "Electromagnetic Devices" a Wiley and Sons book, are appended to this report, and can be used to estimate permeances for configurations of PM generators different from the one discussed in this manual.

FIGURE R-2


POLE HEAD
OUT OF STATOR
LEAKAGE
P_S
POLE HEAD
SIDE LEAKAGE
P_f
P_1 & P_{S1}
POLE
SIDE
LEAKAGE
P_{S2}
POLE
HEAD
P_3
MAGNET

When the rotor is magnetized and then removed from the magnetizing fixture without a keeper, the magnet flux density will decrease to a value determined by the out-of-stator leakage permeance. This leakage permeance consists of all of the flux leakage permeances of the rotor when the rotor is out of the stator.

When the rotor is placed in position in the stator, some of the flux that leaked from pole-to-pole when the rotor was by itself, now becomes useful flux by flowing through the stator iron and linking the conductors in the output winding.

These rotor flux leakage permeances are separated into discrete leakage paths and are illustrated separately in the following sketches:

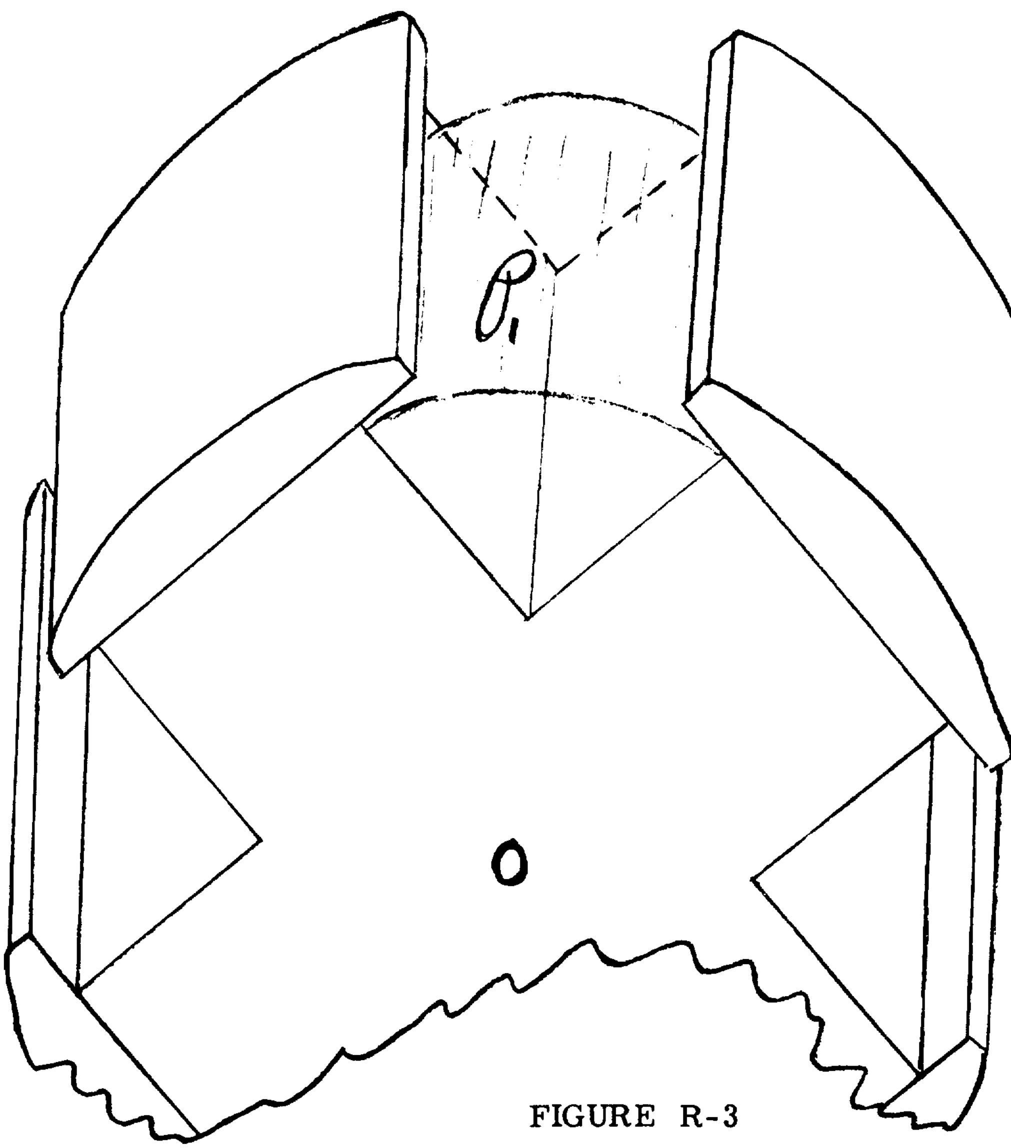


FIGURE R-3

P_1 = The pole-to-pole side leakage permeance. This leakage exists when the rotor is in the stator as well as when it is out and is just unuseable leakage flux.

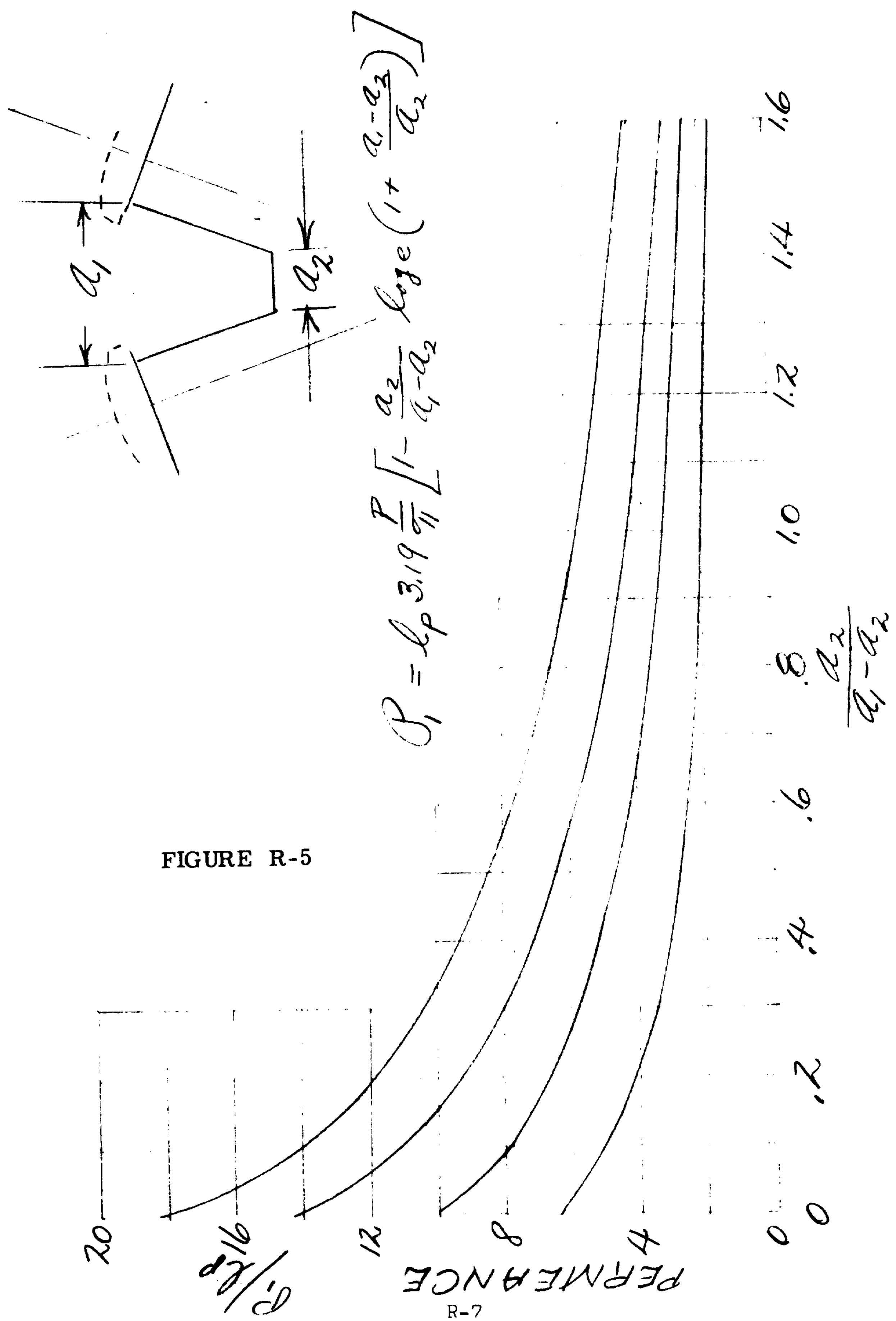
The formula here is taken from Strauss:

$$P_1 = 3.19 \frac{P}{\pi} \ell_p$$

for poles that touch at the base, and

$$P_1 = \ell_p \mu_o \frac{P}{\pi} \left[1 - \frac{a_2}{a_1 - a_2} \ln \left(1 \quad \frac{a_1 - a_2}{a_2} \right) \right]$$

for poles not touching at the base.



a_1
a_2
$P_1 = l_p \, 3.19 \frac{P}{\pi} \left[1 - \frac{a_2}{a_1 - a_2} \log_e \left(1 + \frac{a_1 - a_2}{a_2} \right) \right]$
PERMEANCE P_1/l_p
0
4
8
12
16
20
$\frac{a_2}{a_1 - a_2}$
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6

FIGURE R-5

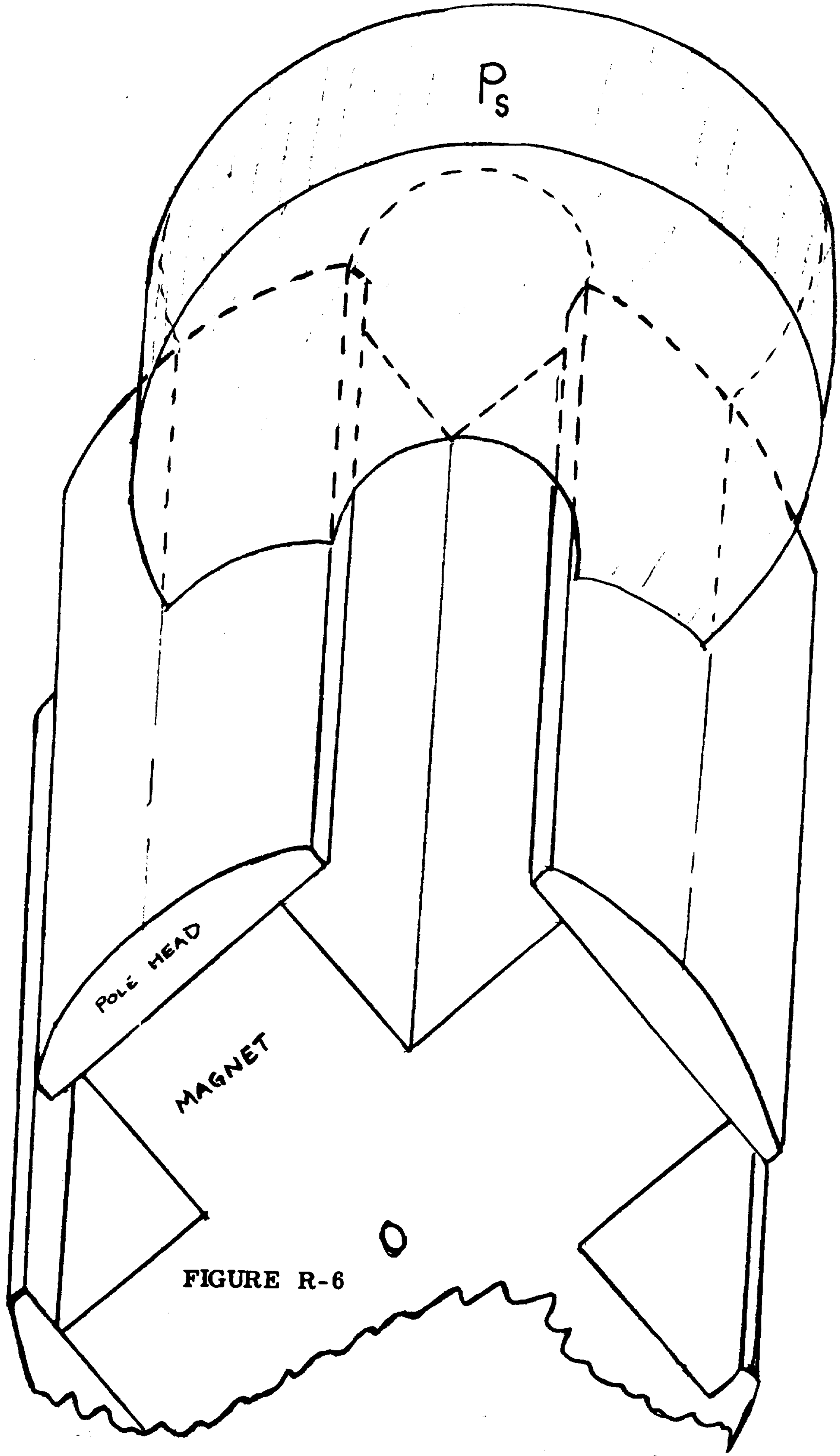


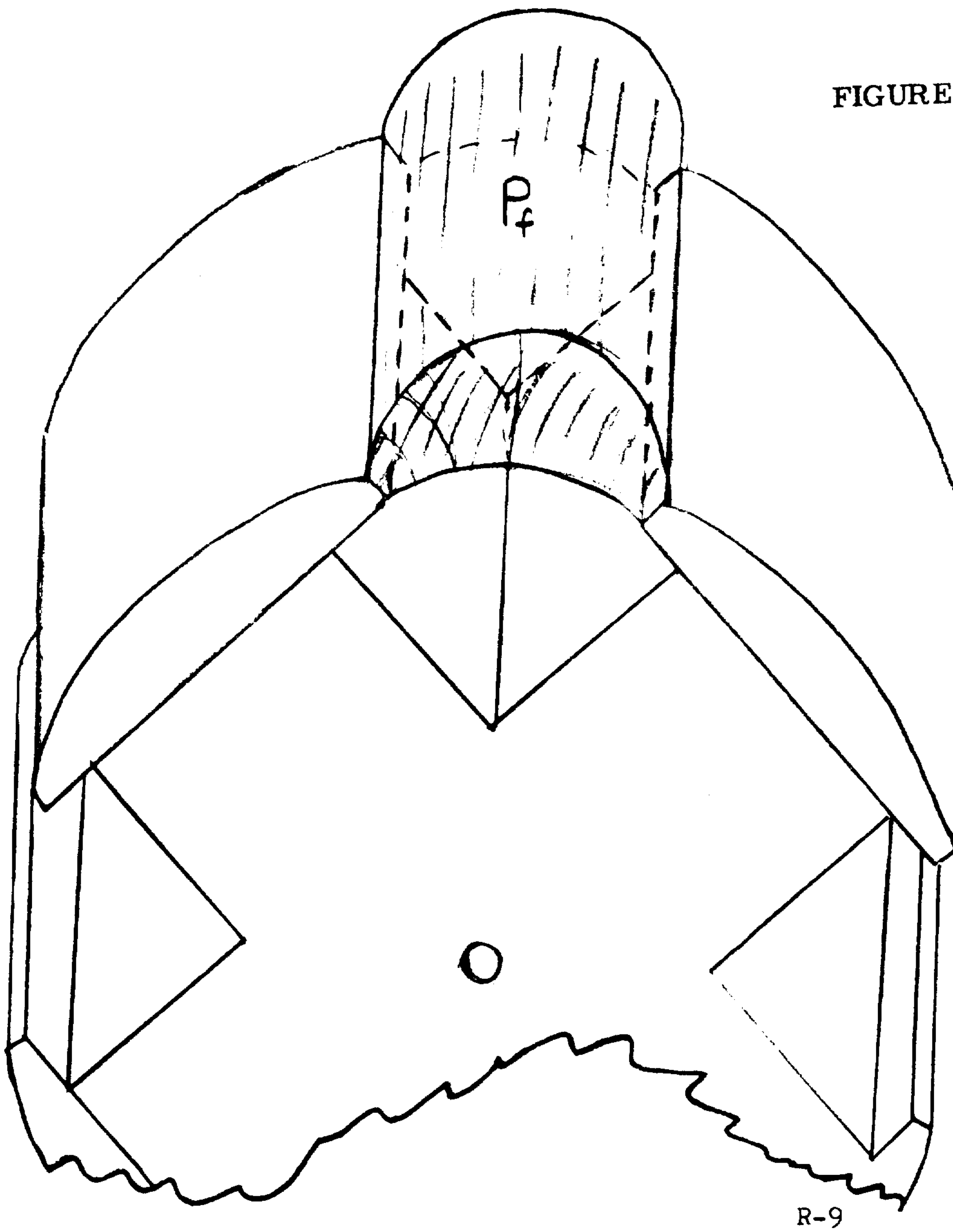
FIGURE R-6

P_s = the permeance of the flux leakage path from the centerline of one pole-head surface to the centerline of the adjacent pole-head surface.

This leakage is part of the out-stator leakage but does not exist when the rotor is inserted in the stator.

$$P_s = 2.03\, \ell_p \ln \frac{\tau_r}{\tau_r - b_h}$$

FIGURE R-7



P_f = the permeance of the flux leakage path between the adjacent ends of the pole heads.

This leakage flux is part of the out-stator leakage but no longer exists when the rotor is placed in the stator.

$$P_f = \mu_0 \ell_p \frac{0.322(\tau_r - b_h)}{\frac{1.220(\tau_r - b_h)}{2}} = 1.66$$

$P_f = 1.66$

$$P_\lambda = P_s + P_f = \ell_p (1.66)\left(1 + 1.23 \log_e \frac{1}{1-\alpha}\right)$$

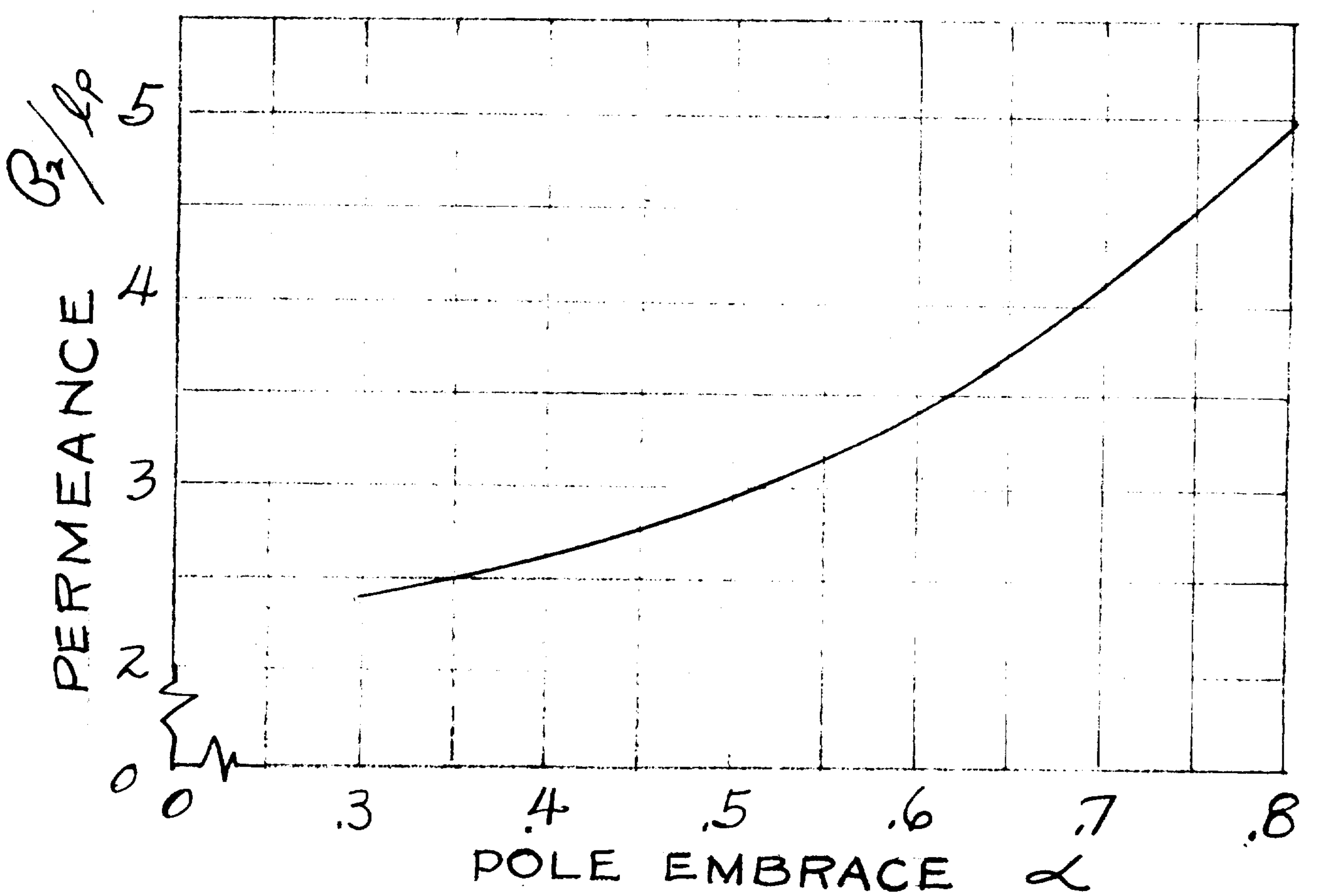
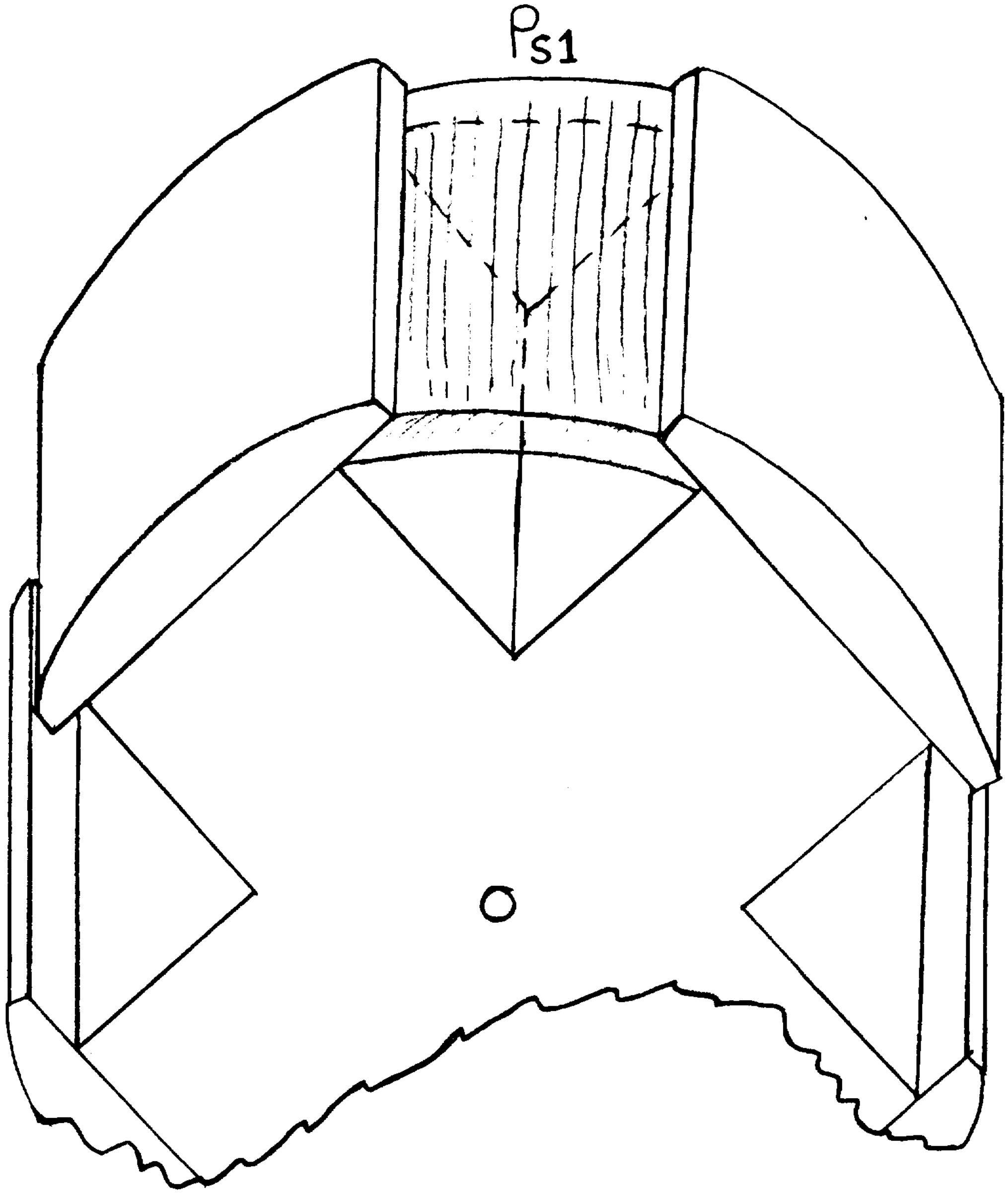


FIGURE R-8

FIGURE R-9



P_{s1} = the permeance of the flux leakage path from the underside of one pole shoe to the underside of the adjacent pole shoe.

This leakage is present when the rotor is in the stator and cannot be utilized.

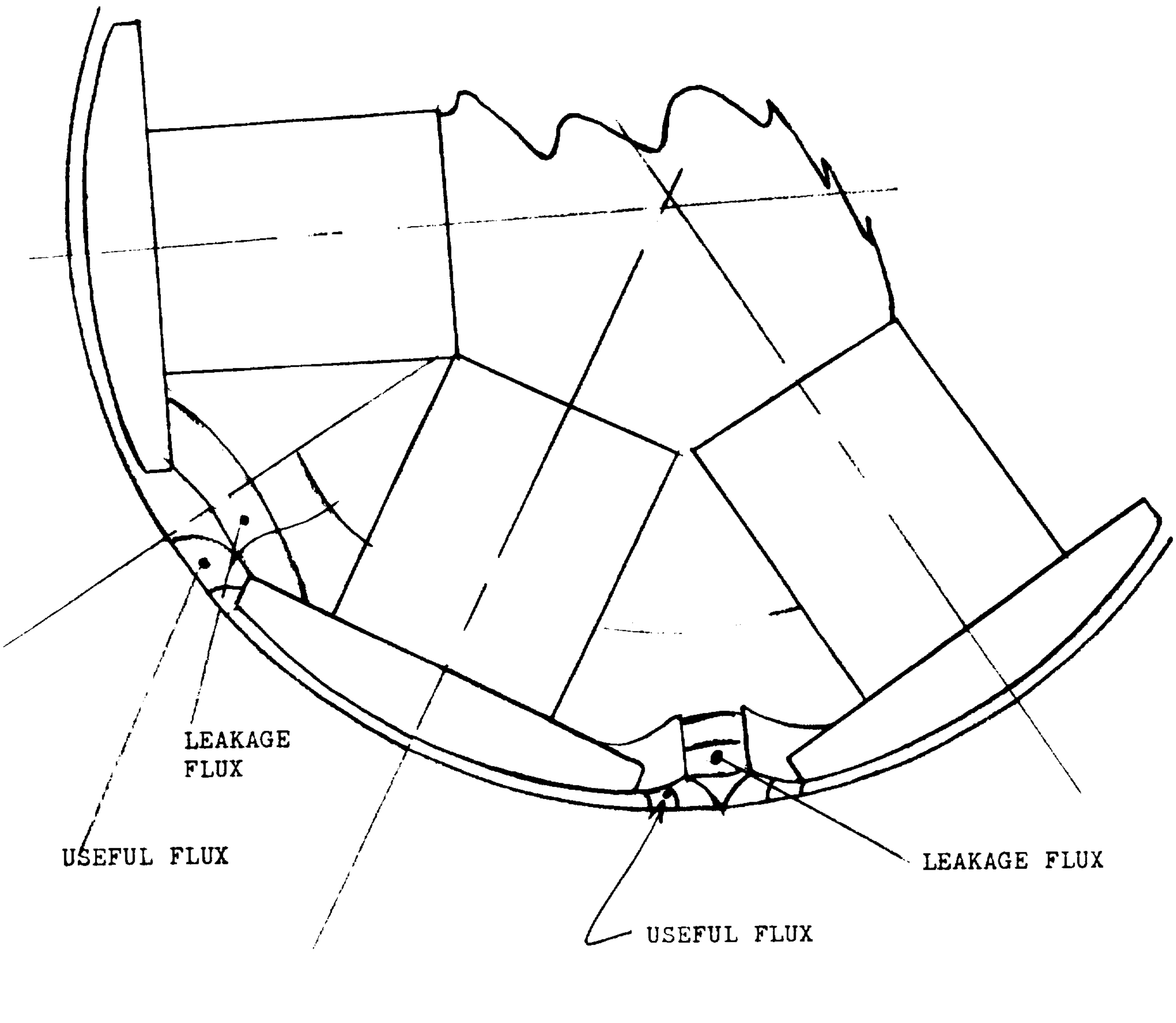
$$P_{s1} = \frac{3.19 \quad h_h \ell_p}{\frac{\frac{\pi d_r}{P} - b_p}{2}}$$

$$= \frac{6.38 \quad h_h \ell_p}{\tau_r - b_p}$$

The formula is an approximation, and is suitable for an estimate of the leakage between the pole heads of the usual four, six or eight pole design. For high leakage pole tips use as h_{h1} the height of the adjacent pole leakage surfaces. See the sketch for two examples.

SKETCH SHOWING HOW FLUX LEAKAGE CONDITIONS CHANGE WHEN EXTENDED POLE HEADS ARE USED. THE ADDED LEAKAGE KEEPS THE MAGNET DENSITY HIGH ON THE MAGNET CHARACTERISTIC MAJOR HYSTERESIS LOOP BUT THE ADDED LEAKAGE FLUX IS NEVER AVAILABLE FOR USE

FIGURE R-10



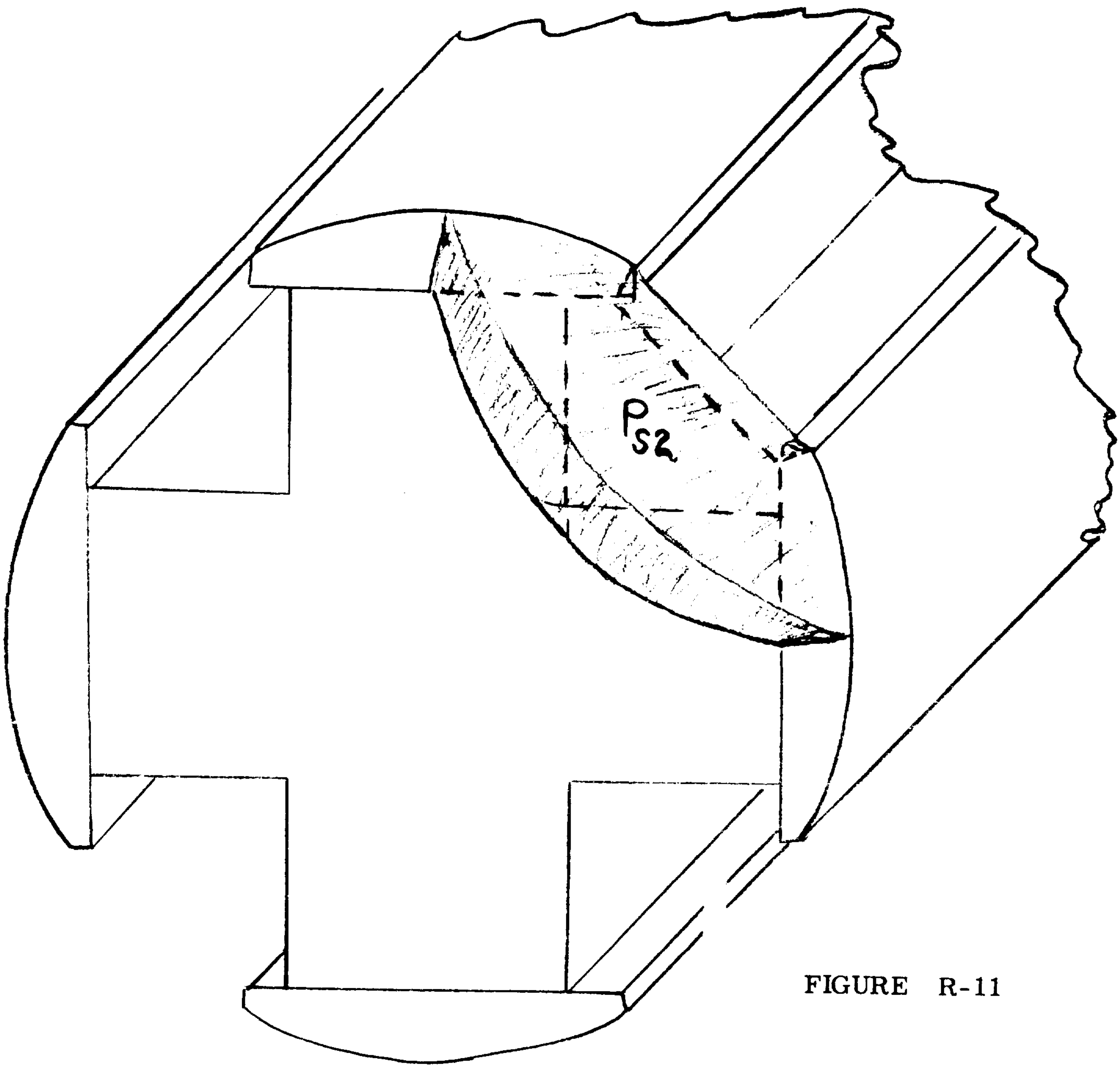


FIGURE R-11

P_{s2} = permeance of the flux leakage path from the centerline of the end surface of one pole head to the centerline of the end surface of the adjacent pole head.

