FIRST QUARTERLY REPORT, 31 Oct. 1963

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(NASA CR 52915)

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BRUSHLESS ROTATING ELECTRICAL GENERATORS FOR SPACE AUXILIARY POWER SYSTEMS

(NASA CONTRACT ~~NO.~~ NAS 3-2783)

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

by

J. N. Ellis and F. A. Collins [1963] 155p

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TECHNICAL MANAGEMENT
NASA-LEWIS RESEARCH CENTER
AUXILIARY POWER GENERATION OFFICE
ATTENTION: HOWARD A. SHUMAKER

ca. LEAR SIEGLER, INC., Cleveland, Ohio

LSi

POWER EQUIPMENT DIV~~ISION~~

CLEVELAND 1, OHIO

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SUMMARY

Design manuals are presented for salient-pole, wound-rotor generators and non-salient-pole, wound-rotor generators.

A computer program and computer coding sheets are presented for salient-pole generators. The program is Bell for a 1620 computer. It will be re-written in Fortran for the second report.

INTRODUCTION

This study is sponsored by The National Aeronautics and Space Adm. under Contract NAS3-2783. It is to be an analysis of the brushless, electrical, generators that might be considered for use by NASA. The analysis is to be complete enough to provide a basis for choosing the proper machine for any specific application, and to provide the tools for optimizing the chosen machine design. The effects of changing design parameter and materials can be evaluated.

The range of generator ratings of most interest for this study are 3 KVA to 100 KVA at speeds of 1800 RPM to 72,000 RPM. Frequencies are 60 cps to 4800 cps.

The maximum coolant temperature for this study will be 200° F. However, the design formulae can be used to evaluate designs operating with higher or lower temperature coolants.

Non magnetic bore seals will be considered to evaluate the effect of the large air gap necessary to accommodate the seal. Material and construction problems of seals are not discussed.

STUDY METHODS

To provide adequate tools for studying the various brushless generators, complete design manuals and Fortran Computer programs will be provided for those machines likely to be used.

Parametric data in the form of curves resulting from the computer programs will be furnished to aid in selecting the machines for specific applications.

STUDY METHODS (Cont)

Four quarterly reports will be issued. Each successive report will contain all of the information of the previous reports.

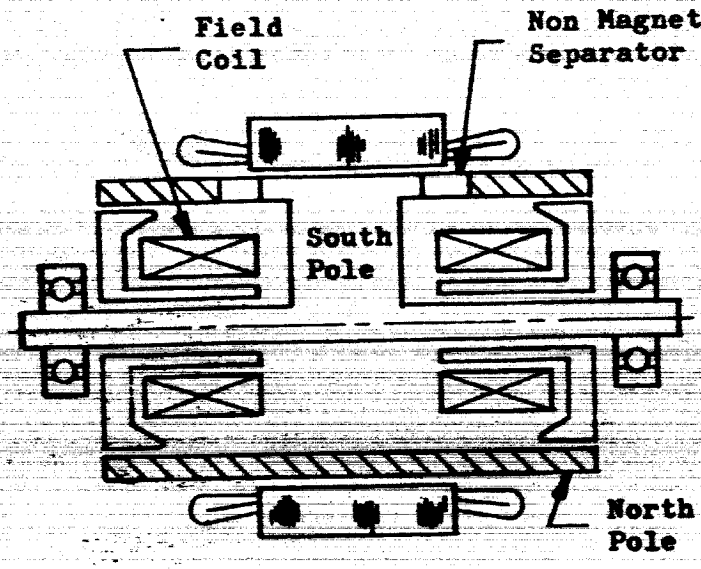
MACHINES STUDIED

For certain modern applications such as auxiliary power generation in space and for remote unattached installations, brushes riding on slip rings or commutators cannot be used. In many of the applications, because of temperature or radiation, rectifiers cannot be used in the rotating machine.