This leakage flux is continuous and cannot be utilized in generating power.

$$P_{s2} = \frac{2\ h_n\ \ P_2}{\ell_p} \qquad \text{where}$$

$$P_2 = P_s + P_f$$

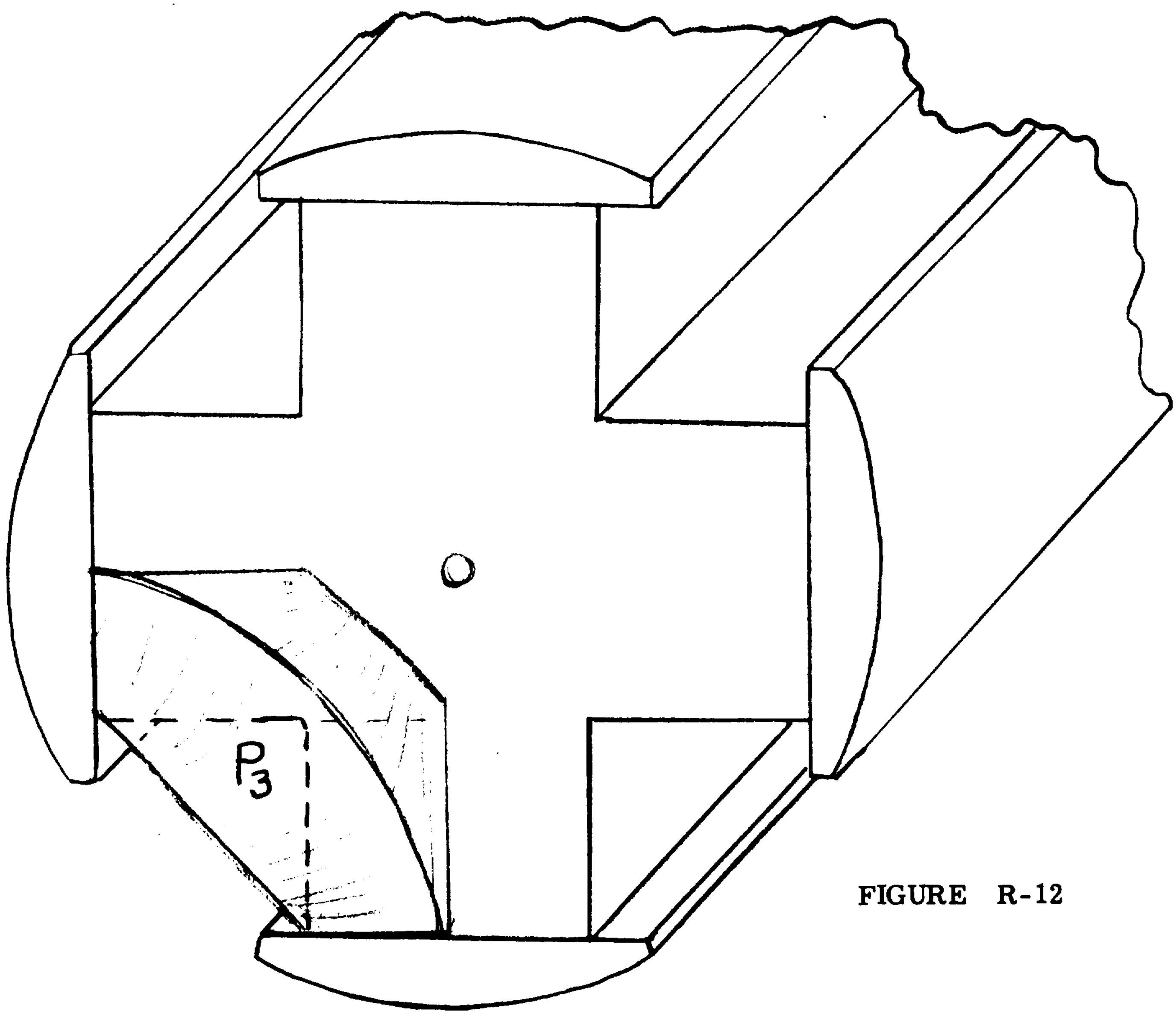


FIGURE R-12

P_3 = the permeance of the flux leakage path from the centerline of the end surface of the pole to the centerline of the adjacent pole end surface.

This leakage flux is always present and cannot be utilized.

$$P_3 = h_p (1.66)\left[1 + 1.23 \log_e\left(1 + \frac{2}{\frac{a_1}{b_p} + \frac{a_2}{b_p}}\right)\right]$$

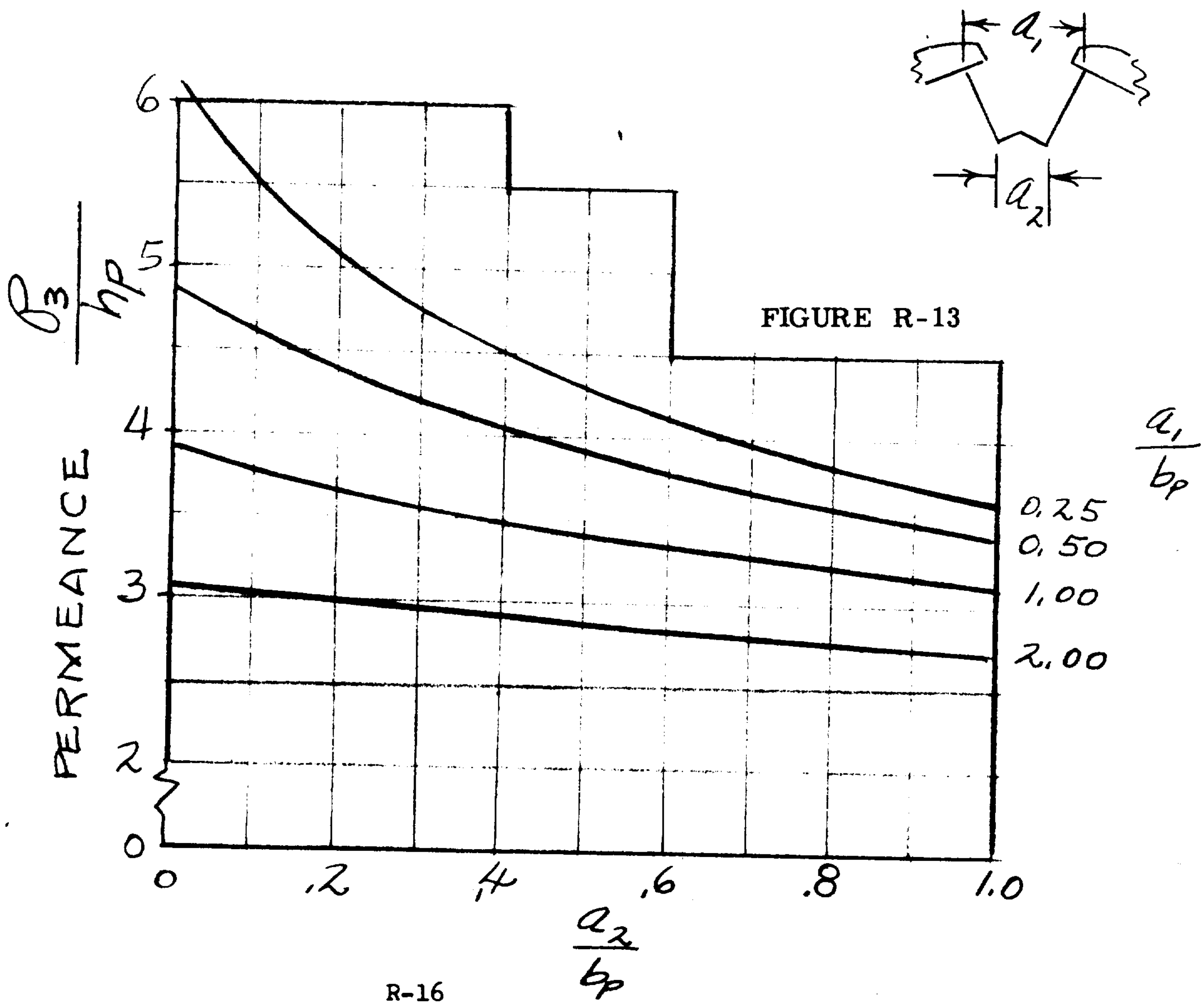


FIGURE R-13

When the rotor is inserted in the stator, the pole-to-pole flux that passed through the permeance paths, $P_s + P_f$ is no longer present as leakage flux. That flux now enters the stator and becomes useful flux.

All of the flux passing through the other pole-to-pole permeance paths is leakage flux that cannot be utilized.

P_i = in-stator leakage permeance

$$P_i = P_o - P_2$$

For convenience, the leakage permeance consisting of the sum of all the permeance paths, through which flux leaks pole-to-pole when the rotor is out of the stator is called P_o = out-stator permeance.

The sum of the pole-to-pole leakage permeance existing when the rotor is installed in the stator is called the in-stator permeance (P_i).

The permeances of the various flux paths have been calculated at this point in the design procedure. They could be used just as they are used in an electromagnetic generator in which case the magnet characteristics would be plotted in terms of total ampere-turns and total magnet flux. This procedure would require a special flux plot for each generator design.

An easier way to determine the magnet performance is to use the characteristic hysteresis loop as it is given by the manufacturer. This loop is plotted in terms of ampere-turns per inch of magnet and flux-density per square inch of magnet.

The calculated permeances are already in terms of leakage flux per ampere turn and if the permeances are multiplied by the magnet length they can be then used in terms of ampere-turns per inch of magnet.

The leakage flux resulting from the calculation would be divided by magnet area to get the flux per square inch of magnet.

The calculation would look like this:

$$P \times \ell_m \times (AT/in) = \phi_\ell$$

$$\frac{P \times \ell_m \times (AT/in)}{\text{Area of Magnet}} = \frac{\phi_\ell}{in^2}$$

$$\frac{P}{\frac{\text{Area Magnet}}{\ell_m}} = \frac{\phi_\ell /in^2}{AT/in}$$

$$\frac{P}{\frac{\ell_p b_p}{h_p}} = \frac{P}{P_m} = \frac{\phi_\ell /in^2}{AT/in}$$

Where $P_m = \frac{\ell_p b_p}{h_p}$

The ideal permanent magnet generator might have high flux leakage in the rotor when the rotor was out-of-stator and low flux leakage when the rotor was inserted in the stator, except that the machine would, in nearly all cases be capable of demagnetizing itself when subjected to a transient or short circuit.

The two following sketches illustrate how a choice is made between magnet materials just on the basis of the out-of-stator leakage characteristic.

The in-stator leakage must be considered in determining whether or not the generator can withstand short circuits and transients without loss of properties.

COMPARISON OF MAGNET PERFORMANCES WHEN THE MAGNETS ARE AIR-STABILIZED AT A HIGH OUT-OF-STATOR LEAKAGE PERMEANCE

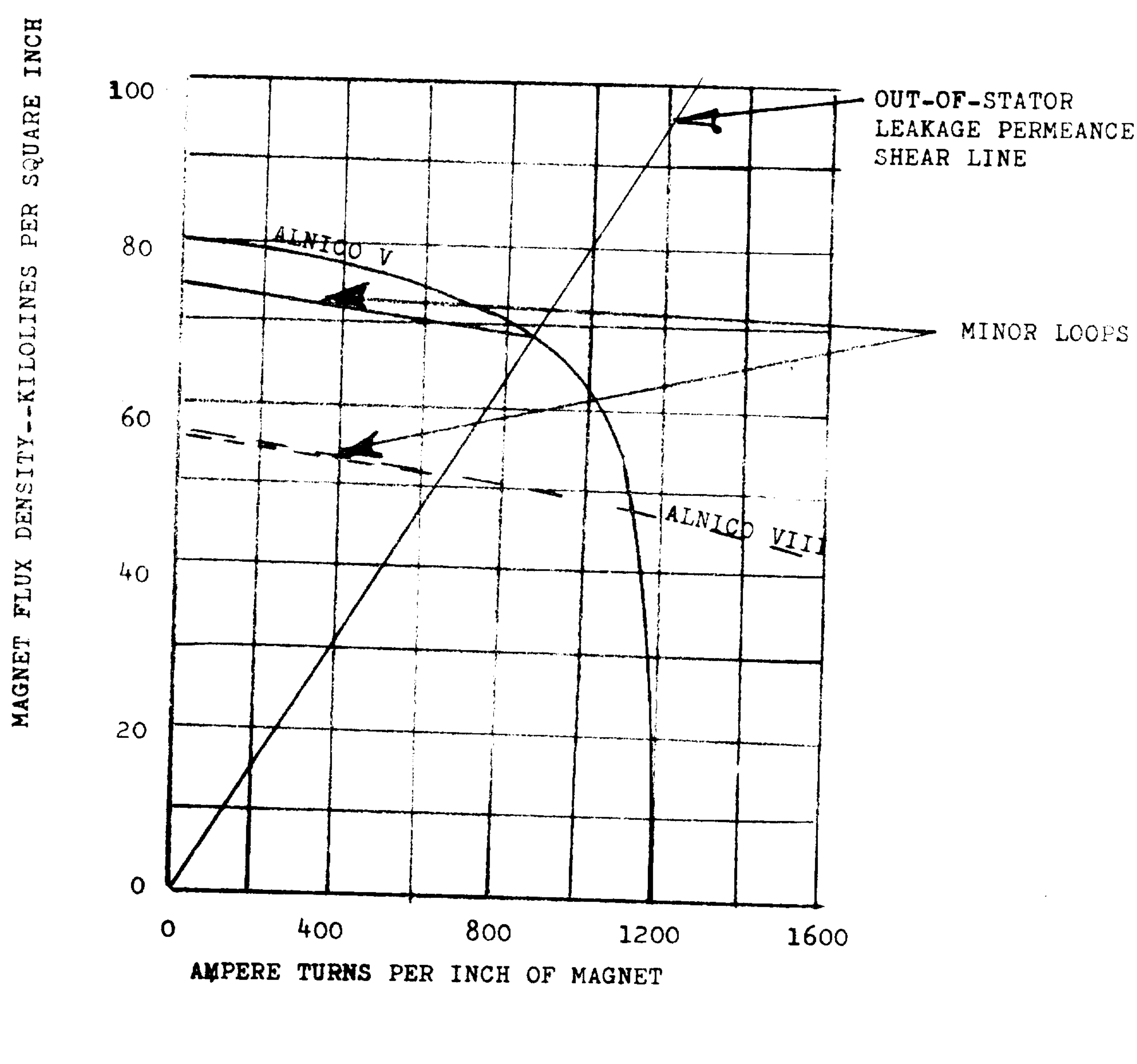


FIGURE R-14

COMPARISON OF MAGNET PERFORMANCES WHEN
THE MAGNETS ARE STABILIZED AT A LOW
OUT-OF-STATOR LEAKAGE PERMEANCE

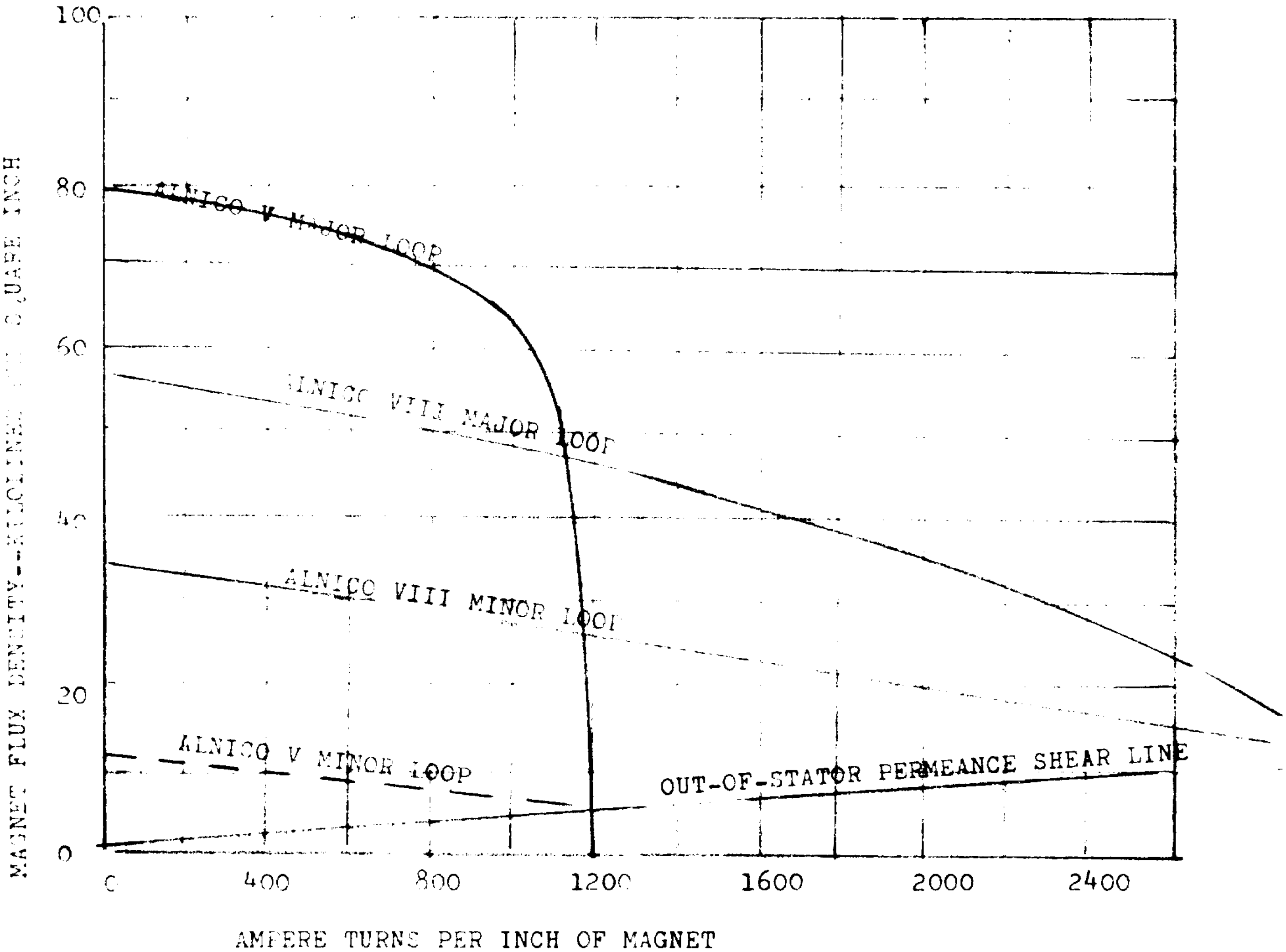


FIGURE R-15

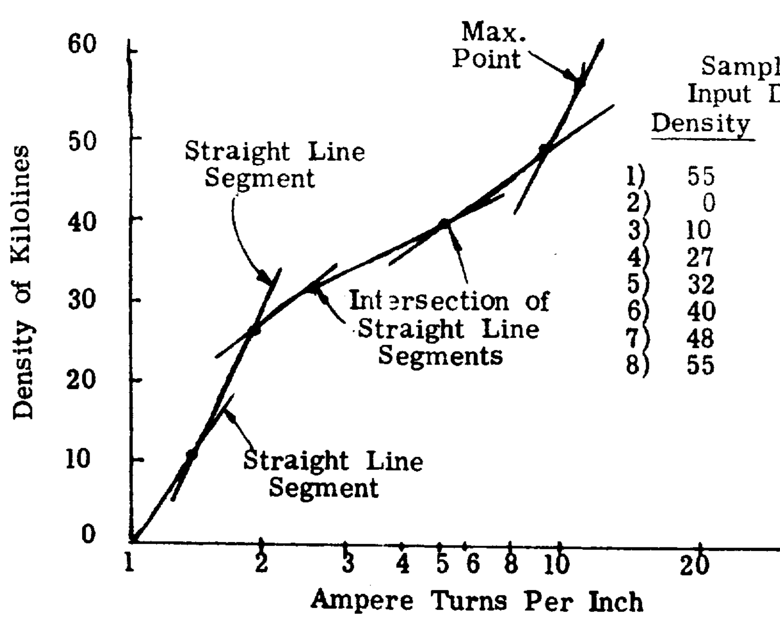
(1)	--	DESIGN NUMBER
(2)	KVA	GENERATOR KVA
(3)	E	LINE VOLTS
(4)	E_{PH}	PHASE VOLTS
(5)	m	PHASES
(5a)	f	FREQUENCY
(6)	P	POLES
(7)	RPM	SPEED
(8)	I_{PH}	PHASE CURRENT
(9)	P. F.	POWER FACTOR
(11)	d	STATOR PUNCHING I.D.
(11a)	d_r	ROTOR O.D.
(12)	D	PUNCHING O.D.
(13)	ℓ	GROSS STATOR CORE LENGTH
(14)	n_v	RADIAL DUCTS
(15)	b_v	RADIAL DUCT WIDTH
(16)	K_i	STACKING FACTOR
(17)	ℓ_s	SOLID CORE LENGTH

(18) **MATERIAL** - This input is used in selecting the proper magnetization curve for stator lamination material and for rotor head laminations when used.

Separate spaces are provided on the input sheet for each section mentioned above. Where curves are available on card decks, used the proper identifying code. Where card decks are not available submit data in the following manner:

The magnetization curve must be available on semi-log paper. Typical curves are shown in this manual on Curves F-15&F-16. Draw straight line segments through the curve starting with zero density. Record the coordinates of the points where the straight line segments intersect. Submit these coordinates as input data for the magnetization curve. The maximum density point must be submitted first.

Refer to Figure below for complete sample



Sample Input Data

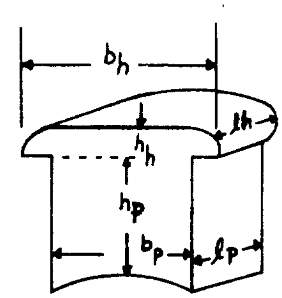
	Density	NI
1)	55	
2)	0	0
3)	10	1.5
4)	27	1.9
5)	32	2.5
6)	40	4.9
7)	48	9.0
8)	55	12.0

(19)	k	WATTS/LB
(20)	B	DENSITY
(21)	--	TYPE OF STATOR SLOT
(22)	--	ALL SLOT DIMENSIONS
(23)	Q	STATOR SLOTS
(24)	h_c	DEPTH BELOW SLOTS
(25)	q	SLOTS PER POLE PER PHASE
(26)	τ_s	STATOR SLOT PITCH
(27)	τ_s 1/3	STATOR SLOT PITCH
(28)	--	TYPE OF WINDING
(29)	--	TYPE OF COIL
(30)	n_s	CONDUCTORS PER SLOT
(31)	y	THROW
(31a)	--	PER UNIT OF POLE PITCH SPANNED
(32)	C	PARALLEL PATHS
(33)	--	STRAND DIA. OR WIDTH
(34)	N_{ST}	NUMBER OF STRANDS PER CONDUCTOR IN DEPTH
(34a)	N'_{ST}	NUMBER OF STRANDS PER CONDUCTOR
(35)	d_b	DIAMETER OF BENDER PIN
(36)	ℓ_{e2}	COIL EXTENSION BEYOND CORE
(37)	h_{ST}	HEIGHT OF UNINSULATED STRAND
(38)	h'_{ST}	DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH

(39)	--	STATOR COIL STRAND THICKNESS
(40)	τ_{SK}	SKEW
(41)	τ_P	POLE PITCH
(42)	K_{SK}	SKEW FACTOR
(42a)	--	PHASE BELT ANGLE
(43)	K_d	DISTRIBUTION FACTOR
(44)	K_p	PITCH FACTOR
(45)	n_e	TOTAL EFFECTIVE CONDUCTORS
(46)	a_c	CONDUCTOR AREA OF STATOR WINDING
(47)	S_S	CURRENT DENSITY
(48)	L_E	END EXTENSION LENGTH
(49)	ℓ_t	1/2 MEAN TURN
(50)	X_s °C	STATOR TEMP °C
(51)	ρ_s	RESISTIVITY OF STATOR WINDING
(52)	$\rho_{s\,(hot)}$	RESISTIVITY OF STATOR WINDING
(53)	R_{SPH} (cold)	STATOR RESISTANCE/PHASE (ALSO CALLED R_a)
(54)	R_{SPH} (hot)	STATOR RESISTANCE/PHASE (ALSO CALLED R_a)
(55)	EF (top)	EDDY FACTOR TOP
(56)	EF (bot)	EDDY FACTOR BOTTOM

(57)	b_{tm}	STATOR TOOTH WIDTH 1/2 way down tooth in inches -
(57a)	$b_{t\ 1/3}$	STATOR TOOTH WIDTH 1/3 distance up from narrowest sect
(58)	b_t	TOOTH WIDTH AT STATOR I.D. in inches -
(59)	g_{min}	MINIMUM AIR GAP in inches
(59a)	g_{max}	MAXIMUM AIR GAP in inches
(60)	C_X	REDUCTION FACTOR
(61)	K_X	FACTOR TO ACCOUNT FOR DIFFERENCE in phase current in coil sides in same slot
(62)	λ_i	CONDUCTOR PERMEANCE
(63)	K_E	LEAKAGE REACTIVE FACTOR for end turn
(64)	λ_E	END WINDING PERMEANCE
(65)	--	WEIGHT OF COPPER
(66)	--	WEIGHT OF STATOR IRON - in lbs.
(67)	K_s	CARTER COEFFICIENT

(68)	A_g	<u>AIR GAP AREA</u>
(69)	g_e	<u>EFFECTIVE AIR GAP</u>
(70)	λ_a	<u>AIR GAP PERMEANCE</u>
(71)	C_1	<u>THE RATIO OF MAXIMUM FUNDAMENTAL</u> of the field form to the actual maximum of the field form
(72)	C_W	<u>WINDING CONSTANT</u>
(73)	C_P	<u>POLE CONSTANT</u>
(74)	C_M	<u>DEMAGNETIZING FACTOR</u>
(75)	C_q	<u>CROSS MAGNETIZING FACTOR</u> - quadrature axis
(76)	--	<u>POLE DIMENSIONS LOCATIONS</u>



Where:

b_h = width of pole head
b_p = width of pole body (MAGNET)
h_h = height of pole head at center
h_p = height of pole body (MAGNET)
ℓ_p = length of pole body (MAGNET)
ℓ_h = length of pole head

all dimensions in inches

(77)	α	POLE EMBRACE
(79)	a_p	POLE AREA
(80b)	$\lambda_{s\ell}$	POLE SIDE LEAKAGE PERMEANCE
(81b)	$\lambda_{t\ell}$	POLE TIP LEAKAGE PERMEANCE
(82b)	$\lambda_{e\ell}$	POLE END LEAKAGE PERMEANCE
(88)	ϕ_T	TOTAL FLUX IN KILO LINES
(91)	B_t	TOOTH DENSITY in Kilo Lines/in^2
(92)	ϕ_P	FLUX PER POLE in Kilo Lines
(94)	B_c	CORE DENSITY in Kilo Lines/in^2
(95)	B_g	GAP DENSITY in Kilo Lines/in^2
(96)	F_g	AIR GAP AMPERE TURNS
(97)	F_T	STATOR TOOTH AMPERE TURNS
(98)	F_c	STATOR CORE AMPERE TURNS
(98a)	F_s	STATOR AMPERE TURNS,

(100a)	ϕ_{ℓ}	**LEAKAGE FLUX** - at no load
(102a)	ϕ_{PT}	**TOTAL FLUX PER POLE** - at no load
(103a)	B_P	**POLE DENSITY** $B_p = \frac{O_p}{A_p} = \frac{(92)}{(79)}$
(128)	A	**AMPERE CONDUCTORS** per inch
(129)	X	**REACTANCE FACTOR**
(130)	X_{ℓ}	**LEAKAGE REACTANCE**
(135)	--	**DAMPER SLOT DIMENSIONS**
(136)	--	**DAMPER BAR DIA OR WIDTH** in inches
(137)	h_{b1}	**DAMPER BAR THICKNESS** in inches - Damper bar thickness considered equal to damper bar slot height (h_b) per item (135). Set this item = 0 for round bar.
(138)	n_b	**NUMBER OF DAMPER BARS PER POLE**
(139)	ℓ_b	**DAMPER BAR LENGTH** in inches
(140)	τ_b	**DAMPER BAR PITCH** in inches
(141)	ρ_D	**RESISTIVITY** of damper bar @ 20°C in ohm-inches - Refer to table given in item (51) for conversion factors.
(142)	X_D °C	**DAMPER BAR TEMP °C** - Input temp at which damper losses are to be calculated.

(143)	ρ_D (hot)	RESISTIVITY of damper bar @ X_D °C
(144)	a_{cd}	CONDUCTOR AREA OF DAMPER BAR
(145)	V_r	PERIPHERAL SPEED
(157)	--	WEIGHT OF ROTOR IRON
(158)	λ_b	PERMEANCE OF DAMPER BAR
(159)	λ_{pt}	PERMEANCE OF END PORTION OF DAMPER BARS
(161 F)	λ_F	ROTOR LEAKAGE PERMEANCE
(162)	λ_{Dd}	PERMEANCE OF DAMPER BAR - in direct axis
(163)	X_{Dd}	DAMPER LEAKAGE REACTANCE - in direct axis
(164)	λ_{Dq}	PERMEANCE IN QUADRATURE AXIS
(165)	X_{Dq}	DAMPER LEAKAGE REACTANCE - in quadrature axis
(168)	X_d''	SUBTRANSIENT REACTANCE in direct axis
(170)	X_2	NEGATIVE SEQUENCE REACTANCE -

(183)	F & W	<u>FRICTION & WINDAGE LOSS</u>
(184)	W_{TNL}	<u>STATOR TEETH LOSS</u> - at no load.
(185)	W_c	<u>STATOR CORE LOSS</u> -
(186)	W_{NPL}	<u>POLE FACE LOSS</u> - at no load.
(187)	K_1	
(188)	K_2	
(189)	K_3	
(190)	K_4	
(191)	K_5	
(192)	K_6	
(193)	W_{DNL}	<u>DAMPER LOSS</u> - at no load at $20^{o}C$.
(196)	--	<u>TOTAL LOSSES</u> - at no load.

(242)	W_{TFL}	STATOR TEETH LOSS at 100% load
(243)	W_{PFL}	POLE FACE LOSS at 100% load
(244)	W_{DFL}	DAMPER LOSS at 100% load
(245)	I^2R	STATOR I^2R at 100% load
(246)	--	EDDY LOSS
(247)	--	TOTAL LOSSES at 100% load
(248)	--	RATING IN KW at 100% load
(249)	--	RATING & Σ LOSSES
(250)	--	% LOSSES
(251)	--	% EFFICIENCY

(500) P_1 The pole-to-pole side leakage permeance. This leakage exists when the rotor is in the stator as well as when it is out and is just unuseable leakage flux.

The formula here is taken from Strauss:

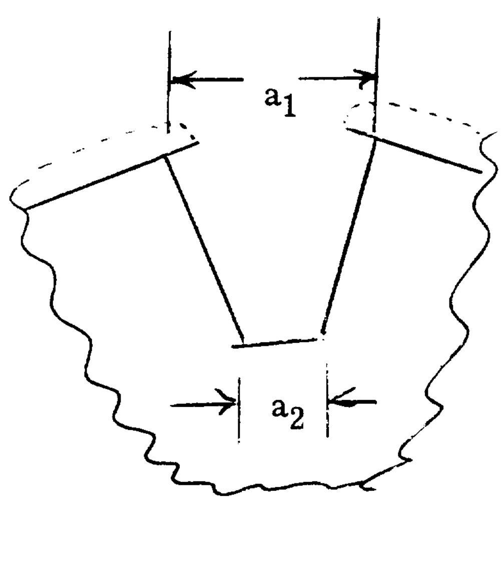
For poles that touch at the base or $(a_2) < .2''$

$$P_1 = 3.19 \frac{(P)}{\pi} \ell_p = 3.19 \frac{(6)(76)}{\pi}$$

For poles not touching at the base or $(a_2) > .2''$

$$P_1 = \ell_p \mu_o \frac{P}{\pi}\left[1 - \frac{a_2}{a_1 - a_2} \ln\left(1 + \frac{a_1 - a_2}{a_2}\right)\right]$$

$$= \mu_o (76)\frac{(6)}{\pi}\left[1 - \frac{(502)}{(501)-(502)} \ln\left(1 + \frac{(501)-(502)}{(502)}\right)\right]$$



(501) a_1 Distance between outer edges of adjacent pole sides

$$a_1 = 2\left(\left\{\left[\frac{(d)}{2} - (g) - (h_h)\right] \tan \frac{\pi}{(P)} - \frac{(b_p)}{2}\right\} \cos \frac{\pi}{(P)}\right)$$

$$= 2\left(\left\{\left[\frac{(11)}{2} - (59) - (76)\right] \tan \frac{\pi}{(6)} - \frac{(76)}{2}\right\} \cos \frac{\pi}{(6)}\right)$$

(502) a_2 Distance between inner edges of adjacent pole sides

$$a_2 = 2\left(\left\{\left[\frac{(d)}{2} - (g) - (h_h) - (h_p)\right] \tan \frac{\pi}{(P)} - \frac{(b_p)}{2}\right\} \cos \frac{\pi}{(P)}\right)$$

$$= 2\left(\left\{\left[\frac{(11)}{2} - (59) - (76) - (76)\right] \tan \frac{\pi}{(6)} - \frac{(76)}{2}\right\} \cos \frac{\pi}{(6)}\right)$$

(503) P_2 Permeance of the flux leakage paths from pole-head surface to pole-head surface and between adjacent pole head edges. This flux leakage is out-stator leakage that becomes useful flux when the rotor is installed in the stator.

(503) (Cont'd.)

$$P_2 = 1.66 \left[1 + 1.23 \ \ln \frac{1}{1 - (\alpha)} \right] \ell_p$$

$$= 1.66 \left[1 + 1.23 \ \ln \frac{1}{1 - (77)} \right] (76)$$

(504) P_3 The permeance of the flux leakage path from the centerline of the end surface of the pole to the centerline of the adjacent pole end surface.

$$P_3 = (h_p)\, 1.66 \left[1 + 1.23 \ \ln \left(1 + \frac{2}{\frac{(a_1)}{(b_p)} + \frac{(a_2)}{(b_p)}} \right) \right]$$

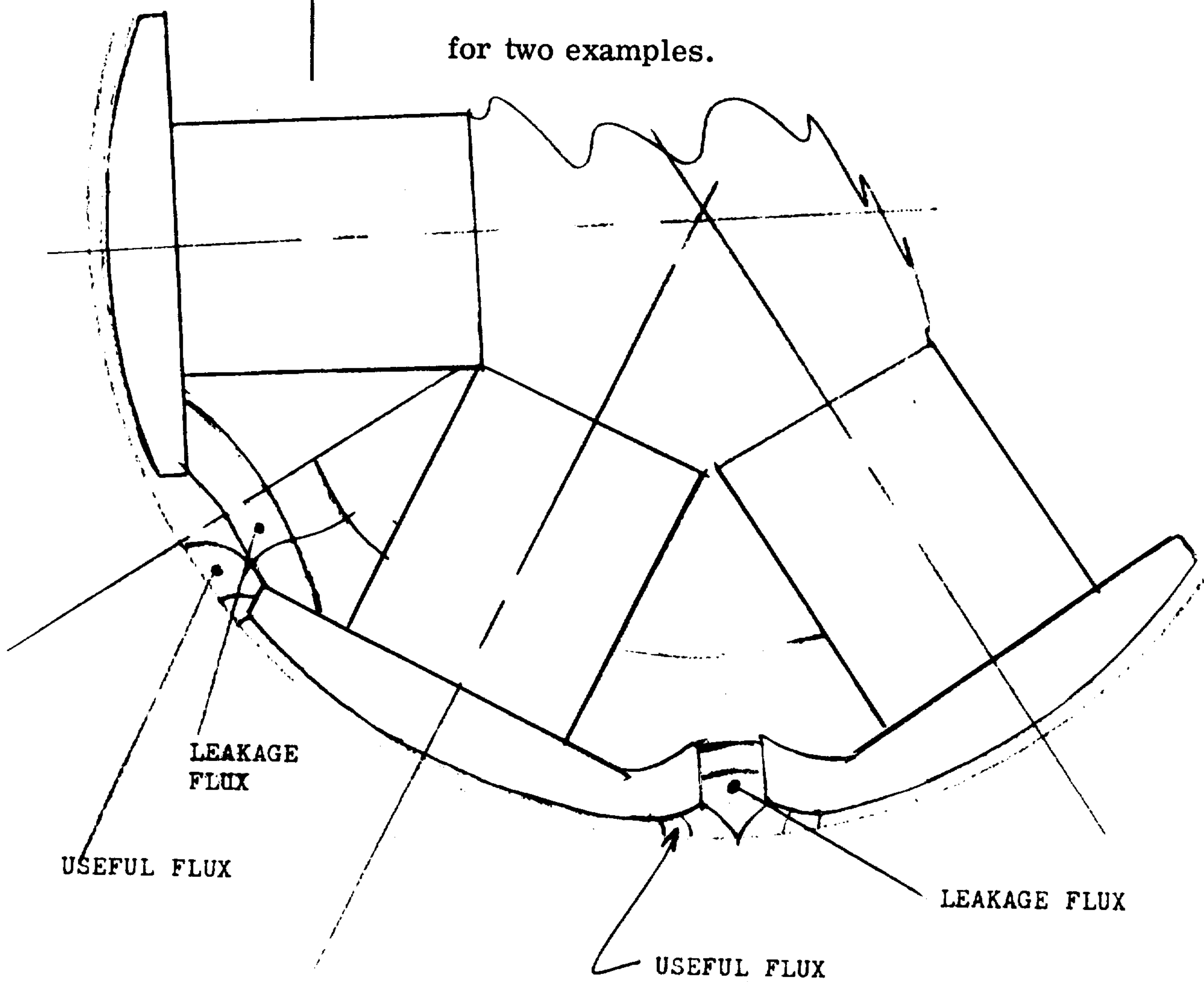
$$= (76)\, 1.66 \left[1 + 1.23 \ \ln \left(1 + \frac{2}{\frac{(501)}{(76)} \quad \frac{(502)}{(76)}} \right) \right]$$

(505) P_{s1} The permeance of the flux leakage path from the underside of one pole shoe to the underside of the adjacent pole shoe. This leakage is present when the rotor is in the stator and cannot be utilized.

$$P_{s1} = \frac{6.38\, (h_h)\, (\ell_p)}{(\tau_p) - (b_p)}$$

$$= \frac{6.38\ (76)(76)}{(41) - (76)}$$

(505)	Cont'd.	The formula is an approximation, and is suitable for an estimate of the leakage between the pole heads of the usual four, six or eight pole design. For high leakage pole tips use as h_h the height of the adjacent pole leakage surfaces. See the sketch for two examples.



SKETCH SHOWING HOW FLUX LEAKAGE CONDITIONS CHANGE WHEN EXTENDED POLE HEADS ARE USED. THE ADDED LEAKAGE KEEPS THE MAGNET OPERATING AT A HIGH MAGNET FLUX DENSITY

(506)	P_{s2}	Permeance of the flux leakage path from the centerline of the end surface of one pole head to the centerline of the end surface of the adjacent pole head.
		This leakage flux is continuous and cannot be utilized in generating power.
		$$P_{s2} = \frac{2\,(h_h)(P_2)}{(\ell_p)} \qquad \frac{2(76)\ (503)}{(76)}$$
(507)	P_m	Adjustment factor to convert the permeance values to the proper scale for use in the general hysteresis loop.
		$$P_m = \frac{\text{magnet area (net)}}{\text{magnet length}}$$
		$$= \frac{(\ell_p)\ (b_p)\ (C)}{2\ (h_p)} \qquad \frac{(76)\ (76)\ (508)}{2\ (76)}$$
(508)	C	C is a factor to account for holes that reduce magnet area

(509) P_i Permeance of the in-stator leakage flux.

$$P_i = P_{s1} + P_{s2} + P_1 + P_3$$

$$= (505) + (506) + (500) + (504)$$

(510) P_o Permeance of the out-stator leakage flux.

$$P_o = P_i + P_2$$

$$= (509) + (503)$$

(511) P_g Air-gap permeance.

$$P_g = 3.19 \frac{\pi}{2} \frac{C_p \, d_r}{g_e \, P} \ell$$

$$= \frac{\lambda_a \pi C_p \ell}{4}$$

$$= .785 \lambda_a C_p \ell = .785 \, (70c)(73)(13)$$

(512) $\frac{P_o}{P_m}$ Slope of the out-stator permeance shear line

$$\frac{P_o}{P_m} = \frac{(510)}{(507)}$$

(513) $\frac{P_i}{P_m}$ Slope of the in-stator permeance shear line

$$\frac{P_i}{P_m} = \frac{(509)}{(507)}$$

(514) P_w

Total apparent permeance of the working air gap. The total permeance of the magnet flux paths when the rotor is in the stator.

$$P_w = P_i + P_g$$

$$= (509) + (511)$$

(515) $\frac{P_w}{P_m}$

Slope of the working-gap shear line.

$$\frac{P_w}{P_m} = \frac{(514)}{(507)}$$

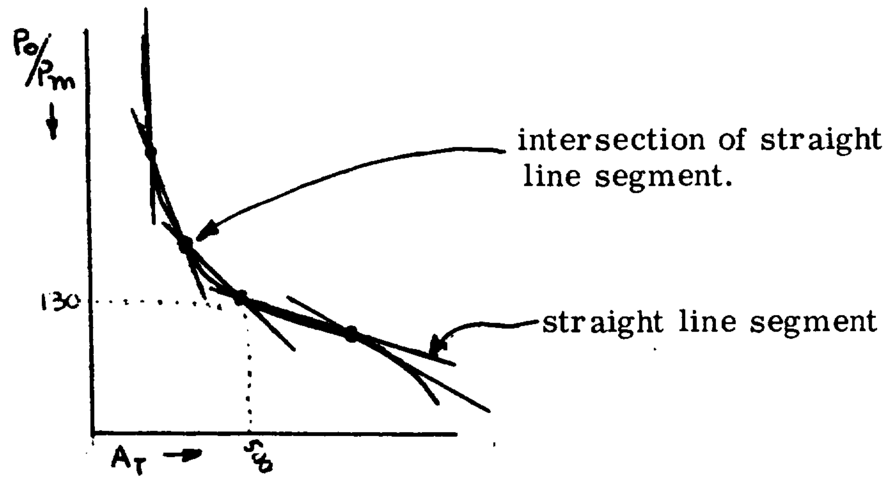
(516) A_T

The ampere-turn/inch of magnet value corresponding to the intersection of the shear line $\frac{P_o}{P_m}$ with the major hysteresis loop of the permanent magnet material.

The value A_T locates the lower end of the minor hysteresis loop and determines the maximum demagnetizing mmf that the magnet can endure without some loss of magnetic properties. Several curves of A_T versus out-stator shear line values $\frac{P_o}{P_m}$ are given in Curves F-17, F-18, F-19.

(516) cont'd

This computer program will determine A_T from a curve of $\frac{Po}{Pm}$ VS A_T. This curve must be submitted on an auxiliary input sheet in the same form as outlined in in item (18) in the master design manual. For example:



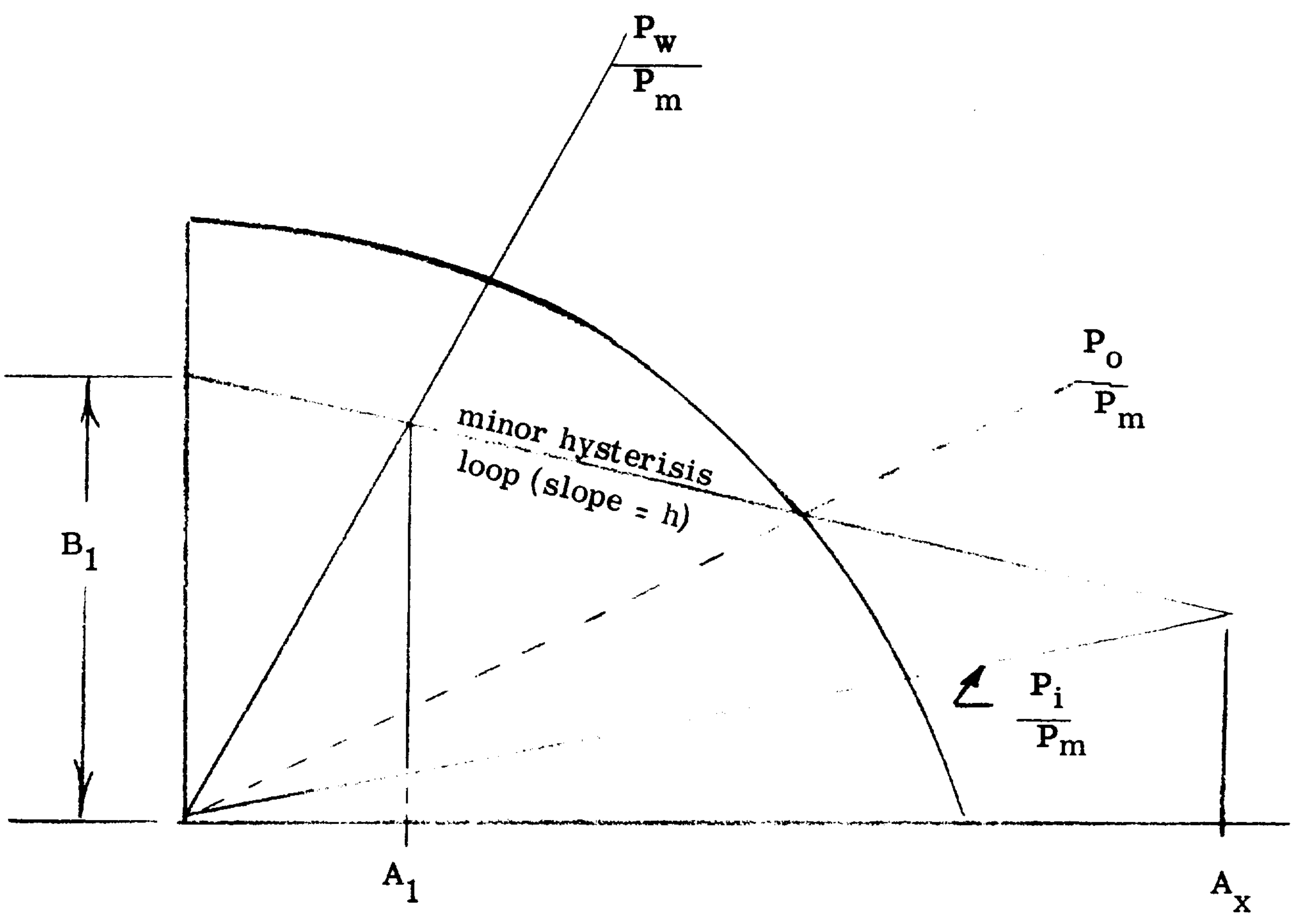
Sample input data for curve of ALNICO VI

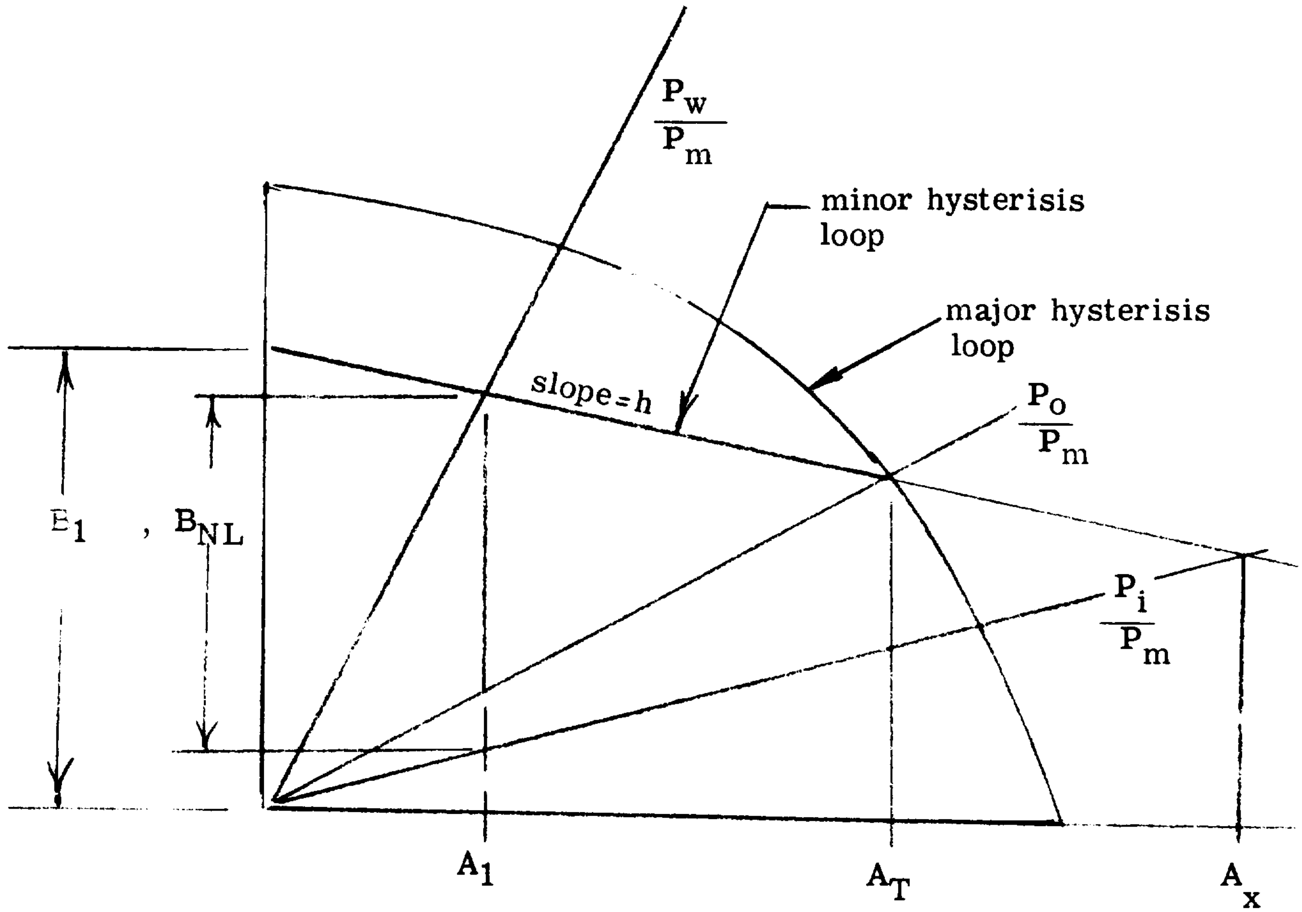
$\frac{Po}{Pm}$	A_T
-	1500 ← MAX AMPERE TURNS
20	1250
32	1100
35	1000
85	640
130	500
150	385
187	315
257	280
340	200

(517) E_{NL} The no load voltage produced by the unregulated PM generator at rated speed.

$$E_{NL} = \frac{E_{PH}(A_T)}{(B_p)} \; \frac{\left(\frac{P_o}{P_m} + h\right)\left(\frac{P_w}{P_m} - \frac{P_i}{P_m}\right) \times 10^{-3}}{\left(\frac{P_w}{P_m} + h\right)}$$

$$= \frac{(4)(516)\left((512) + (519a)\right)\left((515) - (513)\right) \times 10^{-3}}{(103a)\left((515) + (519a)\right)}$$





$$B_1 = A_x\left(\frac{P_i}{P_m} + h\right)$$

$$A_x = \frac{B_1}{\left(\frac{P_i}{P_m} + h\right)} = \frac{A_T\left(\frac{P_o}{P_m} + h\right)}{\left(\frac{P_i}{P_m} + h\right)}$$

(519)	A_x	Ampere turns per inch of magnet -- the value corresponding to the intersection of the shear line P_i/P_m and the extension of the minor hysteresis loop having slope = h
		$$A_x = \frac{A_T\left(\frac{P_o}{P_m} + h\right)}{\left(\frac{P_i}{P_m} + h\right)} = \frac{(516)\left((512) + (519a)\right)}{\left((513) + (519a)\right)}$$
(519a)	h	Slope of hysteresis loop in PM material
(520)	A_1	Ampere turns per inch of magnet -- the value that corresponds to the intersection of the minor hysteresis loop and the shear line P_w/P_m
		$$A_1 = \frac{A_T\left(\frac{P_o}{P_m} + h\right)}{\left(\frac{P_w}{P_m} + h\right)}$$ $$= \frac{(516)\left((512) + (519a)\right)}{(515) + (519a)}$$

(522)	I_{SC}	The current per phase flowing when all phases are shorted together at the machine terminals.

$$I'_{SC} = \frac{E_{NL}\left[A_x - A_1 - H'_{d1}\right]}{\sqrt{R_a^2 - (X_\ell)^2}} \text{ ohms}$$

$$= \frac{(517)\left[(519) - (520) - (522)\right]}{\sqrt{(53)^2 - \left[\frac{(130)(4)}{100\,(8)}\right]^2}}$$

$$H'_{d1} = \frac{.45\,(C_m)(N_e)(I')\,K_d}{P\,h_p}$$

I'_{SC} and H'_{d1} must be solved for simultaneously. For the first trial assume $I' = 2\,I_{ph}$ where I_{ph} = Rated Amps. Then

$$H'_{d1} = \frac{.45(74)(45)(43)\;2(8)}{(6)(76)}$$

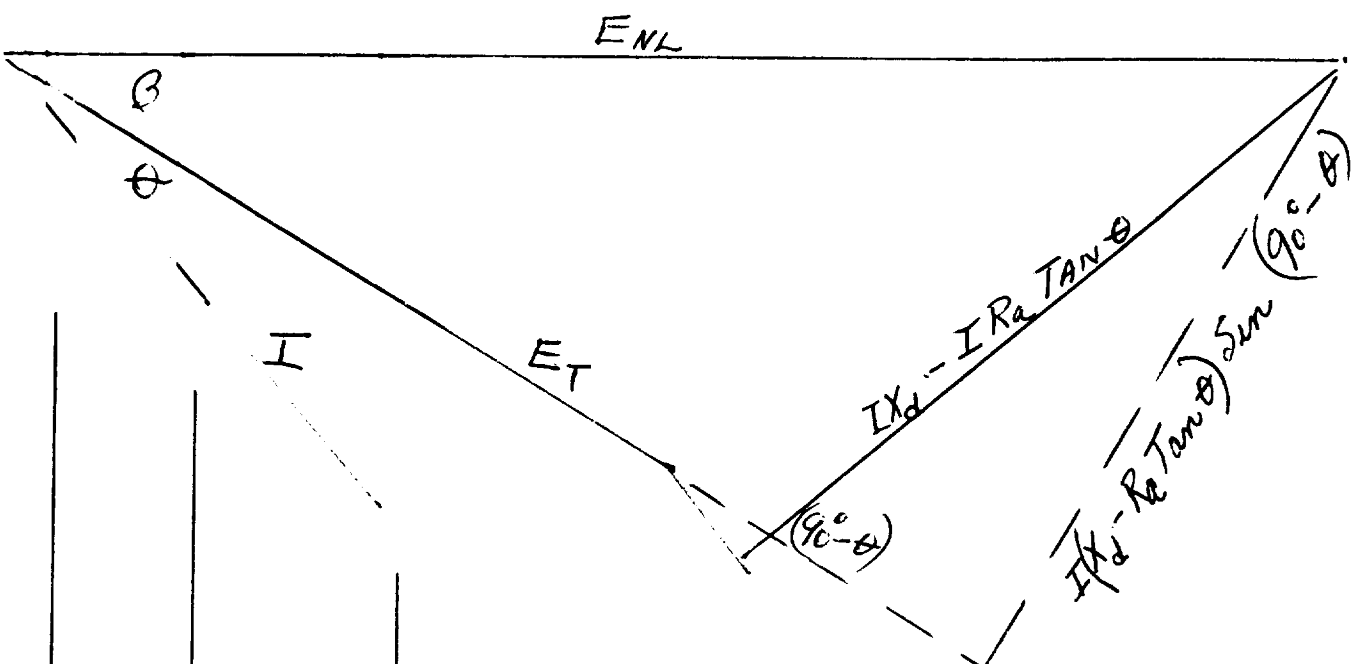
for the first trial. Compare I'_{SC} calculated with the value of I' assumed for H'_{d1}.

If $I'_{SC} = \left[I' \text{ assumed} \pm .05\,I'\right]$, the calculation is completed. If $I_{SC} \neq \left[I' \pm .05\,I'\right]$ try a new value of

$$I'' = I'_{SC} - \left[\frac{I'_{SC} - I'}{2}\right]$$

and repeat until $I'_{SC} = I'' \pm .05\,I''$

(523)	$X_{d(ohms)}$	$X_{d(ohms)} = \frac{E_{NL}}{I_{SC}} = \frac{(517)}{(522)}$
(523a)	X_d percent	$X_d \% = X_{d\,ohms} \times \frac{I_{ph}(100)}{E_{ph}} = (523)\ \frac{(8)}{(4)} \times 100$
(525)	E_{FL}	The voltage supplied to the load at rated current, rated speed, and at a specified power factor.



$$\text{Sin B} = \frac{\left[I X_d - I R_a \text{ Tan } \theta \right] \text{Sin } (90^o - \theta)}{E_{NL}}$$

$$\text{Cos B} = 1 - \text{Sin}^2 \text{ B}$$

$$E_{FL} = E_{NL} \cos B - \left[I X_d - I R_a \tan \theta \right] \cos (90^{o} - \theta) - \frac{IR}{P.F.}$$

$$\theta = \cos^{-1} P.\ F.$$

$$E_{FL} = (517) \cos (525) - \left[(8)(523) - (8)(53) \tan (525) \right] x \cos \left[\frac{\pi}{2} - (525) \right] - \frac{(8)(53)}{(9)}$$

(526) $\frac{E_{FL}}{4}$ Voltage supplied at 1/4 rated current, at rated speed and specified P. F.

This is a repeat of calculation item (525) substituting I/4 for I.

(527) $\frac{E_{FL}}{2}$ The voltage supplied at 1/2 rated current, at rated speed and specified P. F.

This is a repeat of calculation item (525) substituting I/4 for I.

(528) $E_{FL\frac{3}{4}}$ The voltage supplied at 3/4 rated current, at rated speed and specified P. F.

This is a repeat of calculation item (525) substituting I/4 for I.

(529)	$E_{FL\frac{5}{4}}$	<u>The voltage supplied at 5/4 rated current, at rated speed and specified P. F.</u> This is a repeat of calculation item (525) substituting I/4 for I.
(530)	$E_{FL\frac{3}{2}}$	<u>The voltage supplied at 3/2 rated current, at rated speed and specified P. F.</u> This is a repeat of calculation item (525) substituting I/4 for I.

EQUIVALENT CIRCUITS

Equivalent Circuits

Introduction

In the statement of work describing this study, an equivalent circuit is requested. The description in part reads: "The circuit and parameters chosen and evaluated should be capable of completely describing both steady state and transient performance including various overloading and short-circuit capabilities."

"Parameters for the equivalent circuit are to be derived and evaluated."

"Transfer functions and time constants are to be derived and evaluated."

"All applicable reactances are to be derived and evaluated e.g., synchronous, positive and negative sequence, transient and subtransient, direct and quadrature axes, armature, leakage, armature reaction, etc."

This section contains a derivation of an equivalent circuit submitted to satisfy the requirement for a circuit describing steady state and transient performance. The circuit also describes the performance of the generator when subjected to unbalanced loading.

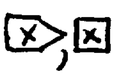
The derivation of the equivalent circuit described here is the work of Liang Liang.

Overloading, short-circuit capabilities, time constants and reactance are derived and calculated elsewhere in the study.

The equivalent circuits themselves are on Pages 31, 33, 72 and 73. The symbols are on Pages 2 and 3. Derivations and explanations are given step-by-step.

Nomenclature

Symbol		Subscript	
τ	- torque	R	- resultant
ℓ	- distance	α, β	- reference frames
v	- velocity	em	- electromagnetic
F	- force	d	- direct axis
e	- voltage	q	- quadratic axis
i	- current	a	- armature
ψ	- flux linkage	f	- excitation field
ω	- frequency in rad/sec	md	- direct axis magnetizing component
R	- resistance	mq	- quadratic axis magnetizing component
L	- inductance	Dd	- direct axis damper bar
θ	- power factor angle	Dq	- quadratic axis damper bar
x	- reactance	g	- generator
p	- power	$a\ell$	- armature leakage
J	- moment of inertia	$f\ell$	- field leakage
D	- damping factor	o	- zero sequence
K	- conversion constant	s	- shaft
f	- frequency in cycles per sec	t	- terminal
P	- number of poles	L	- load
M	- mutual inductance	a	-) phases
N	- turns of winding	b	-) phases
z	- impedance	c	-) phases
s	- Laplace operator	A	- load of phase
G(s)	- transfer function	B	- load of phase b

Symbol		
$\Phi(s)$	-	power density spectrum
$\Phi(t)$	-	correlation function
T	-	time constant
A	-	amplifier
C	-	capacitor
SJ	-	summing junction
t	-	time
E(s)	-	voltage
ε	-	error signal
	-	integrator
	-	operation amplifier
	-	multiplier
	-	square root
O	-	potentiometer
	-	high gain amplifier
$\boxed{sq}$	-	square
$\underline{x}$	-	state vector
$\underline{m}$	-	control vector
$\underline{n}$	-	disturbance vector
A	-	coefficient matrix
B	-	driving matrix
Exp	-	exponential
ℓn	-	natural logarithm
s	-	sensitivity

Subscript		
C	-	load of phase c
i	-	input
ab	-	between phase a and b
bc	-	between phase b and c
ca	-	between phase c and a
r	-	rated
fb	-	feedback
g	-	generator
e	-	excitation
ss	-	steady state

I FUNDAMENTALS

1. Assumptions

(a) Symmetrical three phase, delta or Y-connected machine with field structure symmetrical about the axis of the field winding and interpolar space.

(b) Armature phase mmf in effect, sinusoidally distributed.

(c) Magnetic and electric materials are rigidly connected.

(d) Neglect eddy current in armature iron.

(e) Neglect hysteresis effect.

(f) Neglect magnetic saturation (optional).

(g) Rotor considered as stationary reference frame.

(h) Parameters are time invariant.

2. Classical Approach

For all electric machines, the dynamic equation of Lagrange applies (in tensor):

$$\mathcal{T}^{\alpha} = \frac{d}{dt}\left(\frac{\partial \tau_R}{\partial v^{\alpha}}\right) - \frac{\partial \tau_R}{\partial \ell^{\alpha}} + \frac{\partial F_{em}}{\partial v^{\alpha}} \tag{1}$$

The stator and the rotor of the machine are considered as reference frames respectively. The holonomic expression has to be transformed into unholonomic before the two-reaction theory can be applied. That is, to choose an arbitrary frame (stator or rotor) as stationary and the other considers it as reference. Thus -

$$\mathcal{T}^{\alpha} = \frac{d}{dt}\left(\frac{\partial \tau_R}{\partial v^{\alpha}}\right) - \frac{\partial \tau_R}{\partial \ell^{\alpha}} + \frac{\partial F_{em}}{\partial v^{\alpha}} + \frac{\partial \tau_R}{\partial v^{\alpha}} v^{\beta} Q^{\delta}_{\alpha\beta} \tag{2}$$

$$Q^{\delta}_{\alpha\beta} = \left(\frac{\partial C^{\delta}_{k}}{\partial \ell^{n}} - \frac{\partial C^{\delta}_{n}}{\partial \ell^{k}}\right) C^{k}_{\alpha} C^{n}_{\beta}$$

C_α^k, C_β^n - transformation tensors

- non-holonomic object

The complexity in solving the problem directly is obvious; therefore, other approaches are used.

3. Basic Equations

By means of the two-reaction method and by choosing the rotor as the stationary reference frame, the representation of the dynamic behavior of synchronous generators can be written in set of ordinary equations. The reference frame is resolved into direct and quadratic axis.

Armature -

$$e_d = -R_a i_d + \frac{d}{dt}\Psi_d - \Psi_q \omega_g \tag{3}$$

$$e_q = -R_a i_q + \frac{d}{dt}\Psi_q + \Psi_d \omega_g \tag{4}$$

$$e_t = \sqrt{e_d^2 + e_q^2} \tag{5}$$

$$\Psi_d = L_{md} i_f - (L_{md} + L_{al}) i_d + L_{md} i_{Dd} \tag{6}$$

$$\Psi_q = -(L_{mq} + L_{al}) i_q + L_{mq} i_{Dq} \tag{7}$$

Field -

$$e_f = R_f i_f + \frac{d}{dt}\Psi_f \tag{8}$$

$$\psi_f = (L_{md} + L_{f\ell}) i_f - L_{md} i_d + L_{md} i_{Dd} \tag{9}$$

Damper bar -

$$e_{Dd} = R_{Dd} i_{Dd} + \frac{d}{dt} \psi_{Dd} = 0 \tag{10}$$

$$e_{Dq} = R_{Dq} i_{Dq} + \frac{d}{dt} \psi_{Dq} = 0 \tag{11}$$

$$\psi_{Dd} = L_{md} i_f - L_{md} i_d + (L_{md} + L_{Dl}) i_{Dd} \tag{12}$$

$$\psi_{Dq} = -L_{mq} i_q + (L_{mq} + L_{Dq}) i_{Dq} \tag{13}$$

Zero sequence -

$$e_o = -R_o i_o + \frac{d}{dt} \psi_o \tag{14}$$

$$\psi_o = -L_o i_o \tag{15}$$

Electromagnetic torque -

$$\tau_{em} = \psi_d i_q - \psi_q i_d \tag{16}$$

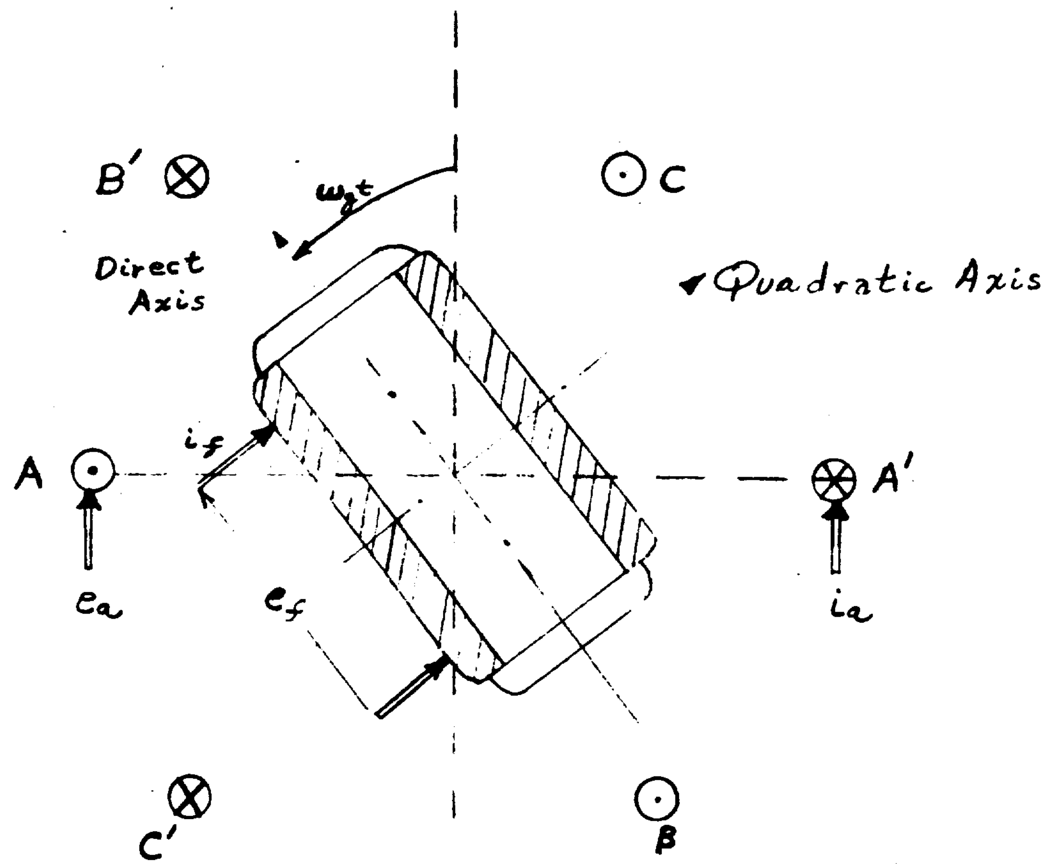


Fig. 1 Physical Arrangement

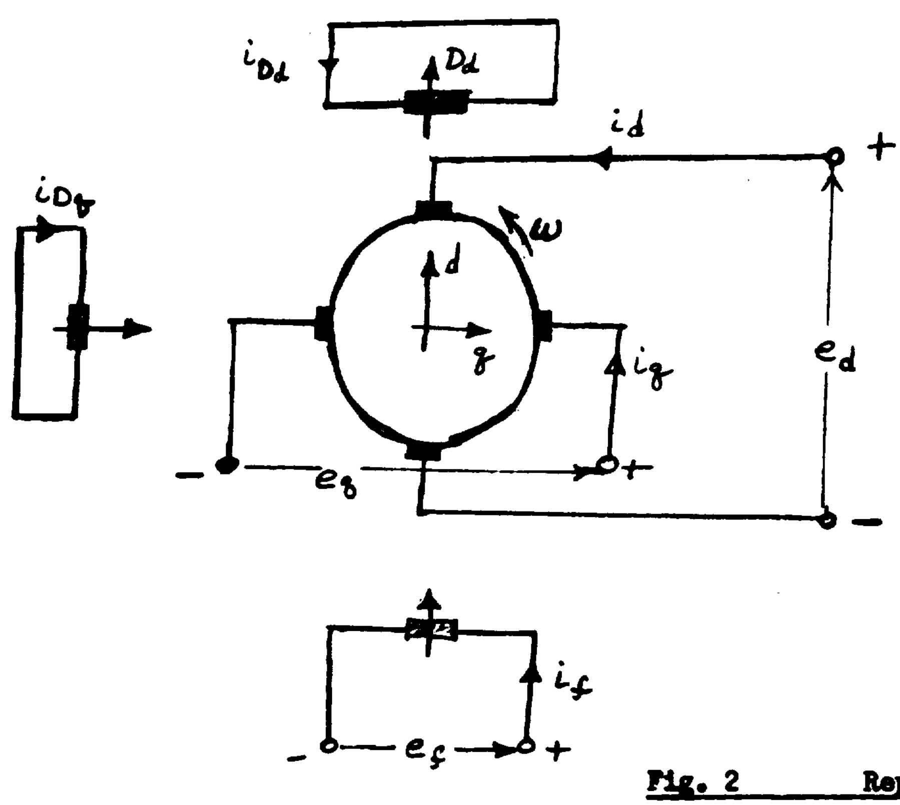
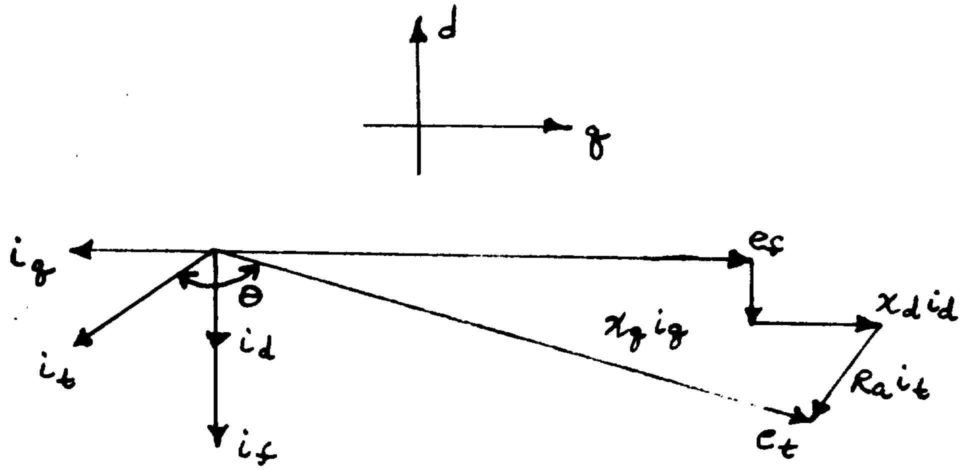
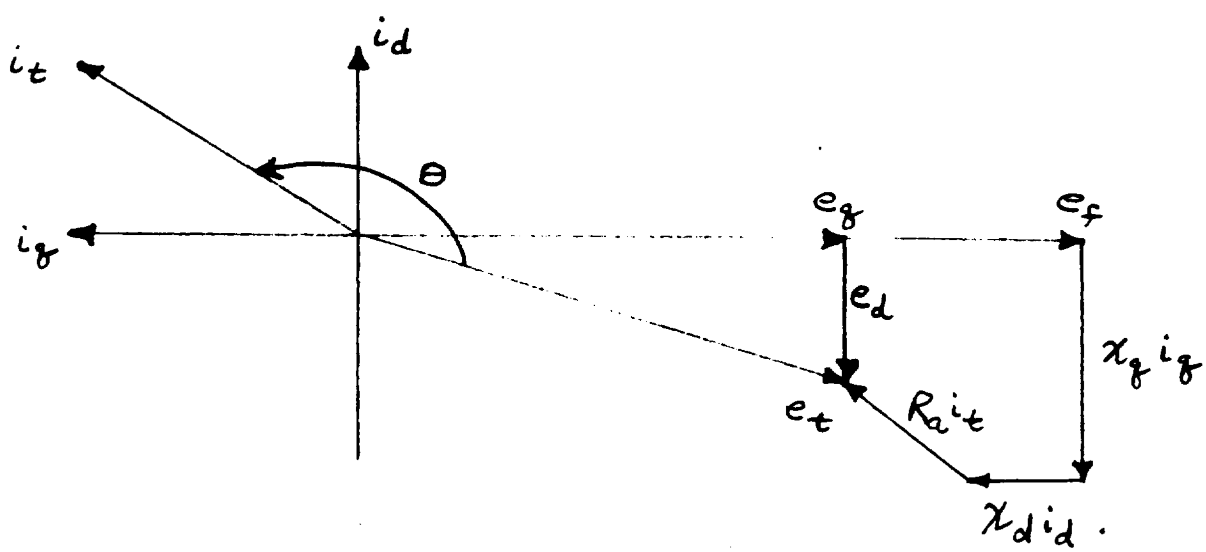