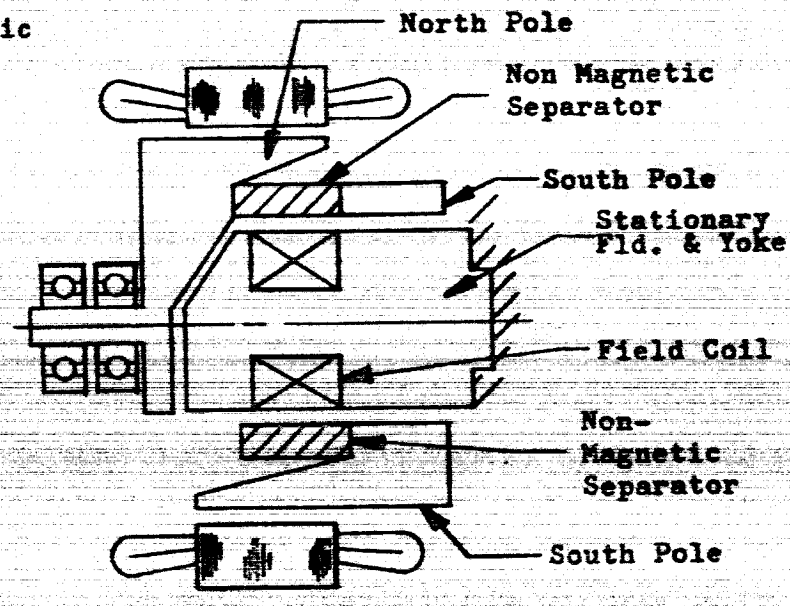
Several generators of the general type needed today were invented and built in the past before there was a real need for them. Some of the generators were re-invented. Others were re-discovered. Those generators considered of most interest at present are:

1. Salient-pole, Wound-rotor, Rotating rectifier, generator.
2. Non Salient-pole, Wound-rotor, Rotating rectifier, generator.
3. Two-coil brushless Lundell.
4. Single-External-Coil brushless Lundell.
5. Single-Internal-Coil brushless Lundell.
6. Axial air gap brushless Lundell.
7. Homopolar Inductor.
8. Heteropolar Inductor.
9. Permanent Magnet Generators.
10. Induction Generators.
11. Cascade Generators.

Of the eleven machines outlined above, only the salient pole and non-salient pole generators will be analyzed in this quarterly report. The nine remaining machines will be studied in detail in the three quarterly reports that remain to be published.



U. S. Patent No. 2,796,542



British Patent No. 614091

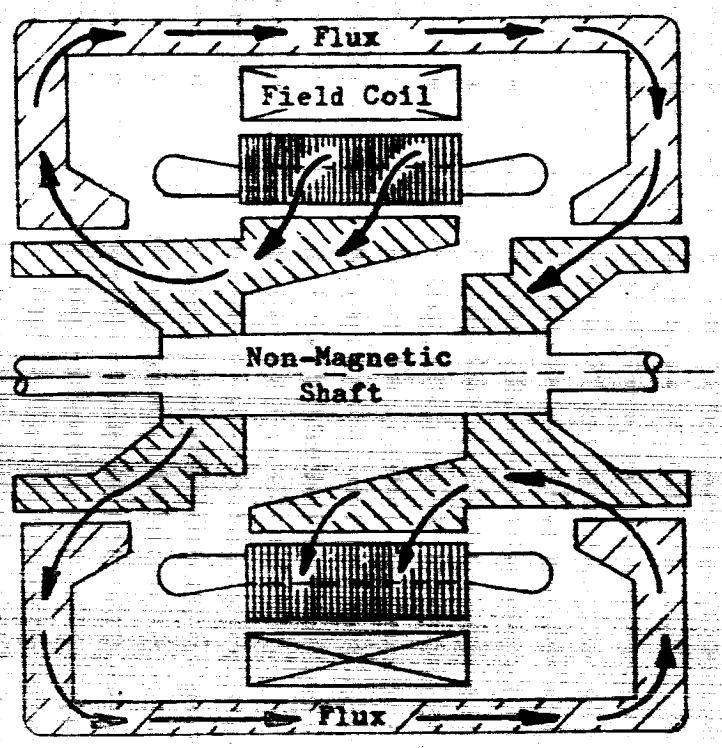
Brushless Lundell, Radial Gap

On January 31, 1893, U. S. Patent No. 490,809 was awarded to Robert Lundell. This patent described an electrical generator, either A-C or D-C, having a ring-shaped field magnet core with one field coil, and with both north and south poles on the same side of the field coil.

From this general concept evolved the radial air gap machines having interlocking finger-type poles and a single field coil. Such machines have for many years been known as Lundell Generators.

Several machine configurations have been developed that eliminate the brushes in the Lundell design. One of these is described in Patent No. 2,796,542 issued June 18, 1957 to A. Bekey and H. M. Robinson.