Fig. 2 Representation



(I) Under excited



(II) Over excited

Fig. 3 Steady state vector representation

4. Simplification

If detailed accuracy is not essential, it can be traded for simplification. Damper bar, armature resistances and leakage reactances have relatively small effects on voltage, current and phase relationship in a normal steady state operation. Therefore, they can be ignored.

$$e_f = R_f i_f + \frac{d}{dt}\psi_f \tag{17}$$

$$e_d = \frac{d}{dt}\psi_d - \psi_q \omega_g \tag{18}$$

$$e_q = \frac{d}{dt}\psi_q + \psi_d \omega_g \tag{19}$$

$$\psi_f = L_{md}(i_f - i_d) \tag{20}$$

$$\psi_d = \psi_f \tag{21}$$

$$\psi_q = -L_{mq} i_q \tag{22}$$

$$\tau_{em} = \psi_d i_q - \psi_q i_d \tag{23}$$

Additional simplification can be made in a situation where only the steady state condition of a synchronous generator is considered in a complex system. Since all the time dependent variables become constant as the transient settles down, their rates of change approach to zero. A set of algebraic equations is derived below.

$$e_f = R_f i_f \tag{24}$$

$$e_d = -\psi_q \omega_g \tag{25}$$

$$e_q = \psi_d \omega_g \tag{26}$$

$$\psi_f = L_{md}(i_f - i_d) \tag{27}$$

$$\psi_d = \psi_f \tag{28}$$

$$\psi_q = -L_{mq} i_q \tag{29}$$

$$T = \psi_d i_q - \psi_q i_d \tag{30}$$

5. Inputs and Outputs

(a) Most literature in discussing the synchronous generator choose the frequency ωg and the field excitation voltage ef as inputs and the terminal voltage which is resolved into two-axis components as outputs. They are applied to the balanced loads while the direct and quadratic currents feedback to the generator.

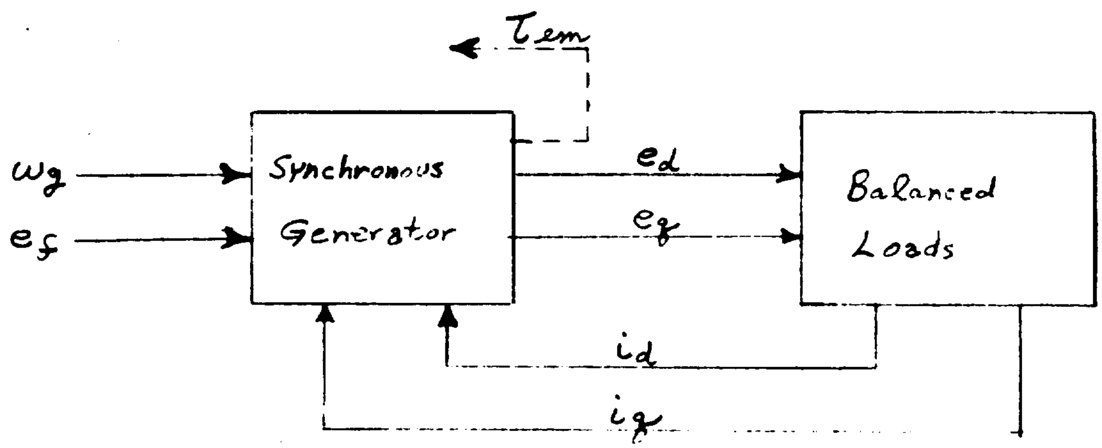


Fig. 4 Balanced load simulation

It should be recognized that the functions of e_d, e_q, and i_d, i_q can be reversed.

(b) For a more detailed representation, electric-mechanical relation can be included. Thus, the fluctuations of the frequency and of its dependent variables can be observed. Otherwise, the shaft speed ws has to be assumed well regulated to stand against any disturbance. Consider the shaft is rigid.

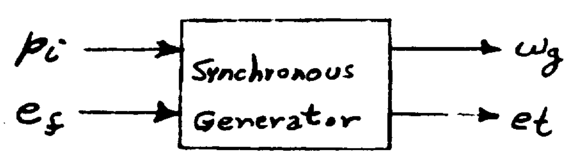


Figure. 5

$$p_i = \tau_i \cdot \omega_s \tag{31}$$

$$\tau_i - \tau_{em} = J \frac{d\omega_s}{dt} + D\omega_s \tag{32}$$

$$\omega_g = \frac{P}{2} \cdot \frac{\omega_s}{60} \tag{33}$$

Where pi is the input power, Υ_i input torque, and P, number of poles.

The moment of inertia J should include that of the prime mover. The damping factor D is a non-linear element which consists of mechanical losses like friction and windage. The latter is proportional to square of shaft speed w_s.

(c) The power supply for the field excitation of a synchronous generator ideally comes from a battery. In practice, it is either from a DC generator or by means of static excitation for the purpose of regulation.

(i) The transfer function of the output voltage and the excitation voltage of a DC generator in frequency domain is

$$\frac{E_g(s)}{E_e(s)} = \frac{K_g}{R_f + L_f s} \tag{34}$$

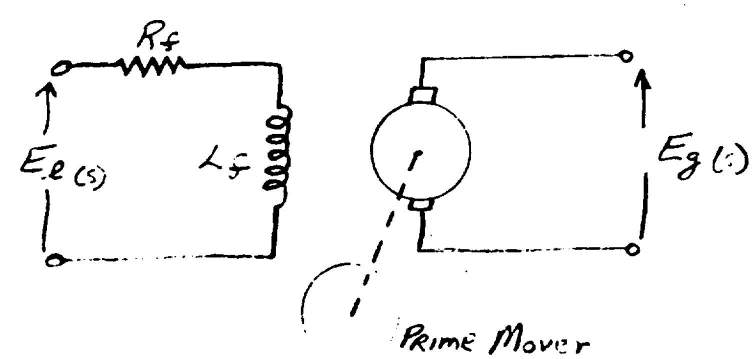
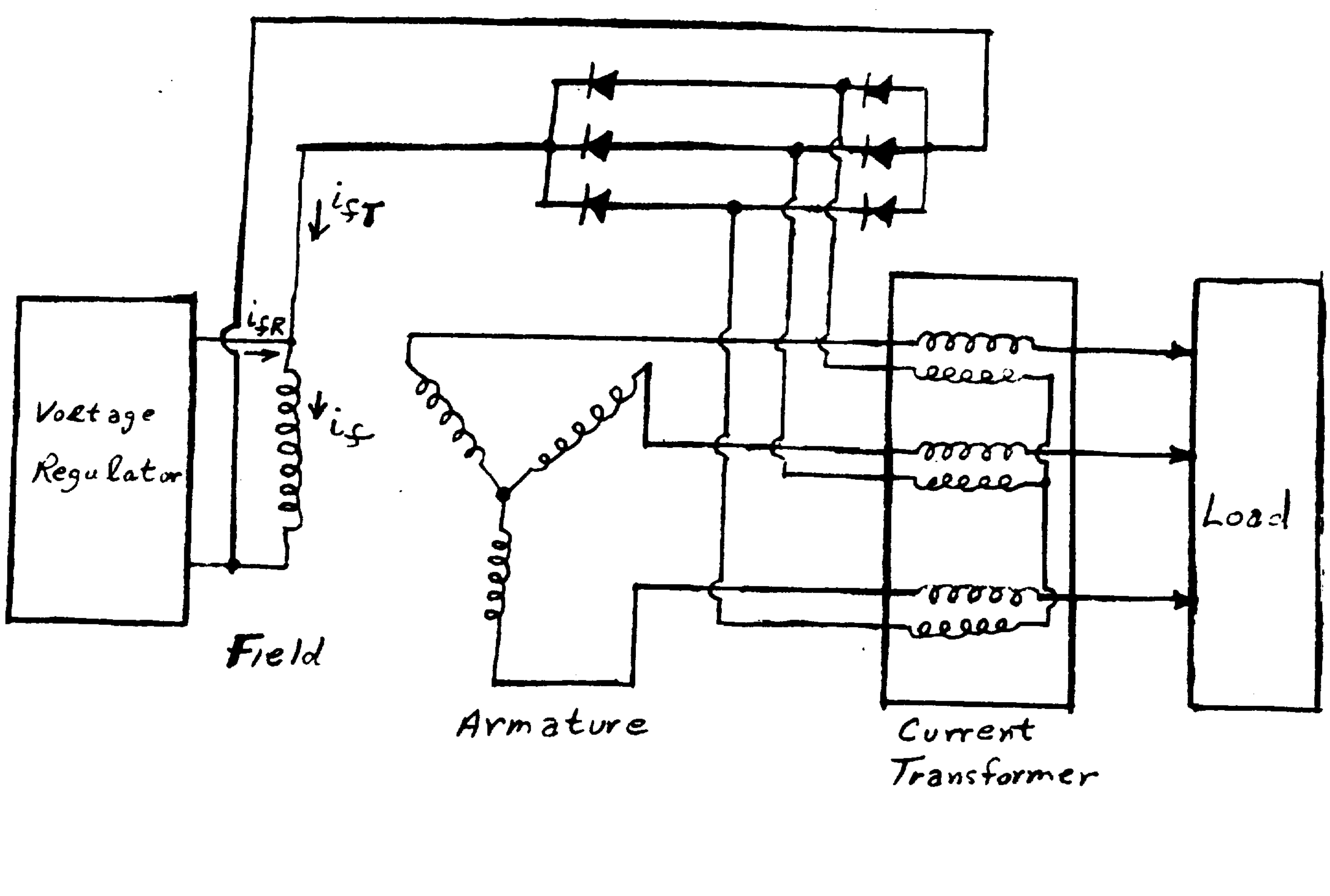


Fig. 6 DC generator

(ii) Static excitation for synchronous generator becomes widely accepted for obvious reasons like faster response and the elimination of rotating excitation machine. A typical approach is stated as follows: Excitation is provided to the generator from load currents through current transformers and rectifiers. The voltage regulator plays the role of no-load excitation and regulation of terminal voltage under different load conditions.

Such a method can be applied, for instance, for a two-coil Lundell generator with both the armature and the field stationary.



$$e_f = R_f i_f + \frac{d}{dt}\psi_f \tag{35}$$

$$i_f = i_{fT} + i_{fR} \tag{35a}$$

$$\psi_f = \psi_{fT} + \psi_{fR} \tag{36}$$

$$i_{fT} = K i_L \tag{37}$$

$$\psi_{fT} = (L_{md} + L_{fl})\, i_{fT} \tag{38}$$

(d) For a detail study of synchronous generator, unbalanced load simulation is suggested. The affects of all kinds of faults due to the load can be pictured simply by adjusting the load parameters. Balanced load condition is only a special case. The major feature of an analog simulation is to convert DC representing voltages of e_d and e_q into three phase AC components e_a, e_b, and e_c which are applied to the unbalanced load. The AC components i_a, i_b, and i_c are converted back into DC level before feeding back to the generator. Certainly the price to pay for is complexity.

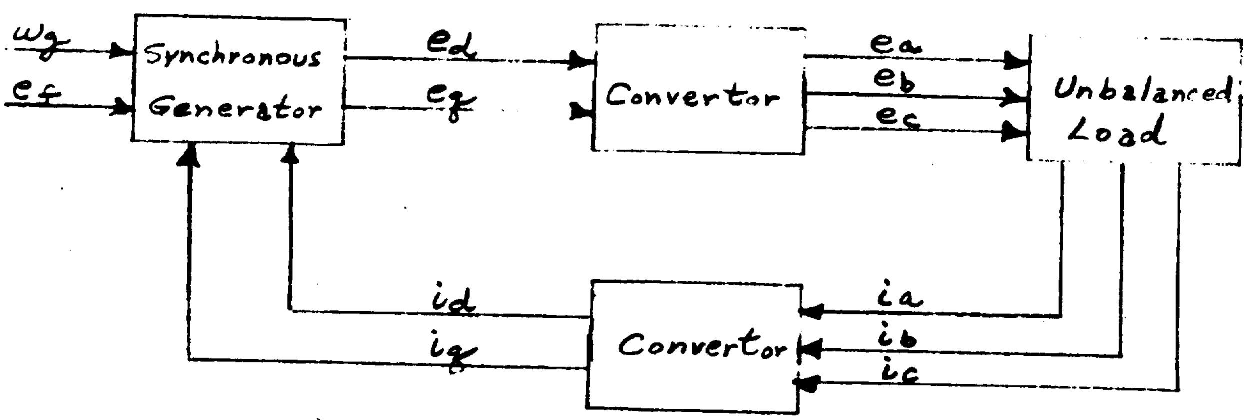


Fig. 8 Unbalanced load analog simulation

6. Conversion

For the unbalanced load simulation, the direct and quadratic output voltages of the generator have to be converted into corresponding three phases before applying to the load. Similarly, the currents from the load have to be converted back into direct and quadratic components before returning to the machine.

$$e_a = e_d \sin(\omega_g t) - e_q \cos(\omega_g t) + e_o \tag{39}$$

$$e_b = e_d \sin\left(\omega_g t - \frac{2\pi}{3}\right) - e_q \cos\left(\omega_g t - \frac{2\pi}{3}\right) + e_o \tag{40}$$

$$e_c = e_d \sin\left(\omega_g t - \frac{4\pi}{3}\right) - e_q \cos\left(\omega_g t - \frac{4\pi}{3}\right) + e_o \tag{41}$$

$$i_d = -\frac{2}{3}\left[i_a \cos(\omega_g t) + i_b \cos\left(\omega_g t - \frac{2\pi}{3}\right) + i_c \cos\left(\omega_g t - \frac{4\pi}{3}\right)\right] \tag{42}$$

$$i_q = \frac{2}{3}\left[i_a \sin(\omega_g t) + i_b \sin\left(\omega_g t - \frac{2\pi}{3}\right) + i_c \sin\left(\omega_g t - \frac{4\pi}{3}\right)\right] \tag{43}$$

$$e_o = \frac{1}{3}(e_a + e_b + e_c) \tag{44}$$

$$i_o = \frac{1}{3}(i_a + i_b + i_c) \tag{45}$$

The load is normally expressed in Y-connection. If delta load is used, proper connection of load can be made as in the analog simulation or convert them into Y-connection by using the following equations:

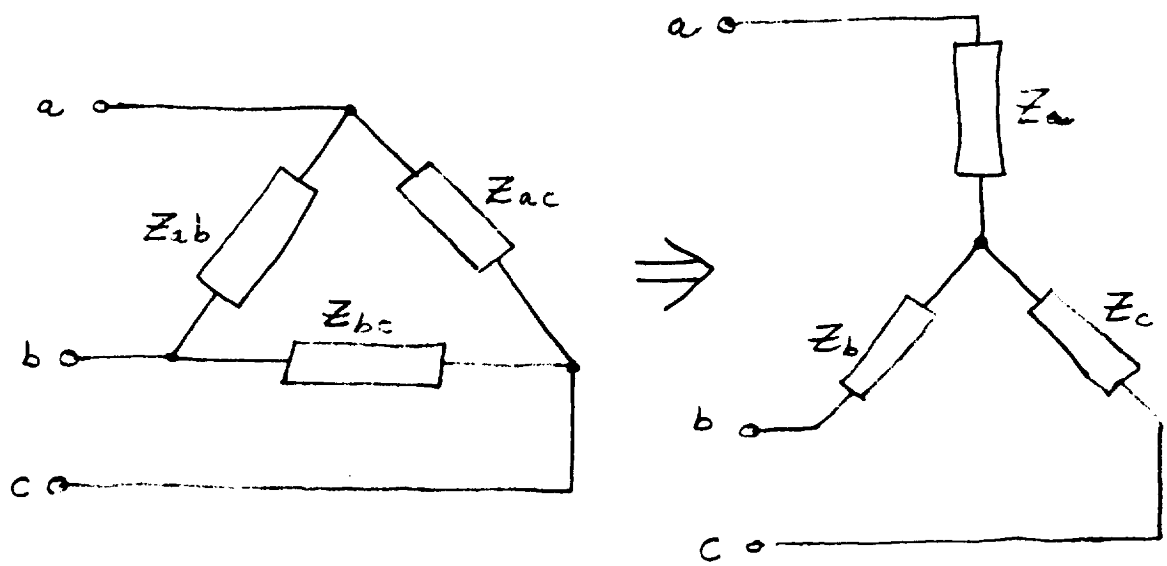


Fig. 9 Delta to Y-connection conversion

$$Z_a = \frac{Z_{ab} Z_{ac}}{Z_{ab} + Z_{bc} + Z_{ac}} \tag{46}$$

$$Z_b = \frac{Z_{ab} Z_{bc}}{Z_{ab} + Z_{bc} + Z_{ac}} \tag{47}$$

$$Z_c = \frac{Z_{ac} Z_{bc}}{Z_{ab} + Z_{bc} + Z_{ac}} \tag{48}$$

7. Load

(a) Balanced load -

Balanced load can also be resolved into two-axis, direct and quadratic components. Only the resistive and inductive load are considered.

$$e_d = R_L i_d + L_L \frac{di_d}{dt} - L_L i_q \omega_g \tag{49}$$

$$e_q = R_L i_q + L_L \frac{di_q}{dt} + L_L i_d \omega_g \tag{50}$$

The load can be expressed in another form.

$$i_d = \frac{\cos\theta}{|Z_L|} e_d + \frac{\sin\theta}{|Z_L|} e_q \tag{51}$$

$$i_q = \frac{-\sin\theta}{|Z_L|} e_d + \frac{\cos\theta}{|Z_L|} e_q \tag{52}$$

$$|Z_L| = \sqrt{R_L^2 + X_L^2} \tag{53}$$

$$\theta = \tan^{-1}(X_L/R_L) \tag{54}$$

Thus, the load is governed by the power factor, or vice versa.

(b) Unbalanced load -

Again, only resistive and inductive load are considered. However, mutual inductances among the loads are included.

$$e_a = R_A i_a + L_A \frac{di_a}{dt} - M_{ab} \frac{di_b}{dt} - M_{ca} \frac{di_c}{dt} \tag{55}$$

$$e_b = R_B i_b + L_B \frac{di_b}{dt} - M_{ab} \frac{di_a}{dt} - M_{bc} \frac{di_c}{dt} \tag{55a}$$

$$e_c = R_C i_b + L_C \frac{di_c}{dt} - M_{bc} \frac{di_b}{dt} - M_{ca} \frac{di_a}{dt} \tag{55b}$$

8. Parameter

All the machine parameters are practically time invariant. Their derivations can be found in the enclosed design manual or other standard texts on synchronous generator. Usually inductive reactance are given. To obtain the absolute inductive value, divide the reactance by the rated generator frequency. The unit of frequency should be in radians per second. The direct and the quadratic reactances computed from the design manual have taken care of whether the armature winding is Y or delta-connected as well as the number of pole pairs.

9. Time constants

Direct-axis open-circuit transient time constant

$$T'_{do} = \frac{L_{fl} + L_{md}}{R_f} \tag{56}$$

Direct-axis short-circuit time constant

$$T'_d = T'_{do} \, \frac{L'_d}{L_d} \tag{56a}$$

where

$$L_d = L_{md} + L_{al} \tag{56b}$$

$$L'_d = L_{al} + \frac{L_{md} \cdot L_{fl}}{L_{md} \cdot L_{fl}} \tag{56c}$$

With external inductive load, the direct-axis short-circuit time constant is adjusted to -

$$T'_{de} = T'_d \, \frac{L'_d + L_L}{L_d + L_L} \cdot \frac{L_d}{L'_d} \tag{57}$$

There is no definite formula to compute the direct-axis short-circuit subtransient time constant. Usually it is obtained from measurement.

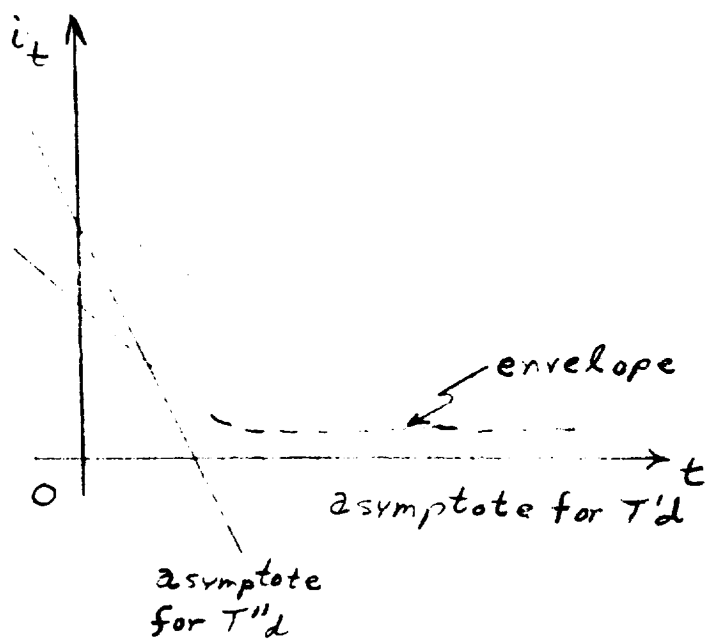


Fig. 10 Short circuit transient time constants measurement

10. Non-Linear Elements

(a) The basic equations -

$$e_d = -R_a i_d + \frac{d}{dt} \psi_d - \psi_q \omega_g \qquad (3)$$

etc., are non-linear. The non-linear term $\omega_q \omega_g$ in this equation is introduced because of the transformation from holonomic reference frames into non-holonomic.

(b) Magnetic saturation -

It is an inherent property of magnetic material. Usually for the design of generators a steel of low retentivity is used. The hysteresis loop is narrow and thus its effect can be neglected. An average saturation curve can be used to describe the characteristics of the magnetic path.

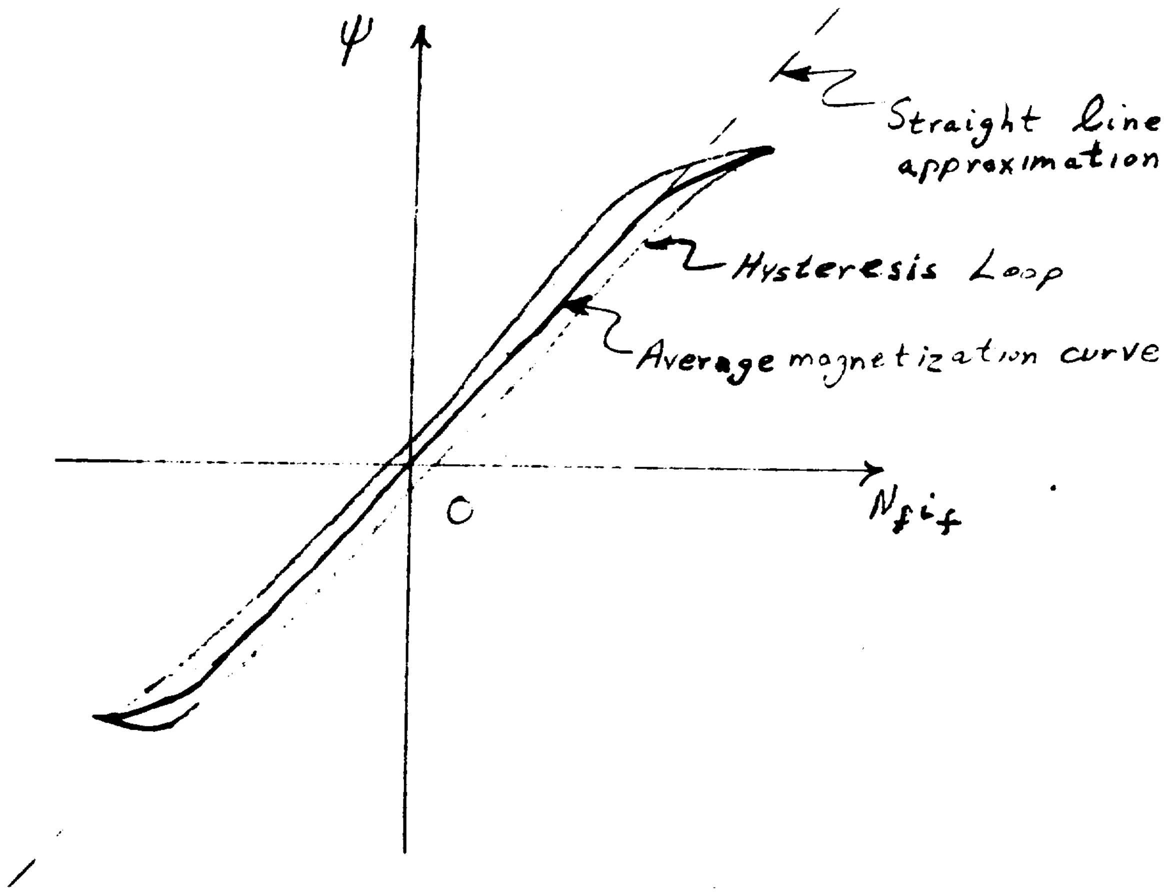


Fig. 11a **Magnetization curve**

The average magnetization curve can also be expressed in terms of e_t and i_f

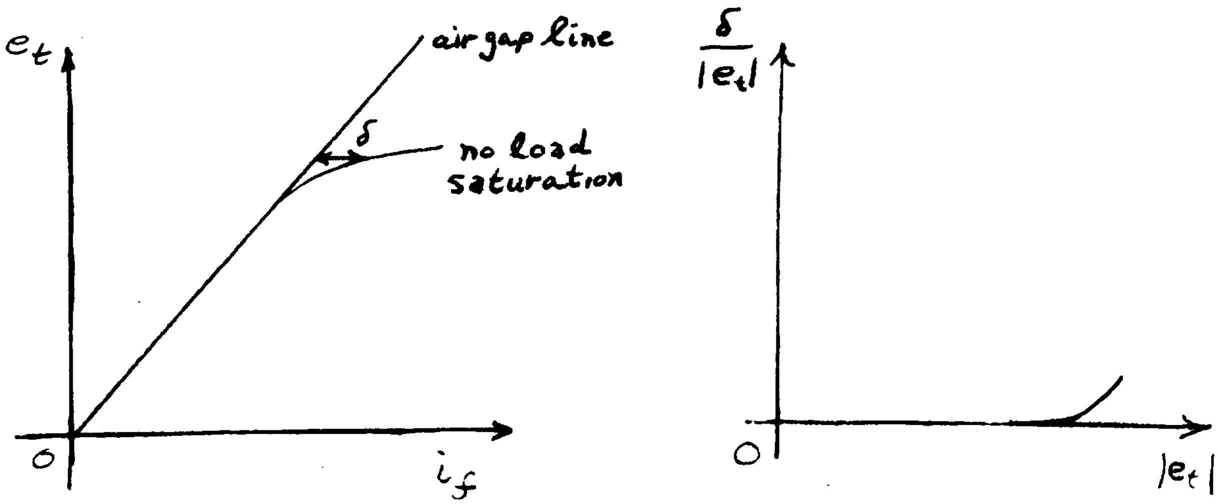


Fig. 11b Magnetic saturation approximation

The compensation δ versus the terminal voltage e_t is derived from the difference between the air gap line and the no-load saturation curve.

Further approximation can be developed by assuming X_{mq} independent or saturation (corresponds to path mostly in air). Only X_{md} varies with the flux. As the generator starts to saturate, X_{md} changes accordingly. This can be approximated by adding a factor to i_f by the amount proportional to the difference between the air gap line and the no-load saturation curve. If the operating point is below the knee of the curve, a linear relation can be assumed.

(c) Mechanical elements -

As in the more detail simulation, the mechanical relation between the prime mover and the generator is included.

(i) If gear is used for coupling, there will be backlash.

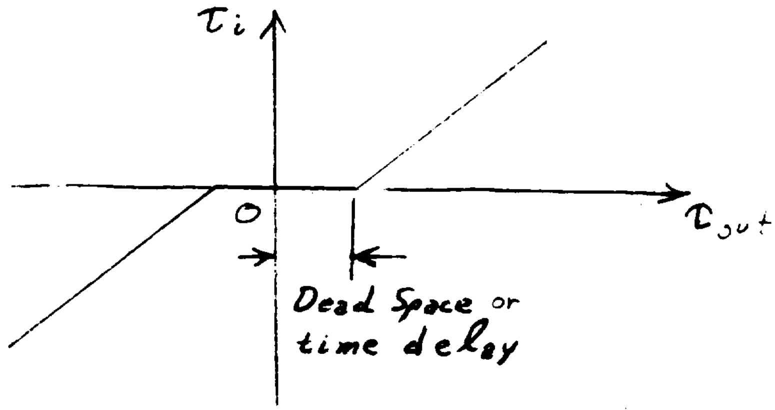


Fig. 12 Backlash

(ii) Sometimes a mechanical damper is used to eliminate the mechanical resonance near the low speed end.

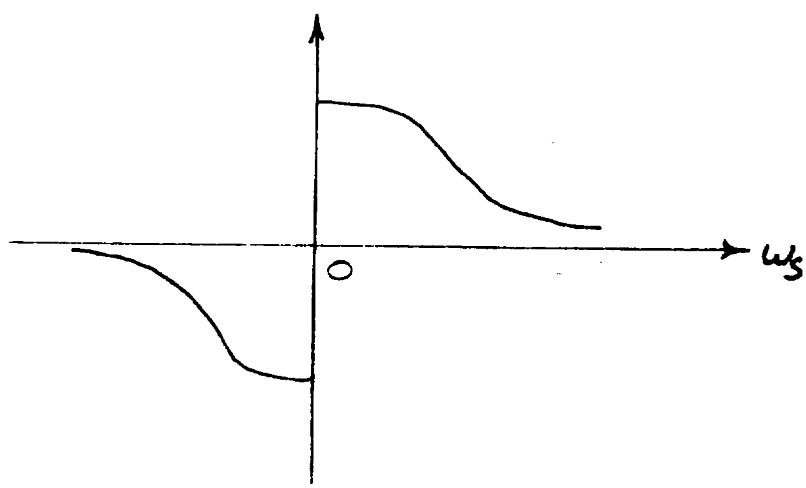


Fig. 13 Mechanical Damper Response

(iii) The windage and friction loss is proportional to the square of the shaft speed.

Analog simulation of

(i) Magnetic saturation - (approximated)

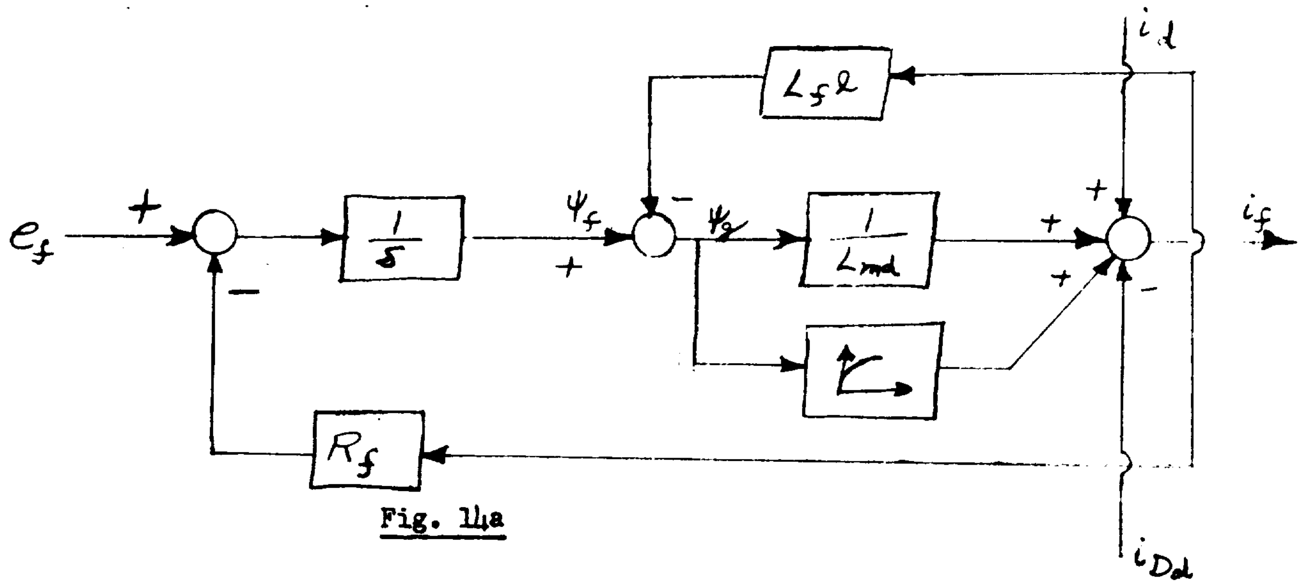


Fig. 14a

(ii) Mechanical relation -

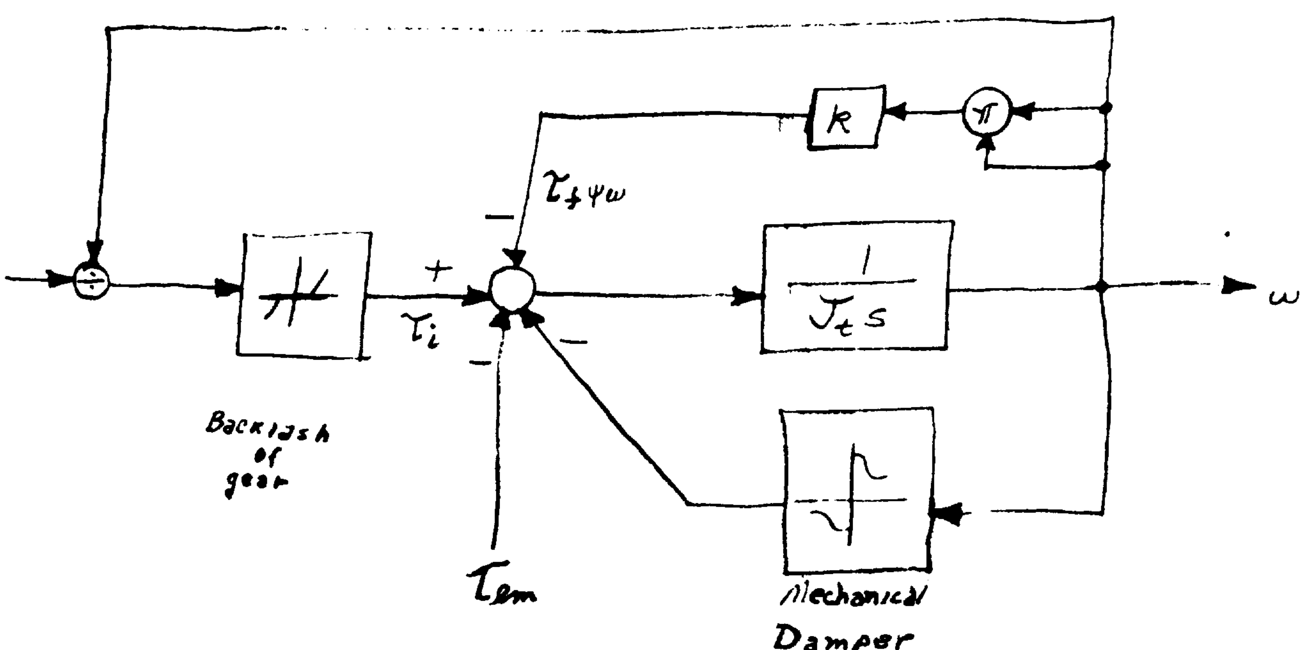


Fig. 14b

11. Linearization

In the basic equation

$$e_d = -R_a i_d + \frac{d}{dt}\psi_d - \omega_g \psi_q$$

the non-linearity is introduced by the product ot two time varying functions ω g and ψ q. Since all the variables are continuous functions of time and are likely to be monotonic, linearization is possible. For small increment of change, the equation can be written in a linear form. (Derivation is in section II-2. $\bar{\omega}$ g, etc., are steady state values.)

$$\Delta e_d = -R_a(\Delta i_d) + \frac{d}{dt}(\Delta \psi_d) - \bar{\psi}_q(\Delta \omega_g) - \bar{\omega}_g(\Delta \psi_q) \quad (58)$$

For constant drive generator, $\Delta \omega g = 0$

$$\Delta e_d = -R_a(\Delta i_d) + \frac{d}{dt}(\Delta \psi_d) - \bar{\omega}_g(\Delta \psi_q) \quad (59)$$

To compare with the original equation by setting $\omega g = \bar{\omega} g$, the choice of magnitude of the increments for accuracy becomes obvious. Indeed they can be simply expressed as -

$$e_d = -R_a i_d + \frac{d}{dt}\psi_d - \bar{\omega}_g \psi_q \quad (60)$$

Another alternative is that the flux linkages are kept constant. Thus all currents are invariant. Neglecting R_a,

$$e_d = -\bar{\psi}_q \omega_g \quad (61)$$

the voltage will be directly proportional to the generation frequency.

However, when the change $\Delta \omega$ g and $\Delta \psi$ q are considered simultaneously, the constraints of the increments are imposed. A larger value of increment will sacrifice the accuracy. Since a steady state value of $\bar{\omega}$ g has been chosen as the coefficient of $\Delta \psi$ q, on the other hand, $\Delta \omega$ g is time varying and its relatively large change will make ω_g invalid. Similar argument applies to the term $\bar{\psi}$ q (Δ ω q) and other related equations.

The linear transfer relations are:

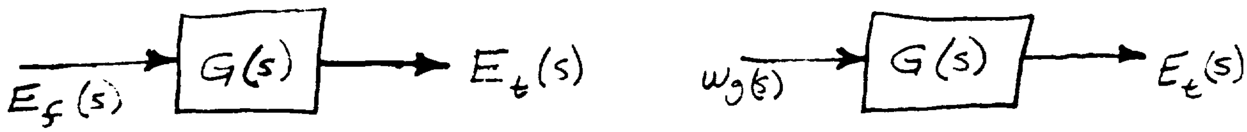


Fig. 15

(a) Constant speed (b) Constant flux linkage

12. Per unit system

It may be convenient for some individuals to use per unit system instead of absolute value.

$$\text{Quantity in per unit} = \frac{\text{actual quantity}}{\text{base value of quantity}} \tag{62}$$

$$p_{base} = e_{base}\, i_{base} \tag{63}$$

$$R_{base},\ X_{base},\ Z_{base} = \frac{e_{base}}{i_{base}} \tag{64}$$

$$T_{base} = \frac{p_{base}}{\omega_{base}} \tag{65}$$

13. Power density spectrum

If the input is in power density spectrum form and the generator is linearized and expressed in frequency domain as G(S) and its conjugate G(-S)

$$\Phi_{oo}(s) = G(s)\,G(-s)\,\Phi_{ii}(s) \tag{66}$$

assuming the input and output spectrums are autocorrelated. The output can be converted into mean square value, say of e_t.

$$\overline{e_t(t)^2} = \phi_{oo}(0)$$

$$= \int_{-\infty}^{\infty} \Phi_{oo}(s) e^{st} ds \Big|_{t=0}$$

$$= \int_{-\infty}^{\infty} G(s) G(-s) \Phi_{ii}(s) ds \tag{67}$$

The evaluation can be implemented analogously or by using the table of integrals which can be found in many advanced control engineering texts.

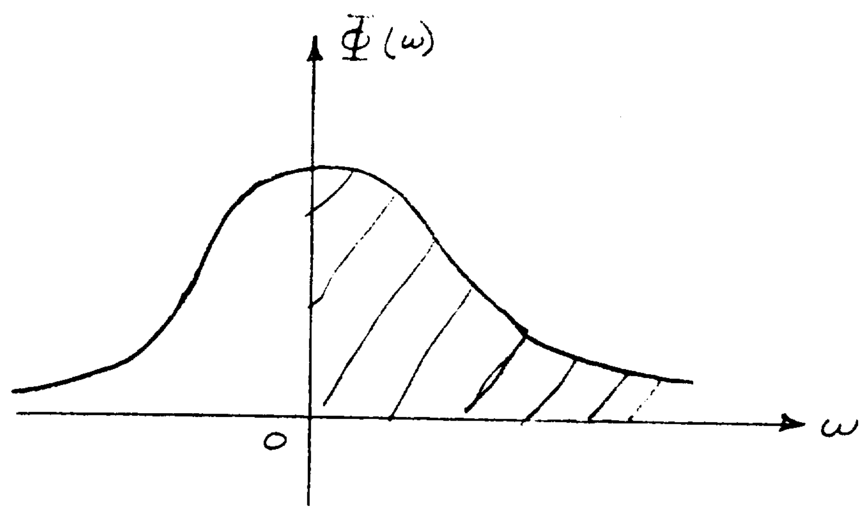


Fig. 16a Power density spectrum

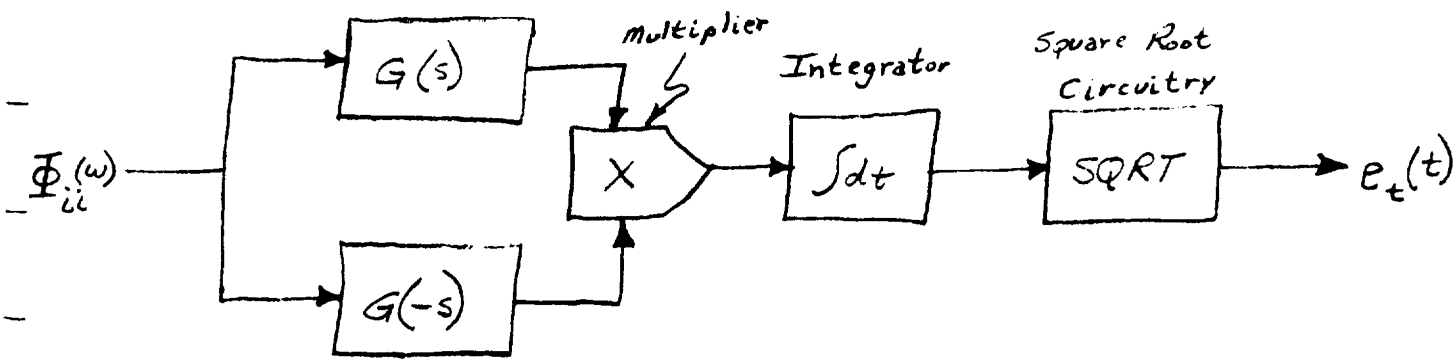


Fig. 16b Analog simulation

14. Faults

Faults are restricted to the load. They may be line to line, line to neutral, etc. In the unbalanced load simulation, the faults can be pictured simply by appropriate arrangement or by adjusting the load parameters of the corresponding phase. For example, if phase a is shorted to neutral, set R_A - 0; L_A - 0.

When it is open, theoretically R_A and L_A become infinity. In computer practice they can be set many orders larger than the normal value. Use the same tactic as inccases like $1/_{LA}$, while L_A is zero.

15. Converter

In the unbalanced load simulation, converters are required to generate ω_o, ωgt and Sin ωgt as functions of ωg. (Refer to eqns. (39) - (43)) By Laplace transformation

$$\mathcal{L}\left[\cos \omega_g t\right] = \frac{s}{s^2 + \omega_g^2} = A \qquad (68a)$$

$$\mathcal{L}\left[\sin \omega_g t\right] = \frac{\omega_g}{s^2 + \omega_g^2} = B \qquad (68b)$$

$$A = \frac{B}{\omega_g} \cdot s \qquad (68c)$$

The analog simulation -

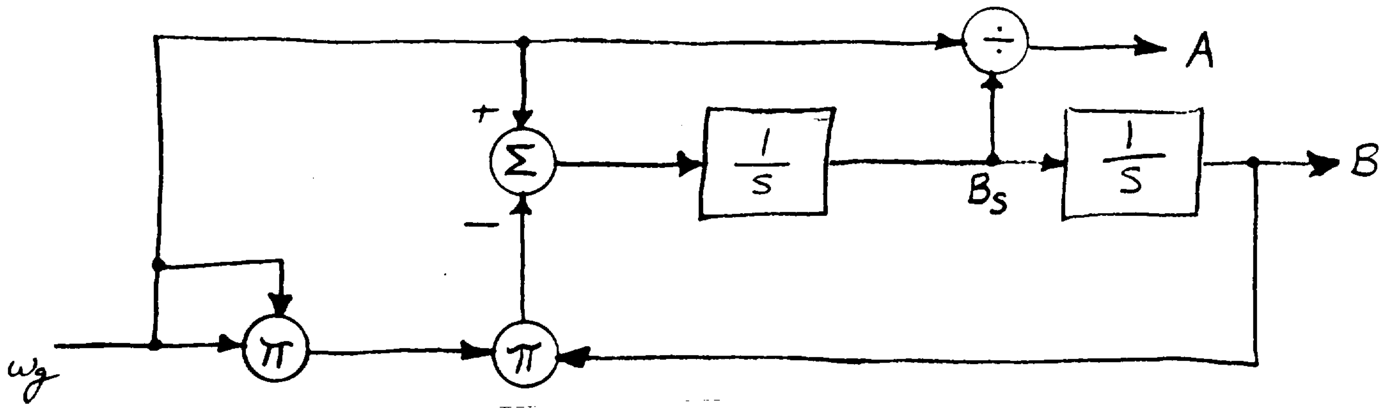


Fig. 17 DC to AC converter analog

16. Minimum Time Starting

It has been proved theoretically that switching control can achieve the minimum time for a system to reach its steady state value after a step disturbance. Due to the inherent defect of physical components like deadband and frictions, dual-mode control is suggested. That is, the switching control takes care of large error signal while the linear control takes care of the small error signal in the feedback control loop to generate the manipulated input, say excitation voltage e_f for the synchronous generator. (Constant shaft drive)

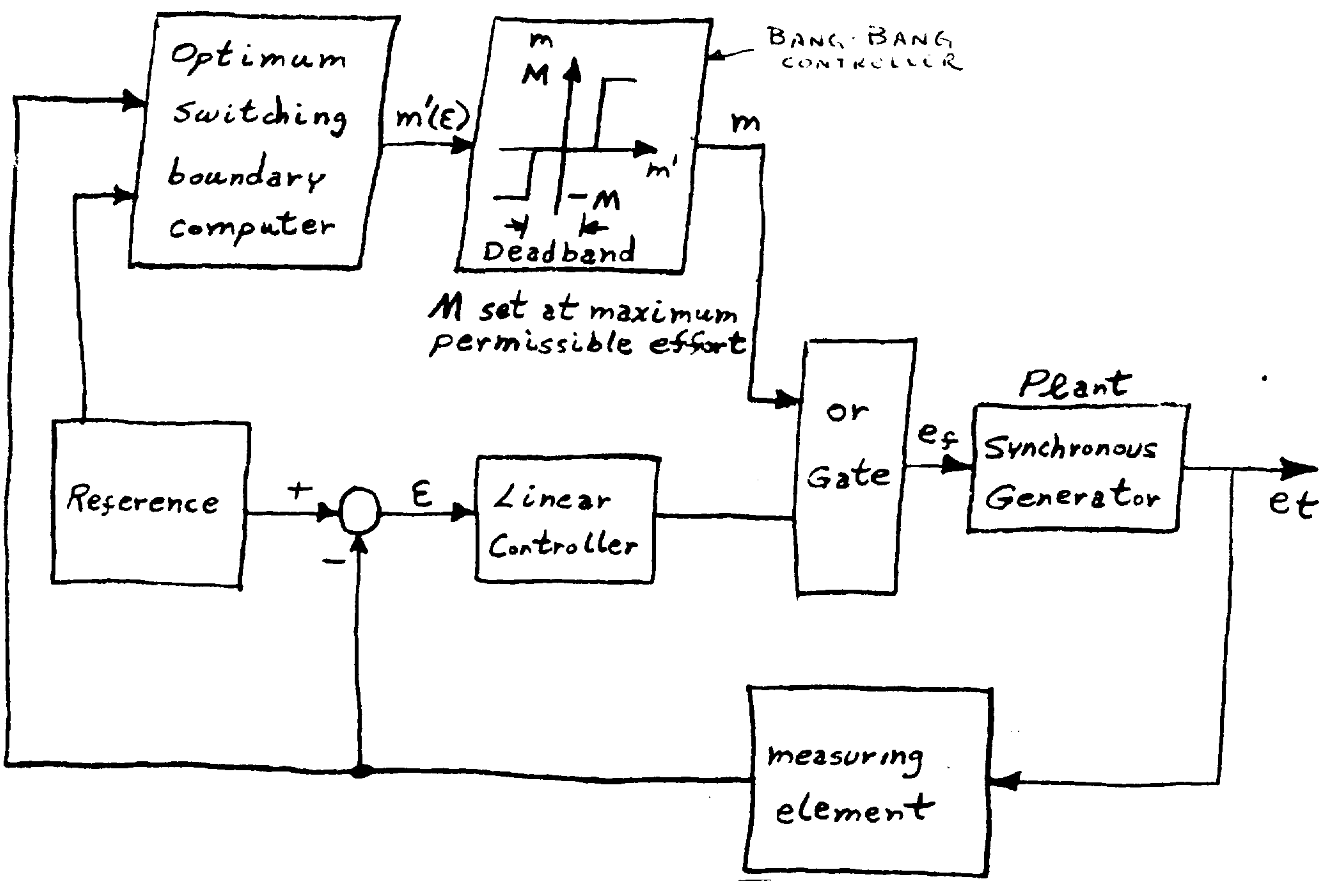


Fig. 18 Dual-mode control for minimum time starting

To start a synchronous generator, considering the shaft drive has assumed its constant speed, the reference as a step function is applied. The optimum switching boundary computer recognizes the zero initial state and the final state from the reference signal and decides the switching points according to the orders of dynamics of the plant. (For an n^{th} order linear time invariant controllable system, with poles real and non-positive, requires no more than n-1 switchings and an initial-on and a final-off operation to reach final steady state in minimum time.) When the error signal falls within the dead-band of bang-bang controller, the linear control takes over.

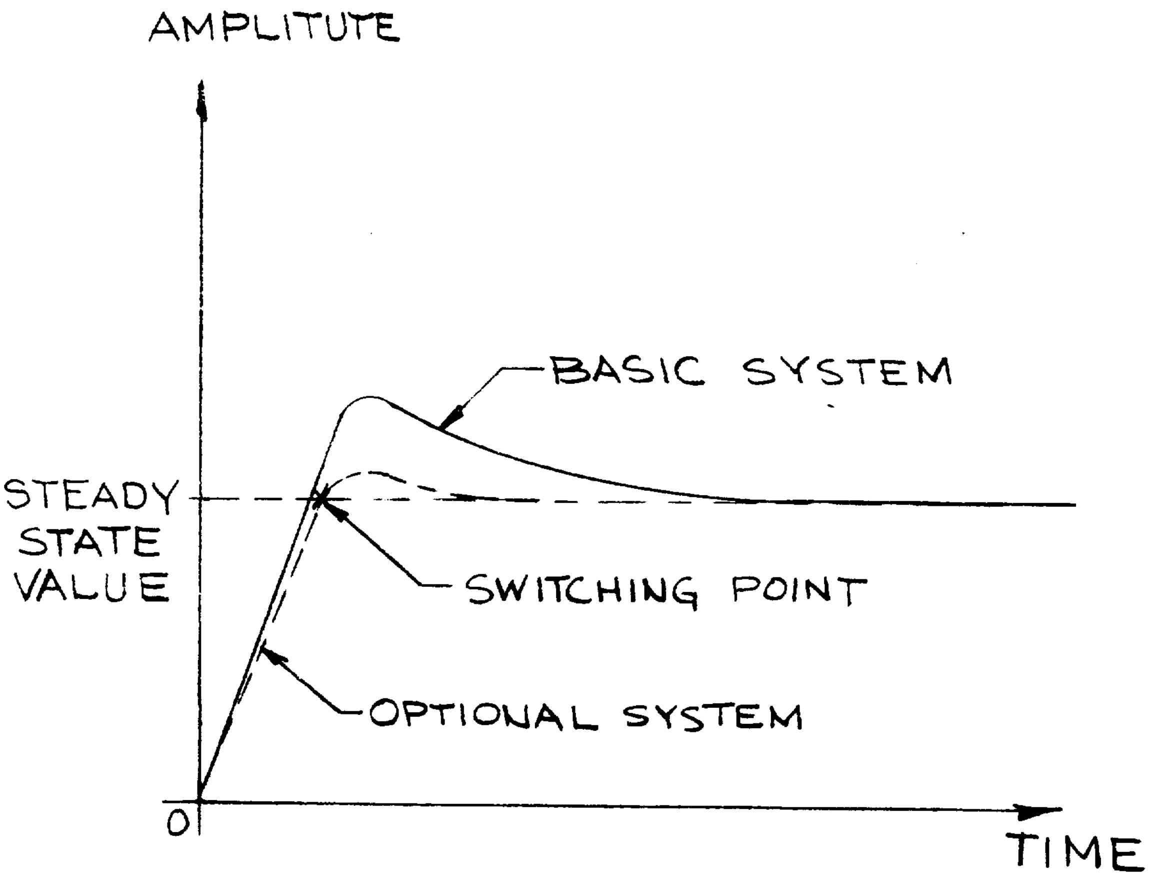


Fig. 18a Second order system step function response

17. Modern Control Formulation

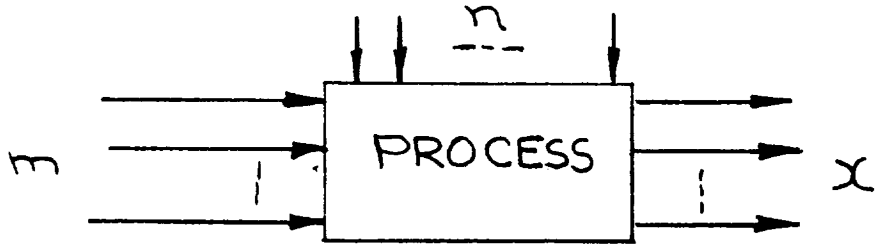


Fig. 19a Multivariable process

$\underline{x}$ - state vector

$\underline{m}$ - control vector

$\underline{n}$ - disturbance vector

For a stationary process, the dynamic characteristics are -

$$\dot{\underline{x}}(t) = A\,\underline{x}(t) + B\,\underline{m}(t) + \underline{n}(t) \tag{69a}$$

$\dot{\underline{x}}$ - differential state vector

A - coefficient matrix

B - driving matrix

The solution will be - (from initial state at time t_0 to final state at t)

$$\underline{x}(t) = \operatorname{Exp} A(t-t_0)\,\underline{x}(t_0) + \int_{t_0}^{t} \left[\operatorname{Exp} A(t-\tau)\right]\left[B\,\underline{m}(\tau) + \underline{n}(\tau)\right] d\tau \tag{69b}$$

Exp: Exponential

1. Analog Simulation

Use the basic synchronous generator dynamic eqs. (3) to (13), (16) and balanced load eqs. (51) to (54). The operating frequency is absorbed into the reactances such as χ md $\doteq$ ω r Lmd where ω r is the rated frequency. Per unit system is used. After some manipulation, a block diagram is concluded in Fig. I where

$$T_{Dd} = \frac{X_{md} + X_{Dd}}{R_{Dd}} \tag{71a}$$

$$T_{Dq} = \frac{X_{mq}}{R_{Dq}} \tag{71b}$$

For the same of convenience, Laplace operator S is used for differentiation while $1/_S$, for integration with initial condition, equals to zero. Magnetic saturation is approximated.

The inputs to the generator are frequency ω g and excitation voltage e_f.

The transfer functions appear in the block diagram.

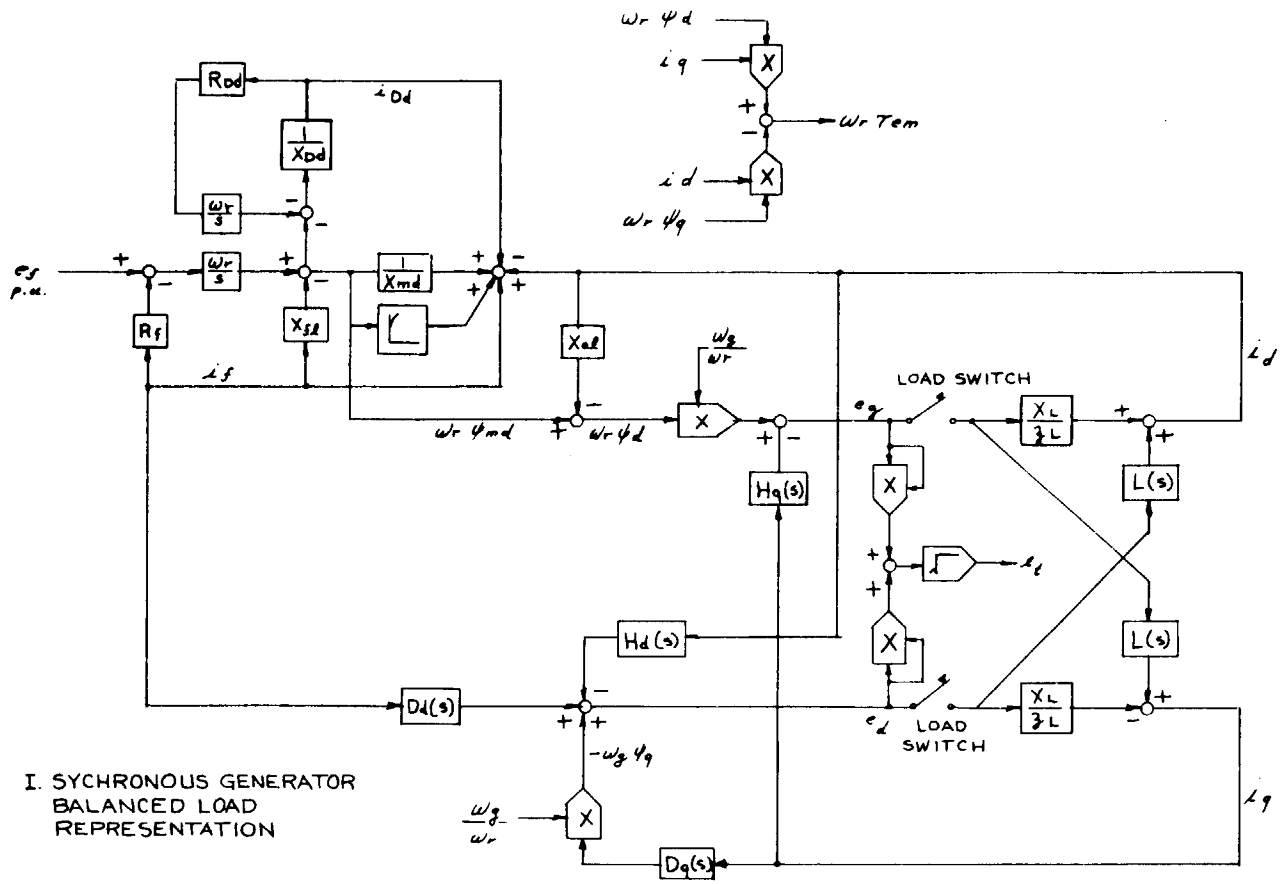
$$H_d(S) = R_a + \frac{S}{\omega_r}\left[X_{al} + \frac{X_{md}\,X_{Dd}}{X_{md}+X_{Dd}}\right] + \frac{X^2_{md}}{X_{md}+X_{Dd}} \cdot \frac{S/\omega_r}{1+T_{Dd}\cdot S/\omega_r} \tag{72a}$$

$$H_q(S) = R_a + \frac{S}{\omega_r}\left[X_{al} + \frac{X_{mq}\,X_{Dq}}{X_{mq}+X_{Dq}}\right] + \frac{X^2_{mq}}{X_{md}+X_{Dq}} \cdot \frac{S/\omega_r}{1+T_{Dq}\cdot S/\omega_r} \tag{72b}$$

$$D_d(s) = \frac{S}{\omega_r} \cdot \frac{X_{mq}\,X_{Dq}}{X_{md}+X_{Dd}} + \frac{X^2_{md}}{X_{md}+X_{Dd}} \cdot \frac{S/\omega_r}{1+T_{Dd}\cdot S/\omega_r} \tag{72c}$$

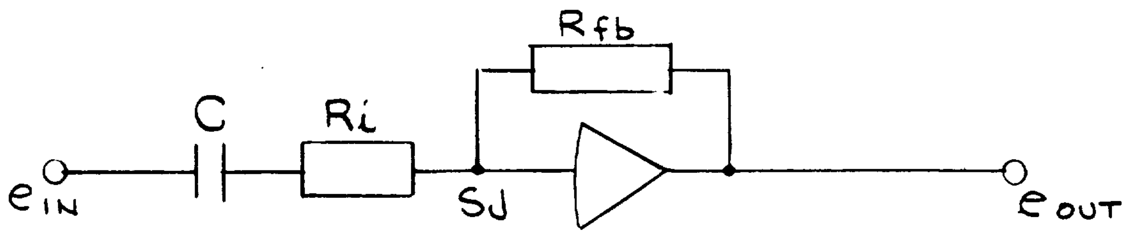
$$D_q(s) = X_{al} + \frac{X_{mq}\,X_{Dq}}{X_{mq}+X_{Dq}} + \frac{X^2_{mq}}{X_{mq}+X_{Dq}} \cdot \frac{1}{1+T_{Dq}\cdot S/\omega_r} \tag{72d}$$

$$L(s) = \frac{R_L}{Z^2_L} + \frac{S}{\omega_r} \cdot \frac{X_L}{Z^2_L} \tag{72e}$$



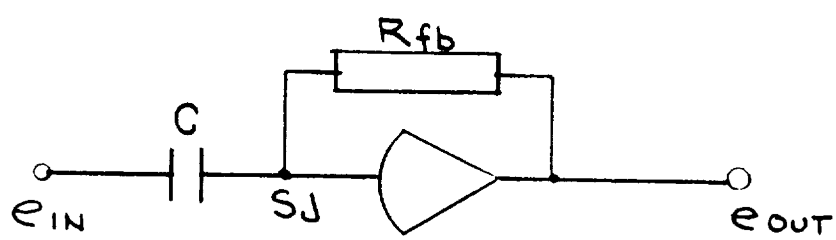
I. SYCHRONOUS GENERATOR
BALANCED LOAD
REPRESENTATION

The analog computer simulation is in Fig. II. Notice the difference between the circuit representing the first order transfer function and the differentiator.



$$\frac{e_{OUT}}{e_{IN}} = -\frac{(R_{fb}C)s}{(R_iC)s+1} \tag{73}$$

Fig. 20a First order transfer function



$$\frac{e_{OUT}}{e_{IN}} = -(R_{fb}C)s$$

Fig. 20b Differentiator

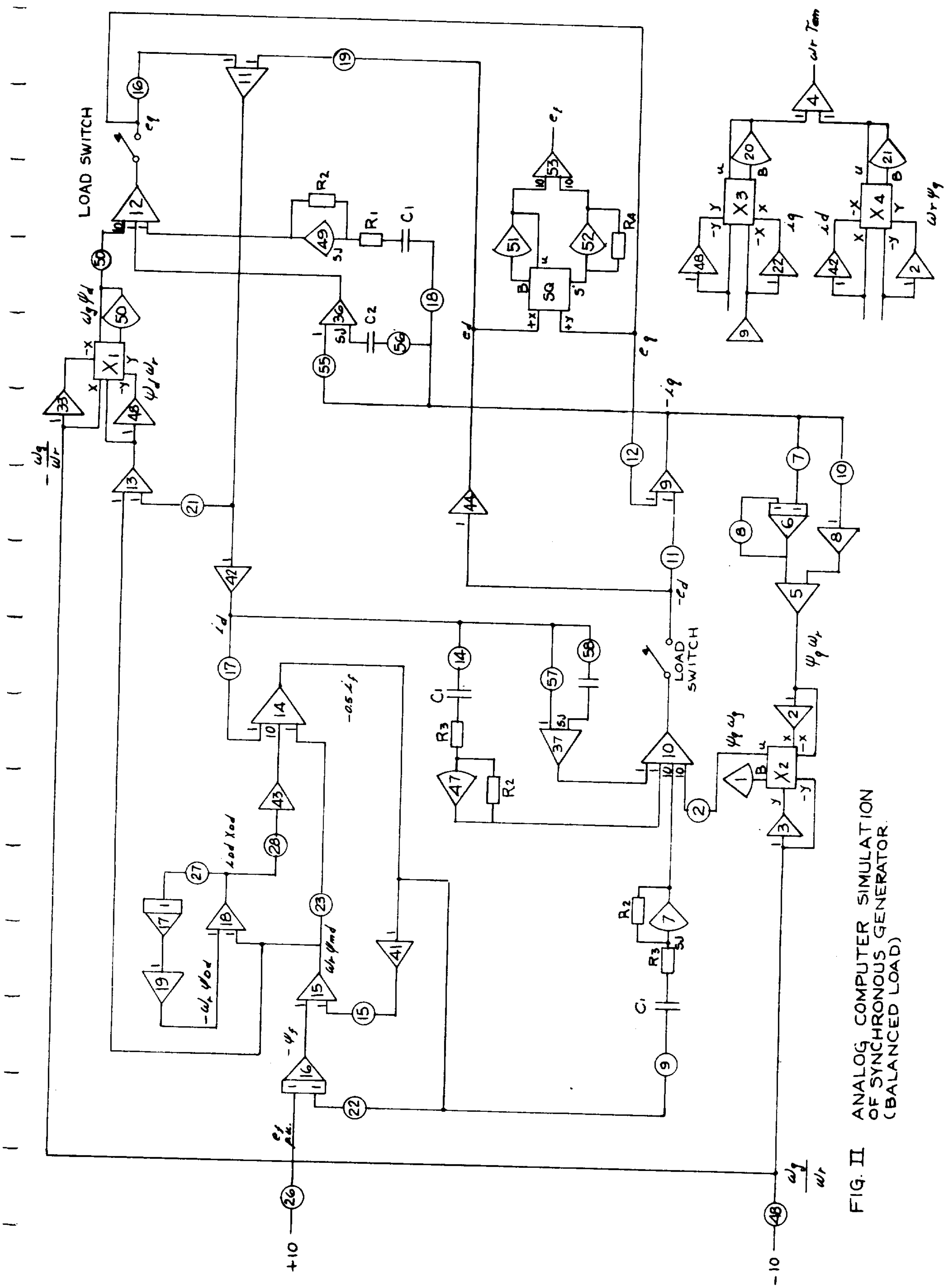
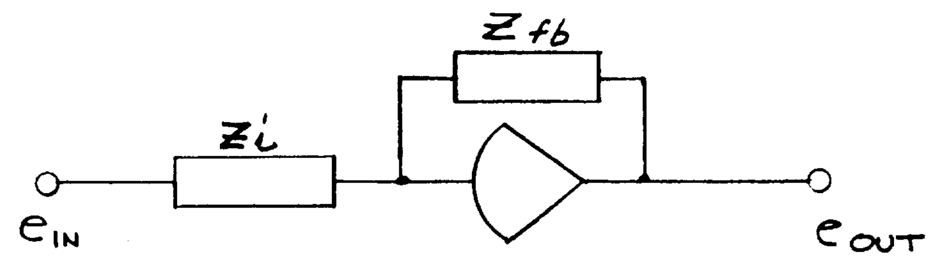


FIG. II ANALOG COMPUTER SIMULATION OF SYNCHRONOUS GENERATOR (BALANCED LOAD)

The basic values of the components in the presenting analog computer are:



$$\frac{e_{OUT}}{e_{IN}} = -\frac{Z_{fb}}{Z_i} \tag{75}$$

Fig. 21

Z_{fb} = 100 K resistor

Z_i = 100 K resistor

for an operational amplifier with unity gain. While

Z_{fb} = 10 microfarad capacitor

Z_i = 100 K resistor

for an integrator with unity gain and a time constant of one sec.

Pot. No.	Variable	Setting
2	Scaling constant	0.2
7	$\dfrac{X_{mq}^2}{X_{mq} + X_{Dq}} \cdot \dfrac{10^{-2}}{T_{Dq}}$	0.253
8	$\dfrac{10^{-2}}{T_{Dq}}$	0.318
9	$\dfrac{(1/\omega_r)\, X_{md}^2}{10^3 (X_{md} + X_{Dd})}$	0.054
10	$X_{al} + \dfrac{X_{mq} X_{Dq}}{X_{mq} + X_{Dq}}$	0.137
11	$\dfrac{X_L}{\lvert Z_L \rvert}$ AT 0.75 P.F.	0.661
12	$\dfrac{R_L}{\lvert Z_L \rvert}$ AT 0.75 P.F.	0.75
14	$\dfrac{X_{m}^2{}_{d}}{\omega_r (X_{md} + X_{Dd})}$	0.536
15	$2\, \omega_g\, X_{fl}$	0.248

Pot. No.	Variable	Setting
16	$\frac{X_L}{\lvert Z_L \rvert}$ AT 0.75 P.F.	0.661
17	Scaling constant	0.5
18	$\frac{X_{mq}^2}{\omega_r (X_{mq} + X_{Dq})}$	0.317
19	$\frac{R_L}{\lvert Z_L \rvert}$ AT 0.75 P.F.	0.75
21	X_{al}	0.083
22	$2\omega_g R_f \cdot 10^{-2}$	0.173
23	$\frac{1}{2} X_{md}$	0.361
26	$\frac{50\,\omega_r}{100\,(e_f)_{base}}$	0.27
28	$\frac{1}{20\,X_{Dd}}$	0.98
48	ω/ω_r	1.0
50	Scaling constant	0.2

Pot. No.	Variable	Setting
55	Ra	0.205
56	$\frac{1}{\omega_r}\left(X_{al} + \frac{X_{mq}\ X_{Dq}}{X_{mq} + X_{Dq}}\right) \cdot 10^{-1}$	0.555
57	Ra	0.205
58	$\frac{1}{\omega_r}\left(X_{al} + \frac{X_{md}\ X_{Dd}}{X_{md} + X_{Dd}}\right) \cdot 10^{-1}$	0.053

Component	Value	Component	Value
R_1	306 K	C_1	10 uf
R_2	10 K	C_2	1 uf
R_3	185 K		
R_4	100 K		

Time scale: Real time: Computer time - 100:1

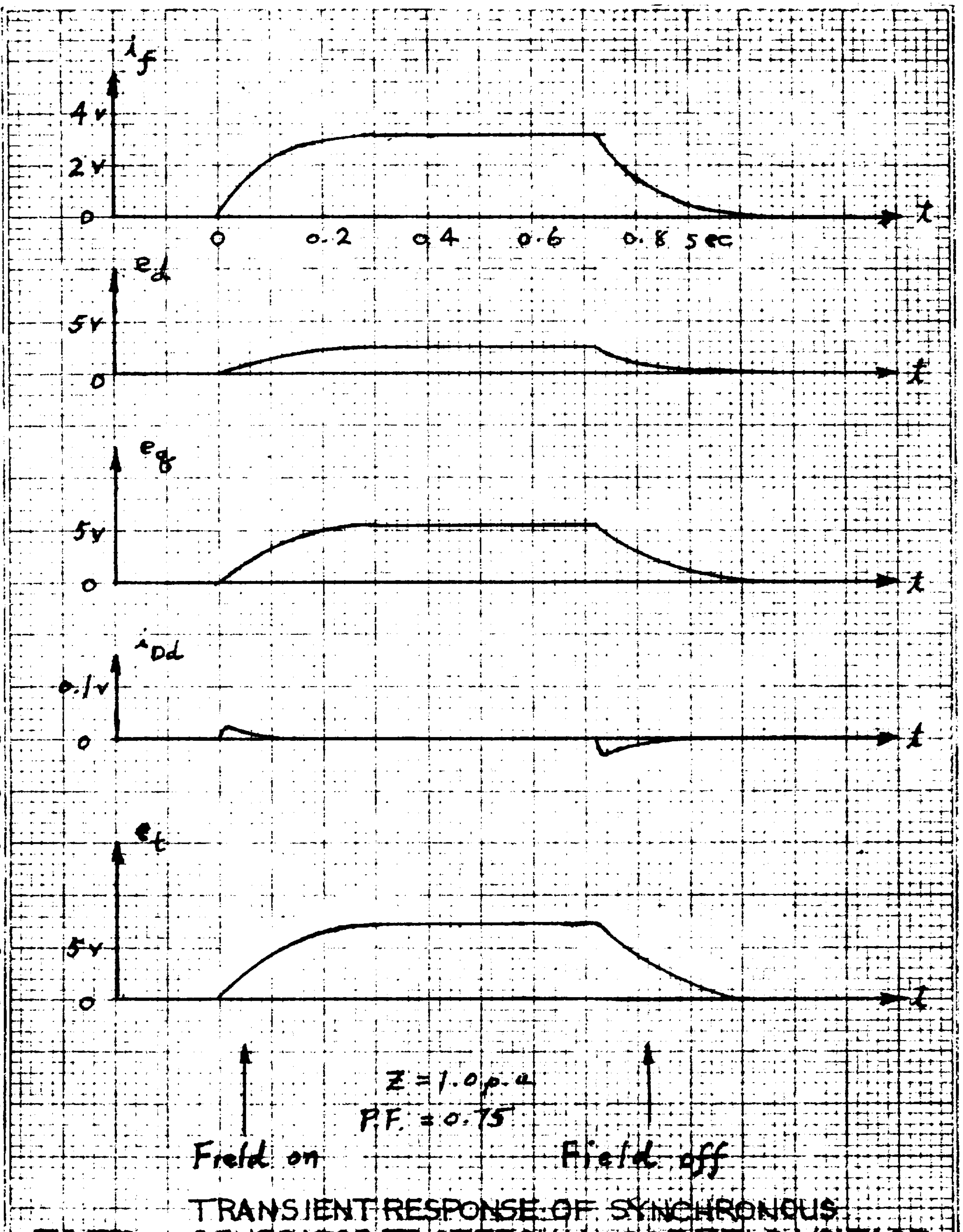


FIG III TRANSIENT RESPONSE OF SYNCHRONOUS GENERATOR TO STEP CHANGE OF FIELD VOLTAGE

2. Digital Computation

(i) Linearization:

For $$e_d = -R_a i_d + \frac{d}{dt}\psi_d - \psi_q \omega_q$$

Let
$$e_d = \bar{e}_d + \Delta e_d$$
$$i_d = \bar{i}_d + \Delta i_d$$
$$\psi_d = \bar{\Psi}_d + \Delta \psi_d$$
$$\psi_q = \bar{\Psi}_q + \Delta \psi_q$$
$$\omega_q = \bar{\omega}_q + \Delta \omega_q$$

where e_d is the steady state value and e_d, a small increment of change. The same definition is applied to other variables.

Let $$X = \psi_q \omega_q$$
$$\Delta X = \frac{\partial X}{\partial \psi_q}\Delta\psi_q + \frac{\partial X}{\partial \omega_q}\Delta\omega_q$$
$$\frac{\partial X}{\partial \psi_q} \triangleq \omega_q$$
$$\frac{\partial X}{\partial \omega_q} \triangleq \bar{\Psi}_q$$

Substitute the relations into the original equation.

$$\Delta e_d = -R_a \Delta i_d + \frac{d}{dt}\Delta\psi_d - (\omega_q \Delta\psi_q + \bar{\Psi}_q \Delta\omega_q)$$

Similar procedure is applied to the other basic equations. The results are expressed in matrix.

Load:

$$\begin{bmatrix} \Delta e_d \\ \Delta e_q \end{bmatrix} = \begin{bmatrix} R_L + sL_L & -\bar{\omega}_q L_L \\ \bar{\omega}_q & R_L + sL_L \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix} + \begin{bmatrix} -L_L i_q \\ L_L \bar{i}_d \end{bmatrix} \begin{bmatrix} \Delta \omega_q \end{bmatrix} \quad (76)$$

Flux linkages:

$$\begin{bmatrix} \Delta\psi_d \\ \Delta\psi_q \\ \Delta\psi_f \\ \Delta\psi_{Dd} \\ \Delta\psi_{Dq} \end{bmatrix} = \begin{bmatrix} -L_{sd} & 0 & L_{md} & L_{md} & 0 \\ 0 & -L_{sq} & 0 & 0 & L_{mq} \\ -L_{md} & 0 & L_{md}+L_{fl} & L_{md} & 0 \\ -L_{md} & 0 & L_{md} & L_{Dd} & 0 \\ 0 & -L_{mq} & 0 & 0 & L_{Dq} \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta i_f \\ \Delta i_{Dd} \\ \Delta i_{Dq} \end{bmatrix} \quad (77)$$

Voltages:

$$\begin{bmatrix} \Delta e_d \\ \Delta e_q \\ \Delta e_f \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} s & -\bar{\omega}_q & 0 & 0 & 0 \\ \bar{\omega}_q & s & 0 & 0 & 0 \\ 0 & 0 & s & 0 & 0 \\ 0 & 0 & 0 & s & 0 \\ 0 & 0 & 0 & 0 & s \end{bmatrix} \begin{bmatrix} \Delta\psi_d \\ \Delta\psi_q \\ \Delta\psi_f \\ \Delta\psi_{Dd} \\ \Delta\psi_{Dq} \end{bmatrix}$$

$$+ \begin{bmatrix} -R_a & 0 & 0 & 0 & 0 \\ 0 & -R_a & 0 & 0 & 0 \\ 0 & 0 & R_f & 0 & 0 \\ 0 & 0 & 0 & R_{Dd} & 0 \\ 0 & 0 & 0 & 0 & R_{Dq} \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta i_f \\ \Delta i_{Dd} \\ \Delta i_{Dq} \end{bmatrix} + \begin{bmatrix} -\bar{\psi}_q \\ \bar{\psi}_d \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \Delta\omega_q \end{bmatrix} \quad (78)$$

Laplace transformation has been applied with initial conditions equal to zero. In order to simplify the problem, neglect damper bar, armature resistance, magnetic saturation, armature and field leakage inductances. Eqs. (76) to (78) and the balanced load equations become:

$$\begin{bmatrix} \Delta e_d \\ \Delta e_q \end{bmatrix} = \begin{bmatrix} R_L + SL_L & -L_L \bar{\omega}_g \\ L_L \bar{\omega}_g & R_L + SL_L \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix} + \begin{bmatrix} -L_L \bar{i}_q \\ L_L \bar{i}_d \end{bmatrix} \begin{bmatrix} \Delta \omega_g \end{bmatrix} \tag{79}$$

$$\begin{bmatrix} \Delta e_f \\ \Delta e_d \\ \Delta e_q \end{bmatrix} = \begin{bmatrix} S & 0 & 0 \\ 0 & S & -\bar{\omega}_g \\ 0 & \bar{\omega}_g & S \end{bmatrix} \begin{bmatrix} \Delta \psi_f \\ \Delta \psi_d \\ \Delta \psi_q \end{bmatrix} + \begin{bmatrix} 0 \\ -\bar{\psi}_q \\ \bar{\psi}_d \end{bmatrix} \begin{bmatrix} \Delta \omega_g \end{bmatrix}$$

$$+ \begin{bmatrix} R_f & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta i_f \\ \Delta i_d \\ \Delta i_q \end{bmatrix} \tag{80}$$

$$\begin{bmatrix} \Delta \phi_f \\ \Delta \phi_d \\ \Delta \phi_q \end{bmatrix} = \begin{bmatrix} L_{md} & -L_{md} & 0 \\ L_{md} & -L_{md} & 0 \\ 0 & 0 & -L_{mq} \end{bmatrix} \begin{bmatrix} \Delta i_f \\ \Delta i_d \\ \Delta i_q \end{bmatrix} \tag{81}$$

$$\begin{bmatrix} \Delta e_f \\ \Delta e_d \\ \Delta e_q \end{bmatrix} = \begin{bmatrix} R_f + SL_{md} & -SL_{md} & 0 \\ SL_{md} & -SL_{md} & \bar{\omega}_g L_{mq} \\ \bar{\omega}_g L_{md} & \bar{\omega}_g L_{md} & -SL_{mq} \end{bmatrix} \begin{bmatrix} \Delta i_f \\ \Delta i_d \\ \Delta i_q \end{bmatrix} \tag{82}$$

Assume constant generator frequency.

That is $\Delta\omega g = 0$. From eqs. (79) to (82). First solve for Δi_d and Δi_q.

$$\left[\Delta e_f\right] = \left[R_f + sL_{md}\right]\left[\Delta i_f\right] - \left[sL_{md} \quad 0\right]\begin{bmatrix}\Delta i_d \\ \Delta i_q\end{bmatrix} \tag{83}$$

$$\begin{bmatrix}\Delta e_d \\ \Delta e_q\end{bmatrix} = \begin{bmatrix}sL_{md} \\ \bar{\omega}_g L_{md}\end{bmatrix}\left[\Delta i_f\right] + \begin{bmatrix}-sL_{md} & \bar{\omega}_g L_{mq} \\ \bar{\omega}_g L_{md} & -sL_{mq}\end{bmatrix}\begin{bmatrix}\Delta i_d \\ \Delta i_q\end{bmatrix} \tag{84}$$

$$\left[R_f + sL_{md}\right]\begin{bmatrix}\Delta e_d \\ \Delta e_q\end{bmatrix} = \begin{bmatrix}sL_{md} \\ \bar{\omega}_g L_{md}\end{bmatrix}\left[\Delta e_f\right]$$

$$+ \begin{bmatrix}-sL_{md}R_f & s\omega_g L_{md}L_{mq} + \bar{\omega}_g L_{mq}R_f \\ -\bar{\omega}_g L_{md}R_f & -s^2 L_{md}L_{mq} - sL_{mq}R_f\end{bmatrix}\begin{bmatrix}\Delta i_d \\ \Delta i_q\end{bmatrix} \tag{85}$$

$$\left[\begin{matrix}s^2 L_{md}L_L + s(L_{md}R_f + L_{md}R_L + L_L R_f) + R_f R_L \\ s\,\bar{\omega}_g L_{md}L_L + \bar{\omega}_g R_f (L_{md} + L_L\end{matrix}\right.$$

$$\left.\begin{matrix}-s\bar{\omega}_g L_{md}(L_{mq} + L_L) - \bar{\omega}_g R_f (L_{mq} + L_L) \\ s^2 L_{md}(L_{mq} + L_L) + s(L_{md}R_L + L_L R_f + L_{mq}R_f) + R_f R_L\end{matrix}\right]\begin{bmatrix}\Delta i_d \\ \Delta i_q\end{bmatrix}$$

$$= \begin{bmatrix}sL_{md} \\ \bar{\omega}_g L_{md}\end{bmatrix}\left[\Delta e_f\right] \tag{86}$$

i.e.

$$[A]\begin{bmatrix}\Delta i_d \\ \Delta i_q\end{bmatrix} = \begin{bmatrix} sL_{md} \\ \bar{\omega}_g L_{md}\end{bmatrix}[\Delta e_f] \tag{87}$$

$$\therefore \begin{bmatrix}\Delta i_d \\ \Delta i_q\end{bmatrix} = [A]^{-1}\begin{bmatrix} sL_{md} \\ \bar{\omega}_g L_{md}\end{bmatrix}[\Delta e_f]$$

$$= \begin{bmatrix} \dfrac{K_1(s^3 + C_{11}s^2 + b_{11}s + a_{11})}{s^4 + d_p s^3 + C_p s^2 + b_p s + a_p} \\ \dfrac{K_2(s^2 + b_{22}s + a_{22})}{s^4 + d_p s^3 + C_p s^2 + b_p s + a_p}\end{bmatrix}[\Delta e_f]$$

$$= \begin{bmatrix} G_1(s) \\ G_2(s)\end{bmatrix}[\Delta e_f] \tag{88}$$

$$K_1 = \frac{1}{L_L} \tag{89a}$$

$$K_2 = \frac{\bar{\omega}_g(L_{mq} + 2L_L)}{L_L(L_{mq} + L_L)} \tag{89b}$$

$$a_p = \frac{R_f^2 R_L^2}{L^2_{md} L_L (L_{mq} + L_L)} + \frac{R_f^2 \bar{\omega}_g^2 (L_{md} + L_L)}{L_{md}^2 L_L} \tag{89c}$$

$$b_p = \frac{R_f R_L\left[2L_{md}R_L + 2L_L R_f + L_{mq}R_f + L_{md}R_f\right]}{L_{md}^2 L_L (L_{mq}+L_L)} + \frac{\bar{\omega}_g^2 R_f (L_{md}+2L_L)}{L_{md} L_L} \tag{89d}$$

$$c_p = \frac{R_f R_L}{L_{md} L_L} + \frac{R_f R_L}{L_{md}(L_{mq}+L_L)} + \bar{\omega}_g^2 + \frac{(L_{md}R_f + L_{md}R_L + L_L R_f)(L_{md}R_L + L_L R_f + L_{mq}R_f)}{L_{md}^2 L_L (L_{mq}+L_L)} \tag{89e}$$

$$d_p = \frac{L_{md}R_f + L_{md}R_L + L_L R_f}{L_{md} L_L} + \frac{L_{md}R_L + L_L R_f + L_{mq}R_f}{L_{md}(L_{mq}+L_L)} \tag{89f}$$

$$a_{11} = \frac{\bar{\omega}_g^2 R_f (L_{md}+L_L)}{L_{md}(L_{mq}+L_L)} \tag{89g}$$

$$b_{11} = \frac{R_f R_L}{L_{md}(L_{mq}+L_L)} - \frac{\bar{a}_g^2 L_L}{L_{mq}+L_L} \tag{89h}$$

$$C_{11} = \frac{R_L}{L_{mq} + L_L} + \frac{R_f}{L_{md}} \tag{89i}$$

$$a_{22} = \frac{R_f R_L}{L_{md}(L_{mq} + 2L_L)} \tag{89j}$$

$$b_{22} = \frac{R_f + R_L}{L_{mq} + 2L_L} + \frac{R_f}{L_{md}} \tag{89k}$$

Generally, $\bar{\omega}_g L_{md}, \bar{\omega}_g L_{mq} >> \bar{\omega}_g L_L, R_f, R_L$
AND $R_f, R_L >> L_{md}, L_{mq}, L_L$

The coefficients can be approximated.

$$K_1 = \frac{1}{L_L} \tag{90a}$$

$$K_2 = \frac{\bar{\omega}_g}{L_L} \tag{90b}$$

$$a_p = \frac{R_f^2}{L_{md} L_L} \left(\frac{R_L^2}{L_{md} L_{mq}} + \bar{\omega}_g^2 \right) \tag{90c}$$

$$b_p = \frac{R_f}{L_L}\left[\frac{R_L(2L_{md}R_L + L_{mq}R_f + L_{md}R_f)}{L_{md}^2 L_{mq}} + \bar{\omega}_g^2\right] \tag{90d}$$

$$c_p = \frac{R_f R_L}{L_{md}L_L} + \frac{(R_L + R_f)(L_{md}R_L + L_{mq}R_f)}{L_{md}L_{mq}L_L} + \bar{\omega}_g^2 \tag{90e}$$

$$d_p = \frac{R_f + R_L}{L_L} \tag{90f}$$

$$a_{11} = \frac{\bar{\omega}_g^2 R_f}{L_{mq}} \tag{90g}$$

$$b_{11} = \frac{1}{L_{mq}}\left(\frac{R_f R_L}{L_{md}} - \bar{\omega}_g^2 L_L\right) \tag{90h}$$

$$C_{11} = \frac{R_L}{L_{mq}} + \frac{R_f}{L_{md}} \tag{90i}$$

$$a_{22} = \frac{R_f R_L}{L_{md}L_{mq}} \tag{90j}$$

$$b_{22} = \frac{R_f R_L}{L_{mq}} + \frac{R_f}{L_{md}} \tag{90k}$$

Thus, solve for Δe_d, Δe_q.

$$\begin{bmatrix} \Delta e_d \\ \Delta e_q \end{bmatrix} = \begin{bmatrix} R_L + sL_L & -\bar{\omega}_g L_L \\ \bar{\omega}_g L_L & R_L + sL_L \end{bmatrix} \begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix}$$

$$= \begin{bmatrix} (R_L + sL_L) G_1(s) - \bar{\omega}_g L_L G_2(s) \\ \bar{\omega}_g L_L G_1(s) + (R_L + sL_L) G_2(s) \end{bmatrix} \begin{bmatrix} \Delta e_f \end{bmatrix}$$

$$= \begin{bmatrix} \dfrac{K3\,(s^4 + d_{33} s^3 + c_{33} s^2 + b_{33} s + a_{33})}{s^4 + dp s^3 + cp s^2 + bp s + ap} \\ \\ \dfrac{K4\,(s^3 + c_{44} s^2 + b_{44} s + a_{44})}{s^4 + dp s^3 + cp s^2 + bp s + ap} \end{bmatrix} \begin{bmatrix} \Delta e_f \end{bmatrix}$$

$$= \begin{bmatrix} G_3(s) \\ G_4(s) \end{bmatrix} \begin{bmatrix} \Delta e_f \end{bmatrix} \tag{91}$$

$$K_3 = 1 \tag{92a}$$

$$a_{33} = \frac{R_L}{L_L} a_{11} - \bar{\omega}_g^2 a_{22} \tag{92b}$$

$$b_{33} = a_{11} + \frac{R_L}{L_L} b_{11} - \omega_g^2 b_{22} \tag{92c}$$

$$c_{33} = \frac{R_L}{L_L} c_{11} + b_{11} - \bar{\omega}_g^2 \tag{92d}$$

$$d_{33} = \frac{R_L}{L_L} + c_{11} \tag{92e}$$

$$K_4 = 2\bar{\omega}_g \tag{92f}$$

$$a_{44} = \frac{1}{2}\left(a_{11} + \frac{R_L}{L_L} a_{22}\right) \tag{92g}$$

$$b_{44} = \frac{1}{2}\left(b_{11} + \frac{R_L}{L_L} b_{22} + a_{22}\right) \tag{92h}$$

$$c_{44} = \frac{1}{2}\left(c_{11} + b_{22} + \frac{R_L}{L_L}\right) \tag{92i}$$

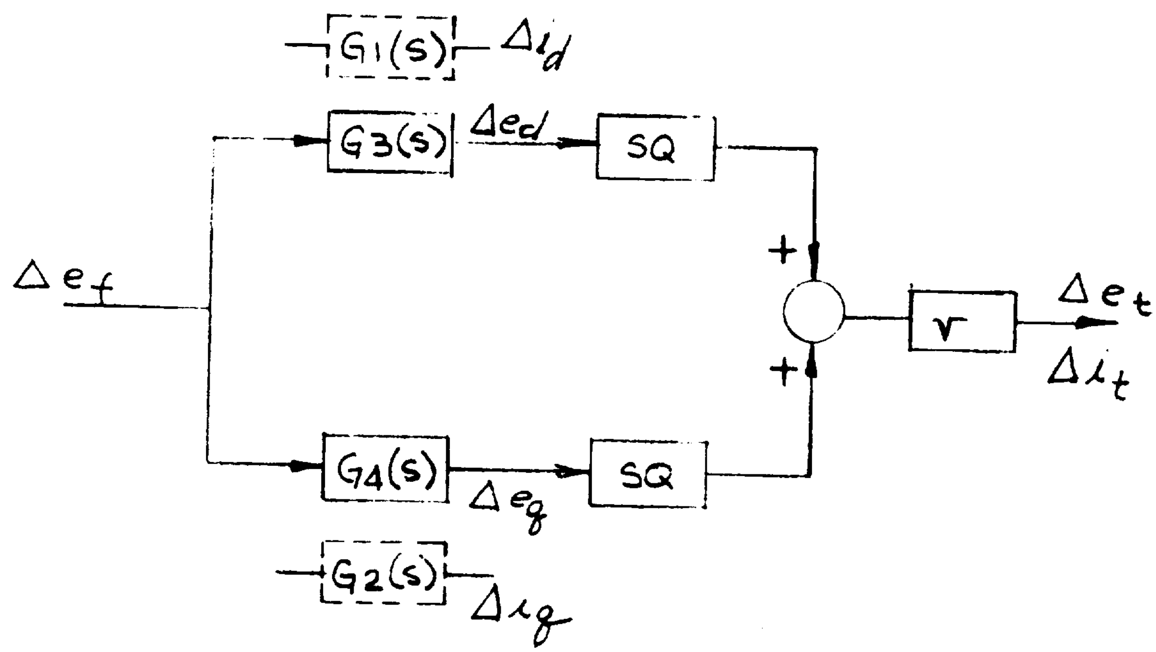


Fig. 22

$G_1(s)$, $G_2(s)$, $G_3(s)$ and $G_4(s)$ are linear filters. They can be implemented on an analog computer. The coefficient of the filters can be tabulated by digital computer so that a new set of values can readily be obtained when the machine and/or load parameters are changed while this implies to change of potentiometer settings of the analog computer. However, this section will emphasize on theoretical analysis of the equivalent filters. Different kinds of stability analysis methods are used to interpret the relative stability, transient and other concerns. Numerical examples are given along with the discussion. Digital computer is used for the computations.

(ii) First, the characteristics of the transfer functions of the models $G_1(s)$, $G_2(s)$, $G_3(s)$ and $G_4(s)$ are investigated. The denominator is a fourth order polynomial with all the coefficients positive. There will be four poles. Their locations depend on the generator and load parameters and the generator frequency which has been assumed constant. For the system to be stable, all these poles of the closed loop system must lie on the left half of the complex plane so as to ensure convergence. The closed loop system is assumed to be: (with constant speed drive)

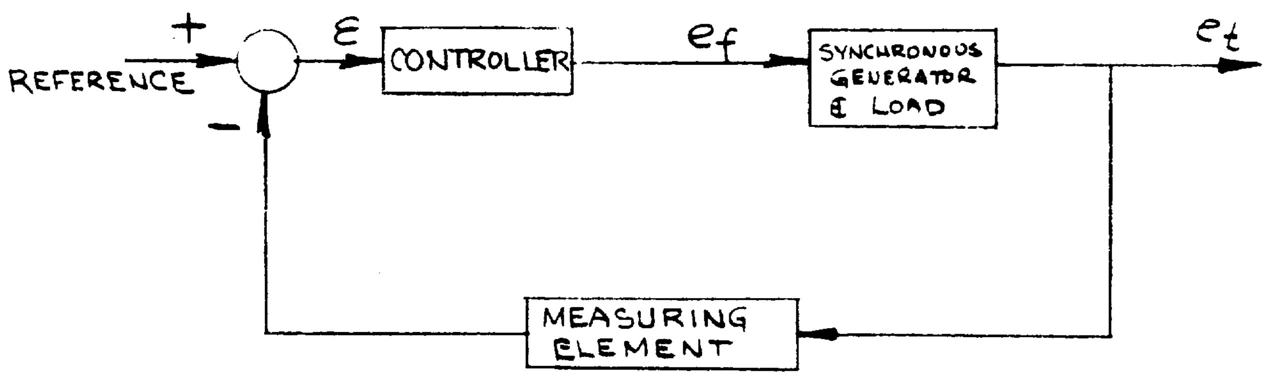


Fig. 23
Closed-Loop System

Thus, the synchronous generator and the load can be considered as an open-loop plant.

A synchronous generator used as a sample throughout the following discussion is rated at 120 volt/111 amp line to neutral with a power factor of 0.75.

$\bar{\omega}_g$ = 2500 radians/second

L_{md} = 0.068 henries

L_{mq} = 0.044 henries

R_f = 1.8 ohms

R_L = 0.8 ohms

L_L = 0.0003 henries

From the previous argument and derivation

$$G_3(s) = \frac{E_d(s)}{E_f(s)} \tag{93a}$$

$$= \frac{s^4 + 2.73\times10^3 s^3 - 6.2\times10^6 s^2 - 6\times10^8 s - 3.84\times10^{11}}{s^4 + 6\times10^3 s^3 + 6.5\times10^6 s^2 + 1.37\times10^{10} s + 3.08\times10^{11}}$$

$$G_4(s) = \frac{E_q(s)}{E_f(s)} \tag{93b}$$

$$= \frac{5\times10^3(s^3 + 1.4\times10^3 s^2 - 1.97\times10^4 s - 7.07\times10^7}{s^4 + 6\times10^3 s^3 + 6.5\times10^6 s^2 + 1.37\times10^{10} s + 3.08\times10^{11}}$$

The steady state gains are -

$$\lim_{s\to 0} \left| G_3(s) \right| = 1.25$$

$$\lim_{s\to 0} \left| G_4(s) \right| = 1.15$$

Factorize $G_3(s)$ and $G_4(s)$

$$G_3(s) = \frac{5\times10^3(s-215)(s+238)(s+1377)}{(s+23)(s+5300)(s+360 \pm j\,1560}$$

$$G_4(s) = \frac{(s-1570)(s+4300)(s+57 \pm j235)}{(s+23)(s+5300)(s+360 \pm j1560)}$$

The denominator determines the locations of the open-loop poles while the numerator determines the open-loop zeros. The poles are the starting points of the root locus which terminate at the corresponding zeros as the gain approaches to infinity. Observe both $G_3(s)$ and $G_4(s)$ have the same denominator and the poles are all in the left half plane, therefore, the open loop plant is a stable one. Only $G_4(s)$ is plotted on the complex plane.

S- plane

$$G_4(s) = \frac{(s+57 \pm j\,235)(s-1570)(s+4300)}{(s+23)(s+5300)(s+360 \pm j\,1560)}$$

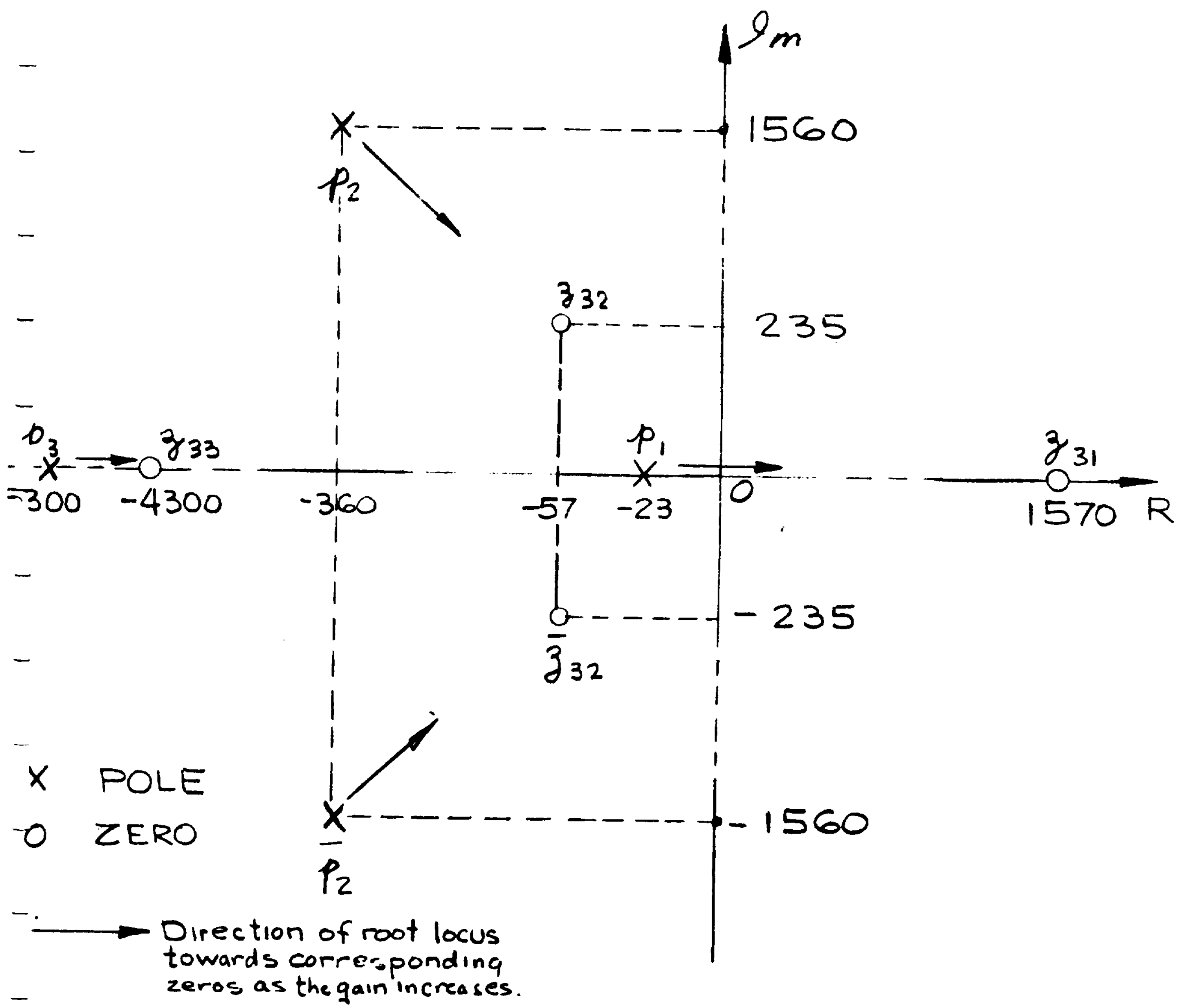


Fig. 24 Root locus of G4(s)

$G_3(s)$ and $G_4(s)$ have poles located at -23, -5300 and -360. The latter is taken from the real part of the pair of complex root. The correspondent time constant are:

$$T_1 - \frac{1}{23} - 0.0435 \text{ sec.} \tag{96a}$$

$$T_2 - \frac{1}{360} - 0.00277 \text{ sec.} \tag{96b}$$

$$T_3 - \frac{1}{5300} - 0.000189 \text{ sec.} \tag{96c}$$

The last two are comparatively insignificant. Thus, for a rough estimate, the synchronous generator with excitation voltage e_f as the only feed forward control effort, can be approximated as a first order systed with a time constant of T_1. Generally, T_2 can be included as subtransient time while T_1 as transient time constant. From eqs. (94a) and (94b) steady state gain of terminal voltage e_t over excitation voltage e_f can be derived.

$$\lim_{s \to 0} \frac{E_t(s)}{E_f(s)} = \lim_{s \to 0} \left\{ \left[G_3(s)\right]^2 + \left[G_4(s)\right]^2 \right\}^{\frac{1}{2}}$$

$$= (1.25^2 + 1 \cdot 15^2)^{\frac{1}{2}}$$

$$= 1.7 \tag{97}$$

Therefore, the approximated linear transfer function of e_t/e_f can be written as:

$$\frac{E_t(s)}{E_f(s)} = \frac{K_t}{(1+T_1 s)(1+T_2 s)} \tag{98}$$

$$= \frac{1.7}{(1+0.0435s)(1+0.00277s)}$$

(iii) Frequency domain plot:

To plot $G_3(s)$ and $G_4(s)$ in the frequency domain, let

$$s = j\omega$$

$$D(s) = s^4 + dp\,s^3 + cp\,s^2 + bp\,s + ap \qquad (99a)$$

$$D(j\omega) = (ap - cp\,\omega^2 + \omega^4) + j\omega(bp - dp\,\omega^2)$$
$$|D(j\omega)| \angle \theta_D \qquad (99b)$$

where

$$|D(j\omega)| = \left[(ap - cp\,\omega^2 + \omega^4)^2 + \omega^2(bp - dp\,\omega^2)^2\right]^{\frac{1}{2}} \qquad (99c)$$

$$\theta_D = \tan^{-1}\left[\frac{\omega(bp - dp\,\omega^2)}{ap - cp\,\omega^2 + \omega^4}\right] \qquad (99d)$$

Similarly:

$$N_3(s) = K_3(s^4 + d_{33}s^3 + C_3 s^2 + b_{33}s + a_{33} \qquad (100a)$$

$$N_3(j\omega) = |N_3(j\omega)| \angle \theta_3 \qquad (100b)$$

where

$$|N_3(j\omega)| = K_3\left[(a_{33} - C_{33}\omega^2 + \omega^4)^2 + \omega^2(b_{33} - d_{33}\omega^2)^2\right]^{\frac{1}{2}} \qquad (100c)$$

$$\theta_3 = \tan^{-1}\left[\frac{\omega(b_{33} - d_{33}\omega^2)}{a_{33} - C_{33}\omega^2 + \omega^4}\right] \qquad (100d)$$

$$N_4(s) = K_4(s^3 + c_{44}s^2 + b_{44}s + a_{44}) \tag{101a}$$

$$N_4(j\omega) = |N_4(j\omega)| \angle \theta_4 \tag{101b}$$

where

$$|N_4(j\omega)| = \left[K_4 \quad (a_{44} - c_{44}\omega^2)^2 + \omega^2(b_{44} - \omega^2)^2\right]^{\frac{1}{2}} \tag{101c}$$

$$\theta_4 = \tan^{-1}\left[\frac{\omega(b_{44} - \omega^2)}{a_{44} - c_{44}\omega^2}\right] \tag{101d}$$

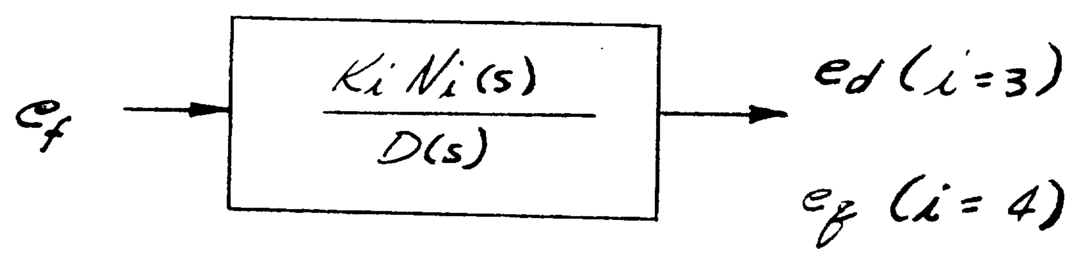
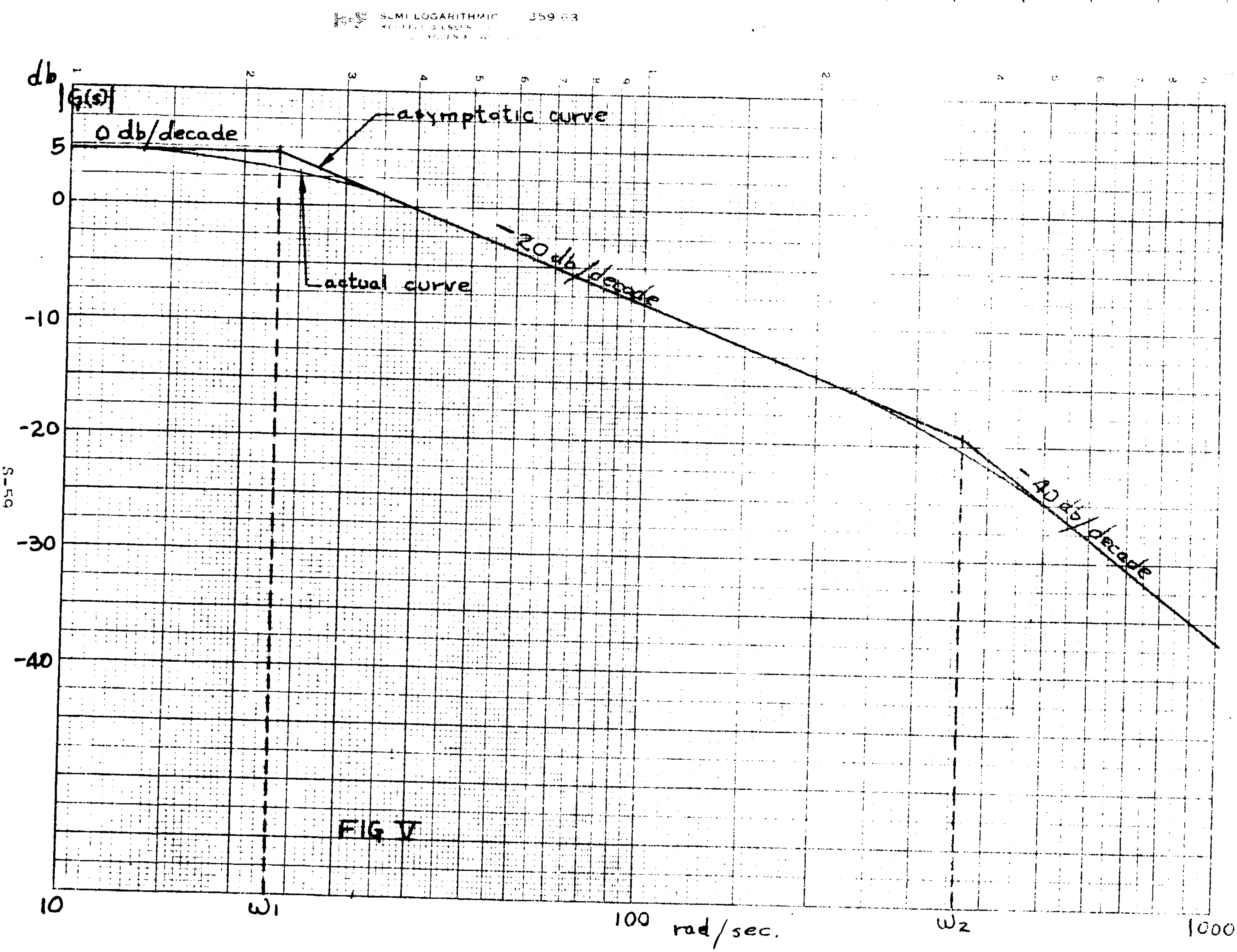


Fig. 25

Use the same data for the synchronous generator and impose the same assumptions as in the previous example. Plot the transfer functions with respect to frequency in Fig. IV. Consider $G_3(s)$, the zero cross-over of the amplitude curve corresponds to a phase lag of 35^0. That is a phase margin of 145^0. $G_3(s)$ is far from unstable. One must know that not all the poles and zeros are in the left half of the complex plane. The non-minimum phase characteristics prevent the direct approximation of the phase angle derived from the asymptotic plot of the amplitude curve.



SEMI-LOGARITHMIC 359-63
db
|G(s)|
0 db/decade
asymptotic curve
actual curve
-20 db/decade
-40 db/decade
5
0
-10
-20
-30
-40
10
ω1
100
rad/sec.
ω2
1000

FIG V

(iv) Transfer function derivation from laboratory data:

Conversely, if a transient response curve is in hand, a transfer function can be derived from asymptotic plot in a frequency domain curve. The break-away points of two asymptotes with 20 db/decade decay difference determines the time constants. The order of the transfer function depends on the need of accuracy in describing the characteristics. It must be noted that a time domain plot which is the usual case of laboratory data, should be transformed into frequency domain plot before applying the approximation technique. The abscissa should be the ratio of output versus input in decibel while the ordinate, frequency on radians per second. Suppose an actual curve is plotted in Fig. D. Three asymptotic lines are approximated. The zero db/decade line is at 4.6 db which determines the gain of the transfer function while the two break-away points at

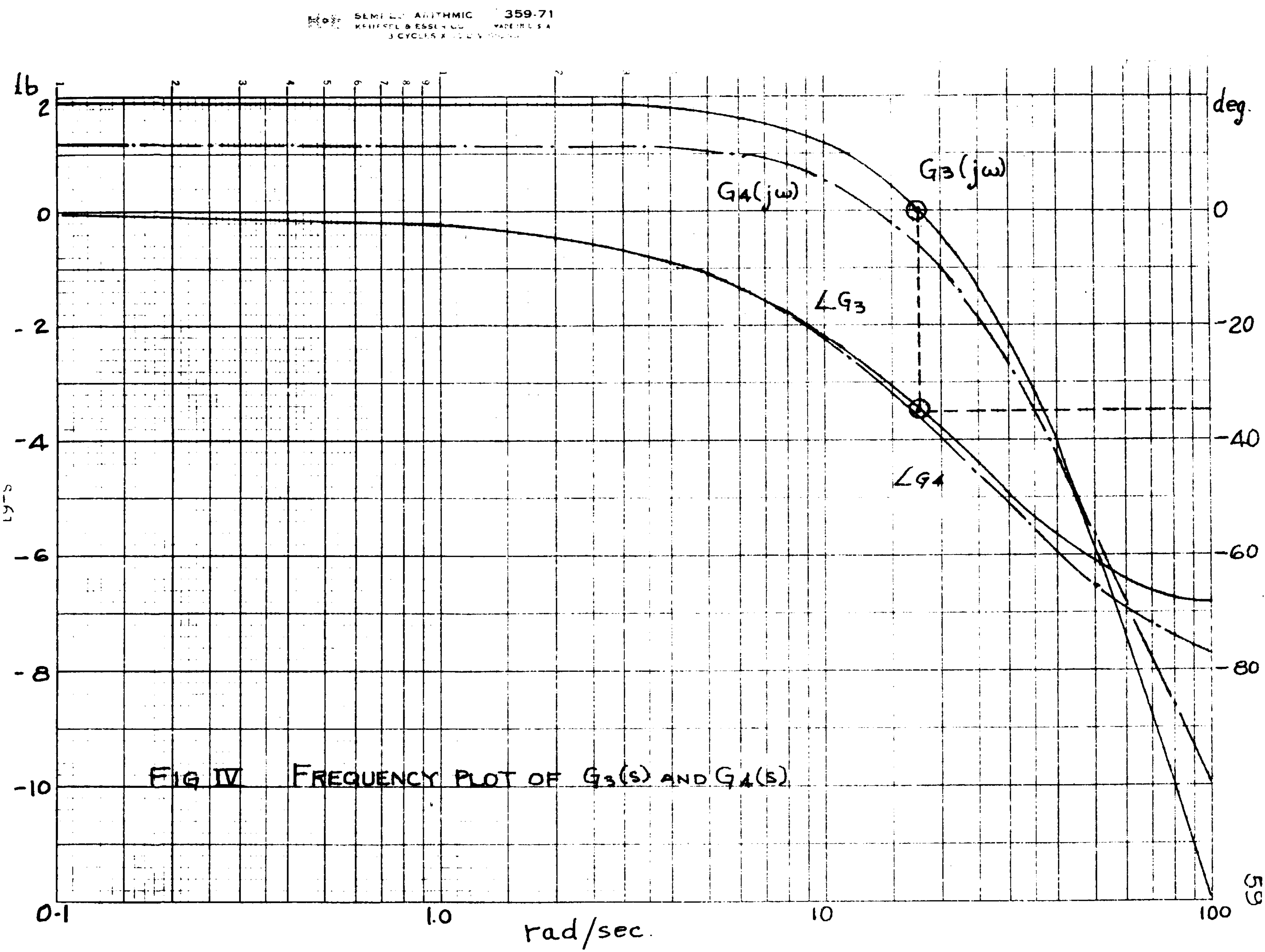


FIG IV FREQUENCY PLOT OF $G_3(s)$ AND $G_4(s)$

$\omega_1 = 23$ rad/SEC AND $\omega_2 = 360$ rad/sec

The transfer function becomes -

$$G(s) = \frac{K}{(1 + T_1 s)(1 + T_2 s)}$$

$$= \frac{\frac{1}{20} \text{antilog}_{10} (4.6)}{(1 + \frac{1}{23} s)(1 + \frac{1}{360} s)}$$

$$= \frac{1.7}{(1 + 0.0435 s)(1 + 0.00277 s)} \qquad (98a)$$

(v) Two manipulated variables:

If both Δ_w and Δe_f are considered simultaneously,

$$\begin{bmatrix} \Delta i_d \\ \Delta i_q \end{bmatrix} = \begin{bmatrix} G_1(s) \\ G_2(s) \end{bmatrix} \begin{bmatrix} \Delta e_f \end{bmatrix} + \begin{bmatrix} A \end{bmatrix}^{-1}$$

$$\begin{bmatrix} R_f \bar{i}_q (L_{mq} + L_L) + s L_{md} \bar{i}_q (L_{mq} + L_L) \\ R_f \{ L_{md} \bar{i}_f - \bar{i}_d (L_{md} + L_L) \} + s L_{md} \{ L_{md} \bar{i}_f - \bar{i}_d (L_{md} + L_L) \} \end{bmatrix} \begin{bmatrix} \Delta \omega \end{bmatrix}$$

$$= \begin{bmatrix} G_1(s) \\ G_2(s) \end{bmatrix} \begin{bmatrix} \Delta e_f \end{bmatrix} + \begin{bmatrix} G_5(s) \\ G_6(s) \end{bmatrix} \begin{bmatrix} \Delta \omega \end{bmatrix} \tag{102}$$

$$G_5(s) = \frac{s^3 d_5 + s^2 c_5 + s b_5 + a_5}{s^4 e_p + s^3 d_p + s^2 c_p + s b_p + a_p} \tag{102a}$$

$$G_6(s) = \frac{s^3 d_6 + s^2 c_6 + s b_6 + a_6}{s^4 e_p + s^3 d_p + s^2 c_p + s b_p + a_p} \tag{102b}$$

$$\begin{bmatrix} \Delta e_d \\ \Delta e_q \end{bmatrix} = \begin{bmatrix} G_3(s) \\ G_4(s) \end{bmatrix} \begin{bmatrix} \Delta e_f \end{bmatrix} + \begin{bmatrix} G_7(s) \\ G_8(s) \end{bmatrix} \begin{bmatrix} \Delta \omega \end{bmatrix} \tag{103}$$

where

$$G_7(s) = \frac{s^4 e_7 + s^3 d_7 + s^2 c_7 + s b_7 + a_7}{s^4 e_p + s^3 d_p + s^2 c_p + s b_p + a_p} \tag{103a}$$

$$G_8(s) = \frac{s^4 e_8 + s^3 d_8 + s^2 c_8 + s b_8 + a_8}{s^4 e_p + s^3 d_p + s^2 c_p + s b_p + a_p} \tag{103b}$$

Again, approximate the coefficients by assuming

$$L_{mq},\ L_{md} >> L_L$$

$$d_5 = L^2_{md} L^2_{mq} \bar{i}_q \tag{104a}$$

$$e_5 = \left[L_{md} (L_{md} R_L + 2 L_{mq} R_f) \bar{i}_q + \bar{\omega}_g L_L L^2_{md} (\bar{i}_f - \bar{i}_d) \right] \tag{104b}$$

$$b_5 = R_f \left[L_{mq} (2 L_{md} R_L + L_{mq} R_f) i_q + \bar{\omega}_g L^3_{md} (\bar{i}_f - \bar{i}_d) \right] \tag{104c}$$

$$a_5 = R_f^2 \left[R_L L_{mq} \bar{i}_q + \bar{\omega}_g L^2_{md} (\bar{i}_f - \bar{i}_d) \right] \tag{104d}$$

$$d_6 = L_L L^3_{md} (\bar{i}_f - \bar{i}_d) \tag{104e}$$

$$c_6 = L^3_{md} (\bar{i}_f - \bar{i}_d)(R_L + R_f) - \bar{\omega}_g L^2_{md} L^2_{mq} \bar{i}_q \tag{104f}$$

$$b_6 = R_f L_{md} \left[L_{md} (2 R_L + R_f)(\bar{i}_f - \bar{i}_d) - 2 \bar{\omega}_g L^2_{mq} \bar{i}_q \right] \tag{104g}$$

$$a_6 = R_f^2 \left[R_L L_{md} (\bar{i}_f - \bar{i}_d) - \bar{\omega}_g L^2_{mq} \bar{i}_q \right] \tag{104h}$$

$$e_7 = L_L (d_5 - e_p \bar{i}_q) \tag{104i}$$

$$d_7 = R_L d_5 + L_L (c_5 - \bar{\omega}_g d_6 - d_p \bar{i}_q) \tag{104j}$$

$$c_7 = R_L c_5 + L_L (b_5 - \bar{\omega}_g c_6 - c_p \bar{i}_q) \tag{104k}$$

$$b_7 = R_L b_5 + L_L (a_5 - \bar{\omega}_g b_6 - b_p \bar{i}_q) \tag{104l}$$

$$a_7 = R_L a_5 - L_L (\bar{\omega}_g a_6 + a_p \bar{i}_q) \tag{104m}$$

$$e_8 = L_L (d_6 + e_p \bar{i}_d) \tag{104n}$$

$$d_8 = R_L d_6 + L_L (c_6 + \bar{\omega}_g d_5 + d_p \bar{i}_d) \tag{104o}$$

$$c_8 = R_L c_6 + L_L (b_6 + \bar{\omega}_g c_5 + c_p \bar{i}_d) \tag{104p}$$

$$b_8 = R_L b_6 + L_L (a_6 + \bar{\omega}_g b_5 + a_p \bar{i}_d) \tag{104q}$$

$$a_8 = R_L a_6 + L_L (\bar{\omega}_g a_5 + a_p \bar{i}_d) \tag{104r}$$

$$e_p = L_{md}^2 L_{mq} L_L \tag{104s}$$

$$d_p = L_{md} \left[L_{md} L_{mq} (R_f + R_L) + L_L (L_{md} R_L + L_{mq} R_f) \right] \tag{104t}$$

$$c_p = L_{md} \left[L_{mq} (R_f R_L + \bar{\omega}_g^2 L_{md} L_L) + (R_f + R_L)(L_{md} R_L + L_{mq} R_f) \right] \tag{104u}$$

$$b_p = R_f \left[R_L \left(2 L_{md} R_L + R_f L_{md} + L_{mq} R_f \right) + \bar{\omega}_g^2 L_{md}^2 L_{mq} \right] \tag{104v}$$

$$a_p = R_f^2 \left(R_L^2 + \bar{\omega}_g^2 L_{md} L_{mq} \right) \tag{104w}$$

The increments of the variables have to be small for the formulation to be valid. The result is an interacting system.

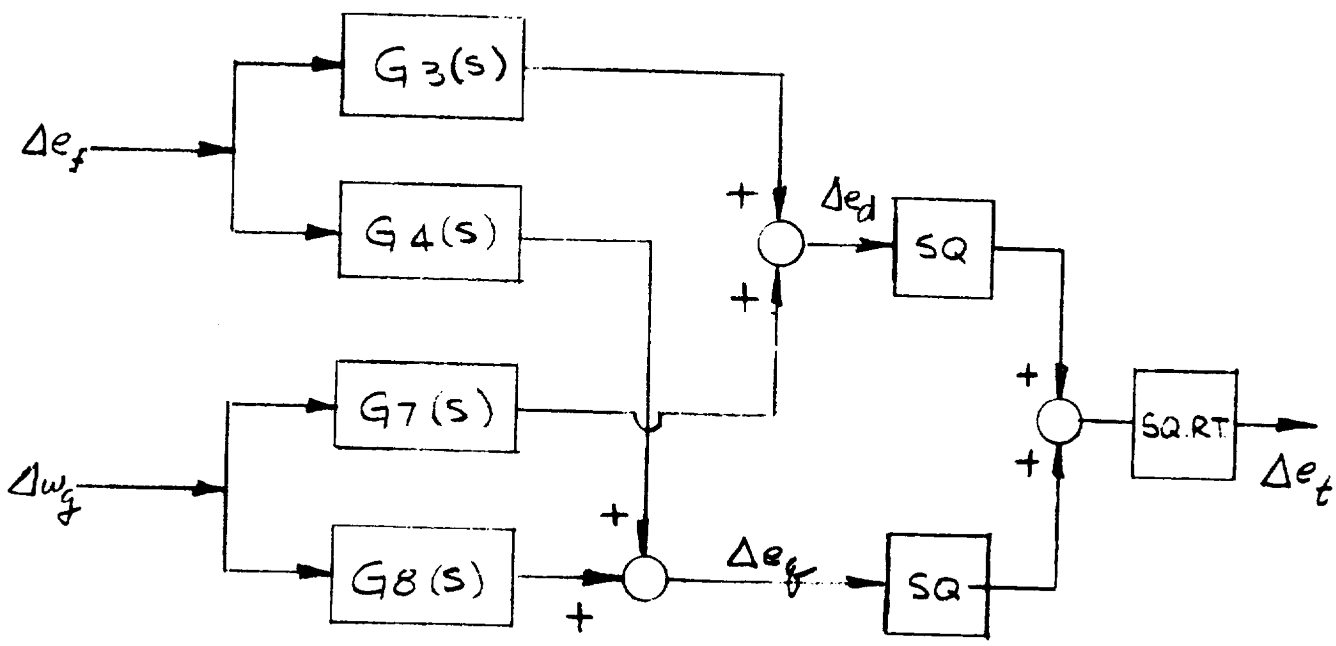
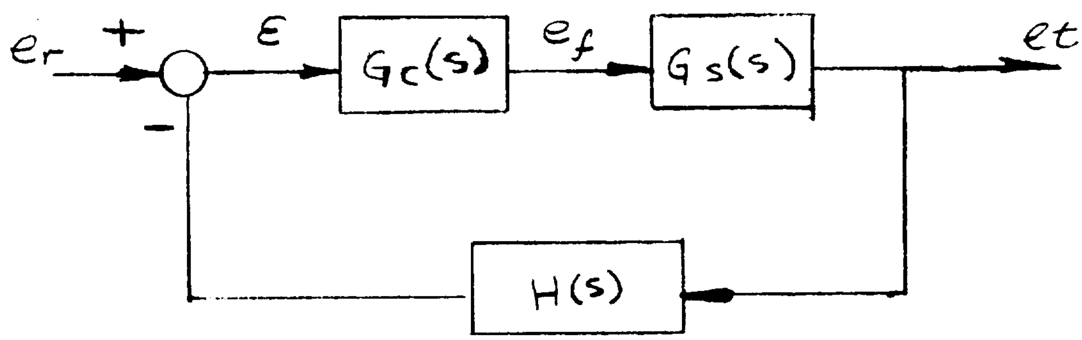


Fig. 26 Linearization of two control variables

(vi) <u>Closed loop control:</u>



$G_s(s)$ = transfer function of synchronous generator

$G_c(s)$ = controller

$H(s)$ = measuring elements

$T(s)$ = closed-loop transfer function

where

$$T(s) = \frac{G_c(s)\,Gs(s)}{1 + H(s)\,G_c(s)\,Gs(s)}$$

Assume:

$$Gs(s) = \frac{s^4 + 2.73\times10^3 s^3 - 6.2\times10^6 s^2 - 6\times10^8 s - 3.84\times10^{11}}{s^4 + 6\times10^3 s^3 + 6.5\times10^6 s^2 + 1.37\times10^{10} s + 3.08\times10^{11}}$$

$$H(s) = 1.0$$

$$G_c(s) = K$$

It is desired to find the maximum permissible gain K for a stable operation. Hurwitz criterion states that a characteristic equation

$$a_n s^n + a_{n-1} s^{n-1} + \text{------} \; a_2 s^2 + a_1 s + a_0 = 0$$

All the determinants

$$\begin{array}{cccc}
a_1 & a_0 & 0 & 0 \; \text{---} \\
a_3 & a_2 & a_1 & 0 \; \text{---} \\
a_5 & a_4 & a_3 & a_2 \; \text{---} \\
a_7 & a_4 & \text{---} & \text{---}
\end{array}$$

must be positive for a stable operation. The characteristic equation of T(s) is

$$1 + H(s)\, G_c(s)\, G_s(s) = 0$$

i.e.,

$$(1+K)s^4 + (6-2.73K)10^7 s^3 + (6.5-6.2K)10^6 s^2$$
$$+ (138-6K)10^8 s + (3.08-3.84K)10^{11} = 0$$

Set the determinants equal to zero for critical condition.

$$(138-6K)10^8 = 0$$

$$K_1 = 23$$

$$\begin{vmatrix} (138 - 6K)10^8 & (3.08 - 3.84K)10^{11} \\ (6 - 2.73K)10^3 & (6.5 - 6.2K)10^6 \end{vmatrix} = 0$$

i.e.,

$$K^2 - 32.6K + 33.3 = 0$$

$$K = 31.6 \text{ or } 1.05$$

Since both values are valid, it is desirable to choose $K_2 = 31.6$

$$\begin{vmatrix} (1.38 - 6K)10^8 & (3.08 - 3.84K)10^{11} & 0 \\ (6 - 2.73K)10^3 & (6.5 - 6.2K)10^6 & (1.38 - 6K)10^8 \\ 0 & 1 + K & (6 - 2.73K)10^3 \end{vmatrix}$$

i.e.,

$$K^3 = 38.6K^2 + 135.5K - 48.6 = 0$$

$$K = 34.76, \ 3.38 \text{ OR } 48.6$$

It is desirable to have $K_3 = 34.76$

To compare with the K_s obtained from the three determinants, in order to satisfy the criterion, the smallest value should be chosen. That is $K = K_1 = 23$.

(vii) Sensitivity:

Since any component of the same kind may not be identical due to various reasons, it is beneficial to learn the variation of total performance with respect to the deviation of characteristics of a certain component. It can be the parameters of the plant, the gain of the amplifier or others. For instance, one would like to know the effect of K on T(s) in the last example. Define sensitivity as

$$S_K^T = \frac{d(\ln T)}{d(\ln K)}$$

$$= \frac{d\left[\ln\left(\frac{KG_s}{1+KG_s}\right)\right]}{d(\ln K)}$$

$$= \frac{1}{1+KG_s}$$

The smaller the value of S_K^T, the less effect of variation of K on T(s). However, in this example, the sensitivity is almost linearly related to K because $KG_s >> 1$.

(viii) Degrees of Freedom:

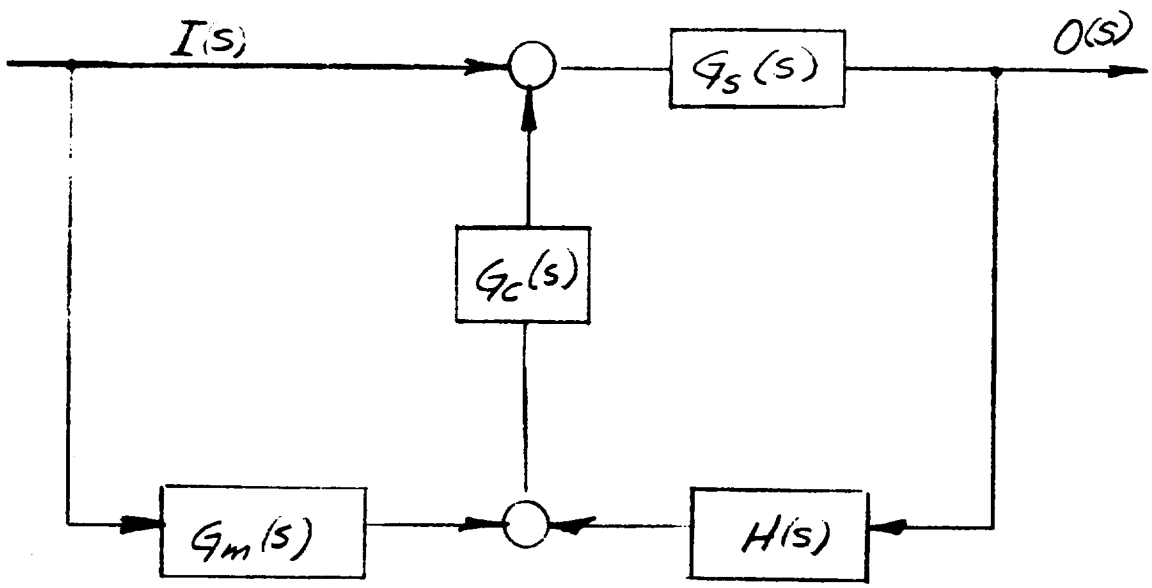
By investigating the closed-loop transfer function

$$T(s) \qquad \frac{G_c(s)\,G_s(s)}{1+H(s)\,G_c(s)G_s(s)}$$

assuming the plant $G_s(s)$ is fixed, one can adjust the controller $G_c(s)$ or feedback element $H(s)$ respectively to obtain a desired $T(s)$. Thus, there is only one degree of freedom. If $G_c(s)$ and $H(s)$ are adjusted simultaneously, there will be two degrees of freedom. The latter is more flexible and many a time the implementation is much easier to be realized.

(ix) Model Approach:

Another method to enforce a specified transient response of a synchronous generator is by introducing a model which describes the specification precisely. The block diagram will be as follows:



$$\frac{O}{I} = \frac{G_s(1 + G_c G_m}{1 + G_c G_s H}$$

Let $H \cong 1$ and make

$$|G_c| >> 1$$

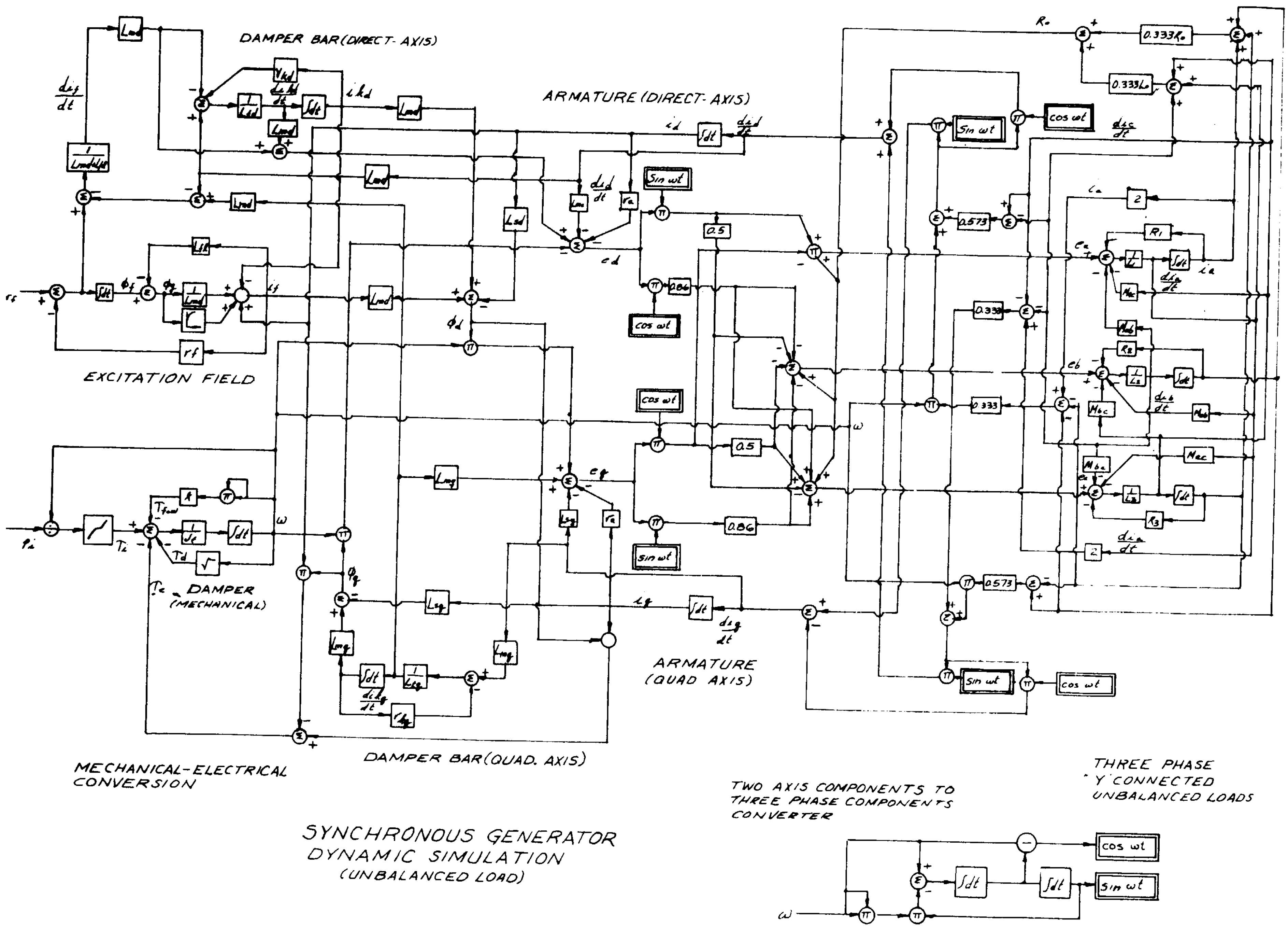
$$\frac{O}{I} = G_m$$

where

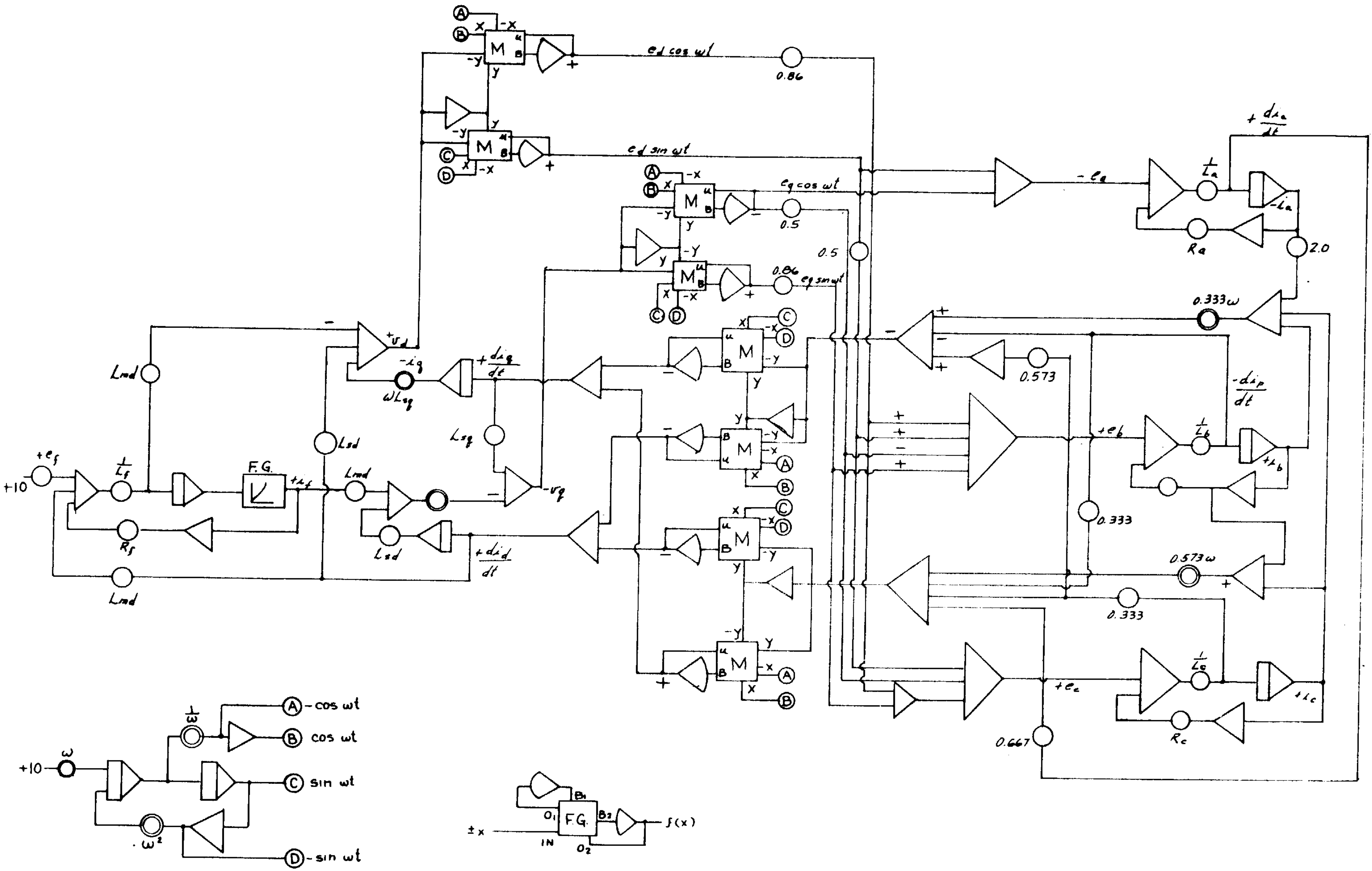
$O(s)$ = output

$I(s)$ = input

$G_m(s)$ = transfer function of model



SYNCHRONOUS GENERATOR
DYNAMIC SIMULATION
(UNBALANCED LOAD)



ANALOG COMPUTER SIMULATION OF SYNCHRONOUS GENERATOR
WITH UNBALANCED LOAD

SYMBOL TABLES

Calculation Number	Electrical Symbol	Explanation
	A, a	
(128)	A	Ampere conductors per inch
(94a)	A_c	Effective area of the core
(68)	A_g	Main gap area
(70)	A_{g2}	Auxiliary air gap (g2) area
(70a)	A_{g3}	Auxiliary air gap (g3) area
(79)	A_p	Pole area
(79)	A_{pi}	Area of pole at entering edge of stator toroid
(79a)	A_{po}	Area of pole at entering edge of stator toroid
(112)	A_{SH}	Area of the shaft
(91b)	A_T	Area of the teeth of one stator
(516)	A_T	Ampere-turn/inch of magnet
(124a)	A_y	Area of the yoke over the exciting coil connecting the two stators
(124b)	A_{yc}	Area of the yoke outside the field coil in generator types 2 and 3
(124c)	A_{yr}	Area of the yoke that is radial and at the sides of the coil in types 2 and 3

Calculation Number	Electrical Symbol	Explanation
(124)	A_{y2}	Cross sectional area of coil yoke
(112)	A_{y4}	Area of shaft
(520)	A_1	Ampere-turn/inch of magnet
(46)	a_c	Conductor area of stator winding
(144)	a_{cd}	Conductor area of damper bar
(153)	a_{cf}	Conductor area of field coil
(170)	a_{dr}	Damper bar end ring area
(79)	a_{np}	North pole area
(79b)	a_{sk}	Area of rotor skirt
(79a)	a_{sp}	Area of south pole
(501)	a_1	Distance between outer edges of adjacent pole sides
(502	a_2	Distance between inner edges of adjacent pole sides

B, b

Calculation Number	Electrical Symbol	Explanation
(20)	B	Density
(94)	B_c	Core flux density
(200g)	B_{cL}	Flux density in the core at full load
(95)	B_g, B'_g	Main air gap density (N. L.)
(122)	B_{g2}	Auxiliary gap (g2) density (N. L.)

Calculation Number	Electrical Symbol	Explanation
(109)	B'_{g2}	Flux density in auxiliary gap
(119)	B_{g3}	Auxiliary gap (g3) density (N.L.)
(224)	$B_{g2\,FL}$	Density in auxiliary gap (g2) (F. L.)
(230)	$B_{g3\,FL}$	Density in auxiliary gap (g3) (F. L.)
(115)	B_{np}	Leakage flux from north pole (spider pole) through the field coil
(104)	B'_{np}	North pole flux density
(234)	B_{NPFL}	North pole density (F. L.)
(104b)	B_p	Pole flux density at N. L.
(103a)	B_p	Pole density
(314)	B_{pc}	Center section density
(319)	$B_{pc\,L}$	Density in the pole center at full load
(104a)	B_{pi}	Flux density in inner pole at N. L.
(222b)	B_{pil}	Flux density in inner pole at full load
(213b)	B_{PL}	Pole flux density at F. L.
(200b)	B'_{pL}	The first approximation of the flux density in the pole at full load
(103)	B_{po}	Flux density in outer pole (N. L.)
(104d)	B_r	Flux density in rotating outer ring at no load

Calculation Number	Electrical Symbol	Explanation
(315)	B_{rc}	Core density
(321)	B_{rcL}	Flux density in the rotor core at 100% load
(222d)	B_{rL}	Flux density in rotating outer ring at no load
(113)	B_{SH}	Shaft flux density
(215a)	B_{SHL}	Shaft flux density at F. L.
(202c)	B'_{SHL}	First approximation of shaft density at full load
(222)	B_{SKFL}	Density in rotor skirt (F. L.)
(105)	B_{SP}	South pole density (N.L.)
(215)	B_{SPFL}	South pole density (F.L.)
(91c)	B'_T	Stator tooth density (N.L.)
(91)	B_T	Stator tooth density (N.L.)
(205)	B_{TL}	Stator tooth density (F.L.)
(126a)	B_y	Yoke flux density
(125a)	B_{yc}	Yoke density at N. L.
(228a)	B_{ycL}	Yoke density at F. L.
(229a)	B_{yL}	Yoke density at F. L.

Calculation Number	Electrical Symbol	Explanation
(125c)	B_{yr}	Yoke density at N.L.
(228c)	$B_{yr\,L}$	Yoke density at F. L.
(125)	B_{y2}	Density of coil yoke
(228)	$B_{y2\ FL}$	Density in coil yoke (F.L.)
(113)	B_{y4}	Density in shaft (N.L.)
(232)	$B_{y4\ FL}$	Density in shaft (F.L.)
(135)	b_{bo}	Width of damper slot opening
(135)	b_{bl}	Width of rectangular damper bar slot
(78)	b_{coil}	Coil width
(76)	b_h	Pole dimension
(116)	b_{NP}	North pole density (N.L.)
(76)	$b_{NP\ (MID)}$	Pole dimension locations
(76)	$b_{NP\ (END)}$	Width of north pole at end of pole
(22)	b_o	Slot dimension
(22)	b_1	Slot dimension
(22)	b_2	Slot dimension

Calculation Number	Electrical Symbol	Explanation
(22)	b_3	Slot dimension
(76)	b_{p2}	Pole dimension
(76)	b_{p1}	Pole dimension
(303)	b_r	Size slots
(314b)	b_{rh}	Height of ventilating holes in rotor core area
(22)	b_s	Slot dimension
(76)	$b_{SP\ (END)}$	Width of south pole at end of pole
(76)	$b_{SP\ (MID)}$	Width of south pole at middle of pole
(58)	b_t	Tooth width at stator
(57a)	$b_{t1/3}$	Stator tooth width 1/3 distance from narrowest end
(57)	b_{tm}	Stator tooth width 1/2 distance from narrowest end
(303)	b_{tr}	Size slots
(15)	b_v	Radial duct width

C, c

(508)	C	C is a factor to account for holes that reduce magnet area

Calculation Number	Electrical Symbol	Explanation
(331)	C_F	Ratio of field interleakage with its own flux to the maximum interleakage of a concentrated field winding
(74)	C_M	Demagnetizing factor
(73)	C_P	Pole constant
(75)	C_q	Cross magnetizing factor
(72)	C_W	Winding constant
(71)	C_1	Ratio of maximum fundamental of field form to the actual maximum of the field form
(32)	c	Parallel paths
	D, d	
(12)	D	Stator lamination outside diameter
(78)	D_{coil}	Coil outside diameter
(10a)	d	Stator equivalent diameter
(11)	d	Stator lamination inside diameter
(35)	d_b	Diameter of bender pin

Calculation Number	Electrical Symbol	Explanation
(78)	d_{coil}	Coil inside diameter
(170)	d_{dr}	Damper bar end ring mean diameter
(78)	d_{g2}	Diameter auxiliary air gap
(78)	d_{ir}	Inside diameter of rotor tube
(78)	d_{os}	Rotor gap dimension
(78)	d_Q	Rotor dimension
(78)	d_q	Outside diameter of shaft
(11a)	d_r	Outside rotor diameter
(314a)	d_s	Inner diameter of rotor punching
(78a)	d_{SH}	Shaft dimension
(78a)	d'_{SH}	Shaft dimension
(78)	d_{s1}	Rotor gap dimension
(78)	d_{s2}	Rotor gap dimension
(78)	d_{s3}	Rotor gap dimension
(78)	d_{s4}	Rotor gap dimension
(78)	d_{s5}	Rotor gap dimension
(78)	d_{tl}	Smallest diameter of tapered gap
(78)	d_{to}	Outside diameter of tapered gap
(78)	d_{yc}	Yoke and coil dimensions for three types of homopolar inductor construction

Calculation Number	Electrical Symbol	Explanation
	E, e	
(3)	E	Line volts
(56)	EF_{BOT}	Eddy factor bottom
(238)	E_{FFL}	Full load field volts
(525)	E_{FL}	Voltage supplied to the load at rated current, rated speed, and at a specified power factor
(127b)	E_{FNL}	No load field volts
(55)	EF_{TOP}	Eddy factor top
(516)	E_{NL}	Ampere-turn/inch of magnet value corresponding to the intersection of the shear line with the major hysteresis loop of the permanent magnet material
(4)	E_{PH}	Phase volts
(198)	e_d	Direct axis voltage behind synchronous reactance
	F, f	
(98)	F_c, F'_c	N. L. stator core ampere turns
(201)	F_{CL}	F. L. stator core ampere turns

Calculation Number	Electrical Symbol	Explanation
(198b)	F_{dm}	Demagnetizing ampere-turns at full load
(236)	F_{FL}	Total full load ampere turns
(96)	F_g, F'_g	N. L. main gap ampere turns
(96a)	$F_g + m$	Total air-gap ampere-turn drop across the single air-gap at no-load, rated voltage
(199)	F'_{gL}	First approximation of the ampere turns drop across the main air-gap at full load.
(203)	F'_{gL}	F. L. air-gap ampere turns
(208a)	F_{gL}	F. L. air-gap ampere turns
(110)	F'_{g2}	Ampere turn drop across auxiliary air gap
(123)	F_{g2}	N. L. gap (g2) ampere turns
(225)	$F_{g2\ FL}$	F.L. gap (g2) ampere turns
(120)	F_{g3}	N. L. gap (g3) ampere turns
(231)	$F_{g3\ FL}$	F. L. gap (g3) ampere turns
(106)	F'_{np}	North pole ampere turn drop

Calculation Number	Electrical Symbol	Explanation
(117)	F_{NP}	N. L. north pole ampere turns
(127)	F_{NL}	Total no load ampere turns
(235)	F_{NPFL}	F. L. north pole ampere turns
(235)	F_{NPFL}	North pole ampere turn drop
(106a)	F_p	N. L. air gap ampere turns
(104a)	F_p	N. L. pole ampere turns
(316)	F_{pc}	Ampere turn drop in the pole center at no load
(320)	F_{pcL}	Ampere turn drop in pole center at full load
(222c)	F_{piL}	Ampere turn drop through inner pole at full load
(222a)	F_{poL}	Ampere turn drop through outer pole
(213 L)	F_{PL}	F. L. pole ampere turns
(213c)	F_{PL}	F. L. pole ampere turns
(200c)	F'_{PL}	First approximation of the ampere turns drop in the pole at full load
(104)	F_{po}	Ampere turn drop through outer pole
(104a)	F_R	Rotor ampere turns or pole ampere turns

Calculation Number	Electrical Symbol	Explanation
(101e)	F_r	Ampere turn drop in ring at no load
(317)	F_{rc}	Ampere turn drop in the rotor core
(322)	F_{rcL}	Ampere turns drop per pole in the rotor core at 100% load
(222e)	F_{rL}	Ampere turn drop in ring at full load
(98a)	F_s	N. L. stator ampere turns
(180)	F_{SC}	Short circuit ampere turns
(114)	F_{SH}	N. L. shaft ampere turns
(216a)	F_{SHL}	F. L. shaft ampere turns
(202d)	F'_{SHL}	First approximation of ampere turn drop in shaft at full load
(223)	F_{SKFL}	F. L. rotor skirt ampere turns
(107)	F_{SP}	N. L. south pole ampere turns
(216)	F_{SPFL}	F. L. south pole ampere turns
(200)	F'_{TL}	Tooth ampere-turn drop under load
(97)	F_T, F'_T	N. L. stator tooth ampere turns
(183)	F & W	Friction and windage
(126b)	F_y	N. L. yoke ampere turns
(126)	F_{y2}	N. L. coil yoke ampere turns
(229)	F_{y2FL}	F. L. coil yoke ampere turns

Calculation Number	Electrical Symbol	Explanation
(114)	F_{y4}	N. L. shaft ampere turns
(233)	F_{y4FL}	F. L. shaft ampere turns
(125b)	F_{yc}	N. L. yoke ampere turns
(228b)	F_{ycL}	F. L. yoke ampere turns
(229b)	F_{yL}	Yoke mmf drop at F. L.
(229c)	F_{yL}	Yoke mmf drop at F. L.
(125d)	F_{yr}	N. L. yoke ampere turns
(228d)	F_{yrL}	The ampere turn drop in the radial section of the yoke at full load
(5a)	f	Frequency

<u>G, g</u>

(59)	g	Main air gap
(59)	g_{min}	Minimum air gap in inches
(59g)	g_{max}	Maximum air gap in inches
(59a)	g_2	Auxiliary air gap
(59c)	g_3	Auxiliary air gap
(59d)	g_{3-1}	Horizontal section of stepped gap g3
(59e)	g_{3-2}	Vertical section of stepped gap g3
(59f)	g_{3e}	Effective value of stepped gap g3
(69)	g_e	Effective main gap

Calculation Number	Electrical Symbol	Explanation
	H, h	
(519a)	h	Slope of hysteresis loop in PM material
(135)	h_b	Damper slot dimension
(137)	h_{b1}	Height of damper bar section
(135)	h_{bo}	Height of damper slot
(24)	h_c	Depth below slot
(76)	h_f	Pole dimension
(76)	h_h	Pole dimension
(78)	h_{NP}	Height of north pole
(22)	h_o	Slot dimension
(76)	h_p	Pole dimension
(76)	h'_p	Pole dimension
(303)	h_r	Slot dimension
(303)	h_{r1}	Slot dimension
(303)	h_{r2}	Slot dimension
(22)	h_s	Slot dimension
(38)	h'_{ST}	Distance between center line of strand in depth
(37)	h_{ST}	Stator coil strand thickness (largest dimension)

Calculation Number	Electrical Symbol	Explanation
(22)	h_t	Slot dimension
(22)	h_w	Slot dimension
(78)	h_y	Height of coil yoke
(22)	h_1	Slot dimension
(22)	h_2	Slot dimension
(22)	h_3	Slot dimension
	I, i	
(194)	I^2R	N. L. stator copper loss
(245)	I^2R_L	N.L. stator copper loss
(241)	I^2R_L	N.L. field copper loss
(182)	I^2R_R	N.L. field copper loss
(237)	I_{FFL}	F.L. field amperes
(8)	I_{PH}	Phase current
(127a)	I_{FNL}	Field current at no load
(182)	I^2R_R	Rotor I^2R at no load
(182)	I^2R_F	Field I^2R at no load
(241)	I^2R_R	Rotor I^2R at 100% load
(241)	I^2R_F	Field I^2R at 100% load
(245)	I^2R	Stator I^2R at 100% load

Calculation Number	Electrical Symbol	Explanation
(522)	I_{SC}	Current per phase flowing when all phases are shorted together at the machine terminals
(11)	I. D.	Stator I. D.
	K, k	
(9a)	K_c	Adjustment factor
(43)	K_d	Distribution factor
(63)	K_e	Leakage reactive factor
(16)	K_i	Stacking factor
(44)	K_p	Pitch factor
(308)	K_r	Carter's coefficient rotor
(67)	K_s	Carter coefficient
(42)	K_{SK}	Skew factor
(2)	KVA	Generator rating
(61)	K_X	Factor to account for difference in phase current in coil sides in same slot
(19)	k	Watts/lb core loss

Calculation Number	Electrical Symbol	Explanation
	L, l	
(48)	L_E	Stator coil end extension length
(161)	L_F	Field inductance
(13)		Gross core length (stator)
(139)	ℓ_b	Damper bar length
(84)	ℓ_c	Length of leakage path 5
(36)	ℓ_{e2}	Coil extension beyond core
(78)	ℓ_{g2}	Horizontal length of (g2) air gap
(76)	ℓ_h	Pole dimension
(76)	ℓ_{NP}	Length of north pole
(76)	ℓ_p	Pole dimension
(305)	ℓ_r	Core length
(305a)	ℓ_{rs}	Solid length of rotor core
(17)	ℓ_s	Solid core length
(76)	ℓ_{s1}	Stepped gap axial dimension
(76)	ℓ_{s2}	Stepped gap axial dimension
(76)	ℓ_{s3}	Stepped gap axial dimension
(76)	ℓ_{s4}	Stepped gap axial dimension
(76)	ℓ_{s5}	Stepped gap axial dimension

Calculation Number	Electrical Symbol	Explanation
(78)	ℓ_{SK}	Length of skirt
(76)	ℓ_{SP}	Length of south pole
(49)	ℓ_t	1/2 mean turn (stator coil)
(147)	ℓ_{tf}	1/2 mean turn of field coil
(147)	ℓ_{tr}	Mean length of field turn
(78)	ℓ_y	Length of field coil yoke
(78)	ℓ_{y4}	Effective length of shaft
(80a)	ℓ_1	Leakage path length
(81a)	ℓ_2	Leakage path length
(82a)	ℓ_3	Leakage path length
(83)	ℓ_4	Length of leakage path 4 (4 pole)
(83)	ℓ_{4a}	Length of leakage path 4 (6 pole)
(85)	ℓ_6	Length of leakage path 6
(86)	ℓ_7	Length of leakage path 7

M, m

(5)	m	Number of phases

N, n

(146a)	N_{co}	Number of field coils
(146a)	N_p	Number of field turns per pole

Calculation Number	Electrical Symbol	Explanation
(306)	N_r	Conductors per slot
(302a)	N_{rc}	Number of slots in pole center
(34)	N_{ST}	Strands per conductor in depth
(34a)	N'_{ST}	Strands per conductor (total)
(138)	n_b	Damper bars
(45)	n_e	Effective conductors
(146)	n_F	Field turns per coil
(30)	n_s	Conductors per slot
(14)	n_v	Radial ducts
	O, o	
(12)	O. D.	Stator O. D.
	P, p	
(9)	PF	Power factor
(511)	P_g	Air-gap permeance
(509)	P_i	Permeance of the in-stator leakage flux
(80c)	P_m	Leakage permeance
(507)	P_m	Adjustment factor to convert the permeance values to the proper scale for use in the general hysteresis loop

Calculation Number	Electrical Symbol	Explanation
(510)	P_o	Permeance of the out-stator leakage flux
(505)	P_{si}	Permeance of the flux leakage path from the underside of one pole shoe to the underside of the adjacent pole shoe
(506)	P_{s2}	Permeance of the flux leakage path from the centerline of the end surface of one pole head to the centerline of the end surface of the adjcacent pole head
(514)	P_w	Total apparent permeance of the working air gap
(80)	P_1	Pole head end leakage permeance
(500)	P_1	Pole-to-pole side leakage permeance
(81)	P_2	Pole head side leakage permeance
(503)	P_2	Permeance of the flux leakage paths from pole-head surface to pole-head surface and between adjacent pole head edges

Calculation Number	Electrical Symbol	Explanation
(82)	P_3	Pole body end leakage permeance
(504)	P_3	Permeance of the flux leakage path from the centerline of the end surface of the pole to the centerline of the adjacent pole end surface
(83)	P_4	Pole body side leakage permeance
(84a)	P_5	Coil leakage permeance
(84)	P_5	Coil leakage to north pole permeance
(85)	P_6	Coil leakage to south pole permeance
(85a)	P_6	Leakage permeance
(86a)	P_7	Stator to rotor leakage
(86)	P_7	Stator core to rotor skirt leakage permeance
(86a)	P_8	Flux plate to flux plate leakage permeance
(6)	p	Number of poles

<u>Q, q</u>

(23)	Q	Number of slots
(300)	Q_r'	Slots punched
(301)	Q_r	Slots wound

Calculation Number	Electrical Symbol	Explanation
(25)	q	Slots per pole per phase
	R, r	
(154)	$R_{f\,(cold)}$	Cold field resistance at 20° C
(155)	$R_{f\,(hot)}$	Hot field resistance at X° C
(7)	RPM	Revolutions per minute
(53)	$R_{SPH\,(cold)}$	Stator resistance per phase at 20° C
(54)	$R_{SPH\,(hot)}$	Stator resistance per phase at X° C
	S, s	
(181)	SCR	Short circuit ratio
(127c)	S_F	Current density in field conductor
(239)	S_{FL}	F. L. current density in field conductor
(47)	S_S	Current density in stator conductor
	T, t	
(177)	T_a	Armature time constant
(178)	T'_d	Transient time constant
(179)	T''_d	Subtransient time constant
(176)	T'_{do}	Open circuit time constant
(78)	T_{SK}	Thickness of rotor skirt

Calculation Number	Electrical Symbol	Explanation
(78)	T_{SP}	Thickness of south pole
(76)	t_{p1}	Pole dimension
(76)	t_{p2}	Pole dimension
(304)	t_{rs}	Tooth pitch
(78)	t_y	Yoke dimension
(78)	t_{yc}	Yoke dimension
(78)	t_{yr}	Yoke dimension

V, v

(145)	V_r	Peripheral speed

W, w

(185)	W_C	Stator core loss
(244)	W_{DFL}	F. L. damper loss
(193)	W_{DNL}	N.L. damper loss
(186)	W_{NPL}	N.L. pole face loss
(243)	W_{PFL}	F. L. pole face loss
(242)	W_{TFL}	F. L. stator teeth loss
(184)	W_{TNL}	N. L. stator teeth loss

Calculation Number	Electrical Symbol	Explanation
(81b)	λ_t	Pole tip leakage permeance
(77)	α	Pole embrace
(198a)	θ	P. F. angle

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Calculation Number	Electrical Symbol	Explanation
(78)	T_{SP}	Thickness of south pole
(76)	t_{p1}	Pole dimension
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(304)	t_{rs}	Tooth pitch
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(242)	W_{TFL}	F. L. stator teeth loss
(184)	W_{TNL}	N. L. stator teeth loss

Calculation Number	Electrical Symbol	Explanation
	X, x	
(129)	X	Reactance factor
(131)	X_{ad}	Reactance direct axis
(132)	X_{aq}	Reactance quadrature axis
(133)	X_d	Synchronous reactance
(167)	X'_d	Saturated transient reactance
(168)	X''_d	Subtransient reactance direct axis
(142)	X_D °C	Damper bar temperature
(163)	X_{Dd}	Damper bar leakage reactance direct axis
(523)	X_d (ohms)	Direct axis synchronous reactance
(165)	X_{Dq}	Damper bar leakage reactance quadrature axis
(166)	X'_{du}	Unsaturated transient reactance
(160)	X'_F	Effective field leakage reactance
(150)	X_f °C	Expected field temperature at full load
(130)	X_ℓ	Leakage reactance
(172)	X_o	Zero sequence reactance
(307)	X_p	Potier reactance

Calculation Number	Electrical Symbol	Explanation
(169)	X''_q	Subtransient reactance quadrature axis
(134)	X_q	Synchronous reactance quadrature
(50)	X_s °C	Stator expected temperature at F. L.

Y, y

(31)	Y	Throw

(140)	τ_b	Damper bar pitch in inches
(26)	τ_s	Stator slot pitch
(27)	$\tau_{s\,1/3}$	Stator slot pitch
(40)	τ_{SK}	Skew
(41)	τ_P	Pole pitch

Ø

(200f)	ϕ_{cL}	F. L. core flux
(311)	ϕ_{gp}	Flux in pole center
(108)	ϕ_{g2}	N. L. auxiliary air gap flux
(221)	$\phi_{g2\,L}$	Flux crossing the auxiliary air gap under load
(100a)	ϕ_{ℓ}	Rotor leakage flux

Calculation Number	Electrical Symbol	Explanation
(312a)	$\phi_{\ell \ell s}$	Slot leakage flux in each pole center at 100% load
(312)	$\phi_{\ell s}$	Leakage flux
(91a)	ϕ_{m}	Leakage flux
(202e)	ϕ_{mL}	F. L. leakage flux
(198c)	ϕ'_{mL}	First approximation of the leakage flux from the shaft to the stator between the rotor lobes or poles (or teeth)
(92)	ϕ_{p}	N. L. flux per pole
(93)	ϕ'_{p}	Estimated flux per pole
(318)	ϕ_{PCL}	Flux in the pole center at full load
(213)	ϕ_{PL}	Flux per pole F. L.
(200a)	ϕ'_{PL}	First approximation of the flux per pole at full load
(102a)	ϕ_{PT}	N. L. flux per pole
(213a)	ϕ_{PTL}	F. L. flux per pole
(104c)	ϕ_{r}	Flux in rotating outer flux ring at no load
(313)	ϕ_{rc}	Total flux in the pole center
(111)	ϕ_{SH}	Flux in shaft at no load

Calculation Number	Electrical Symbol	Explanation
(112a)	ϕ_{SH}	N. L. shaft flux
(202b)	ϕ'_{SHL}	First approximation of the shaft flux at full load
(214a)	ϕ_{SHL}	F. L. shaft flux
(221)	ϕ_{SKFL}	F. L. skirt flux
(88)	ϕ_T	Total flux
(90)	ϕ'_T	Estimated total flux
(208)	ϕ_{TL}	Total flux F. L.
(204)	ϕ'_{TL1}	Theoretical flux at full load
(100)	ϕ_1	N. L. leakage flux in Path 1
(209)	ϕ_{1L}	F. L. leakage flux in Path 1
(101)	ϕ_2	N. L. leakage flux in Path 2
(210)	ϕ_{2L}	F. L. leakage flux in Path 2
(102)	ϕ_3	N. L. leakage flux in Path 3
(211)	ϕ_{3L}	F. L. leakage flux in Path 3
(103)	ϕ_4	N. L. leakage flux in Path 4
(212)	ϕ_{4L}	F. L. leakage flux in Path 4
(115)	ϕ_5	Leakage flux from north pole (spider pole) through the field coil

Calculation Number	Electrical Symbol	Explanation
(118)	$\emptyset_5$	N. L. leakage flux in Path 5
(226)	$\emptyset_{5L}$	F. L. leakage flux in Path 5
(200d)	$\emptyset'_{5L}$	First approximation of the leakage flux through P_5 at F. L.
(121)	$\emptyset_6$	N. L. leakage flux in Path 6
(121a)	$\emptyset_6$	N. L. leakage flux in Path 5
(220)	$\emptyset_{6L}$	F. L. leakage flux in Path 6
(220a)	$\emptyset_{6L}$	Final value at full load
(200e)	$\emptyset'_{6L}$	First approximation of the leakage flux through P_6 at full load
(99)	$\emptyset_7$	N. L. leakage flux in Path 7
(89)	$\emptyset'_7$	Estimated value of leakage flux $\emptyset_7$
(207)	$\emptyset_{7L}$	F. L. leakage flux in Path 7
(207a)	$\emptyset_{7L}$	F. L. leakage flux in Path 7
(202)	$\emptyset'_{7L}$	First approximati of the leakage flux through P_7 at full load
(103b)	$\emptyset_8$	Flux plate to flux plate leakage flux (kilolines)
(198b)	$\emptyset_{8L}$	Leakage flux at F. L.

Calculation Number	Electrical Symbol	Explanation
(70c)	λ_a	Air gap permeance
(158)	λ_b	Permeance of damper bar
(175)	λ_{Bo}	
(162)	λ_{Dd}	Leakage permeance of damper bar in direct axis
(164)	λ_{Dq}	Permeance in quadrature axis
(64)	λ_E	End winding permeance
(82b)	λ_e	Pole end leakage permeance
(161f)	λ_F	Rotor leakage permeance
(332)	λ_F	Leakage permeance of the field winding
(333)	λ_{FE}	Leakage permeance of the rotor winding end extension
(62)	λ_i	Conductor permeance
(159)	λ_{pt}	Permeance of end portion of damper bars
(312b)	λ_{rs}	Rotor slot leakage permeance per inch of stator length
(80b)	λ_s	Pole side leakage permeance

Calculation Number	Electrical Symbol	Explanation
(81b)	λ_t	Pole tip leakage permeance
(77)	α	Pole embrace
(198a)	θ	P. F. angle

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