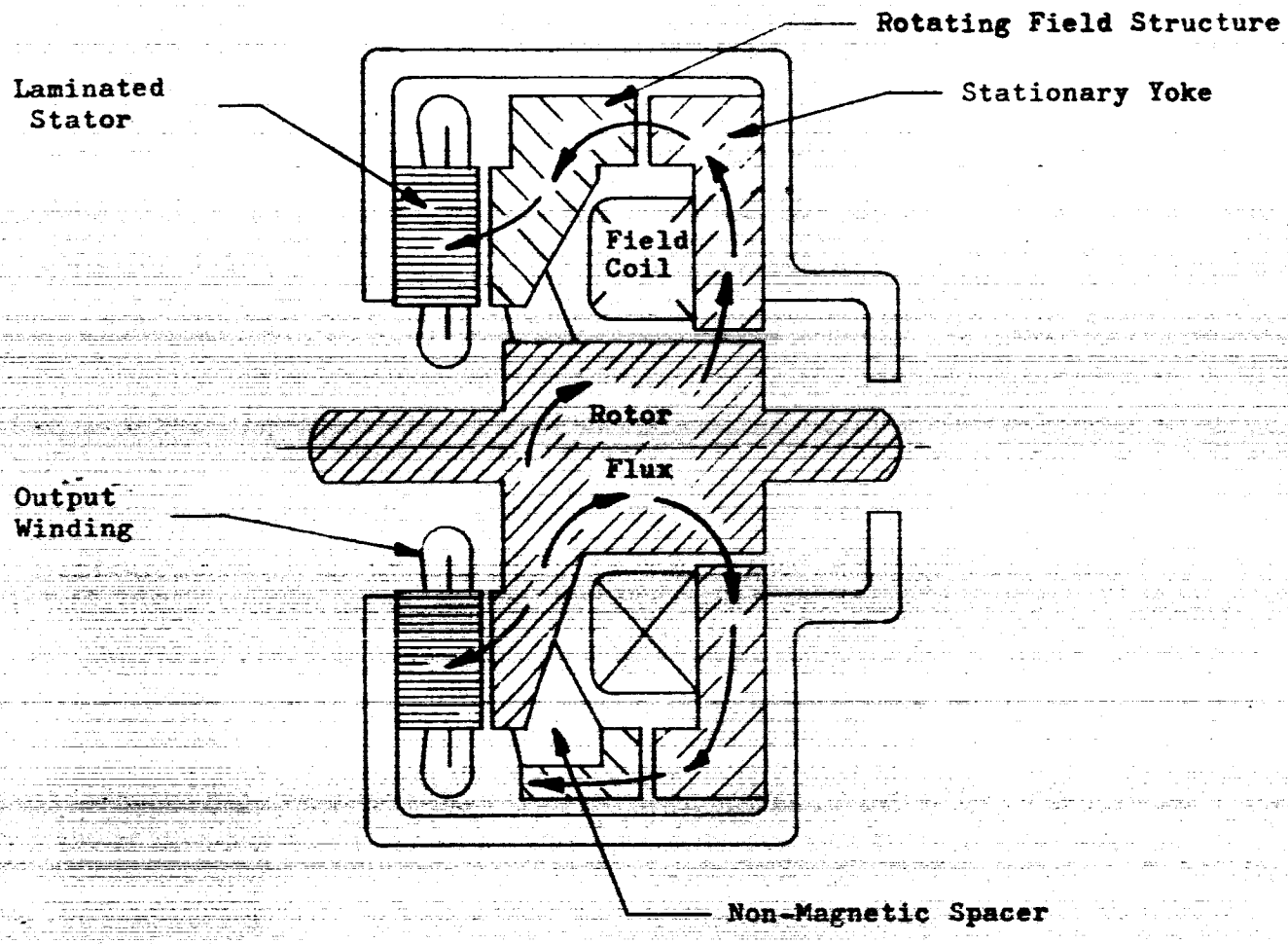
Another brushless Lundell type is described in British Patent 614091 issued July, 1947 to Ball and Binney; also in U. S. Patent 2987637 issued in 1961 to Bertsche and Gegenheimer.



Brushless Lundell, Sometimes Proposed for High Temperature Use

Essentially this same machine, except with non-magnetic steel brazed into the space between the rotor poles is being proposed by U. S. companies.

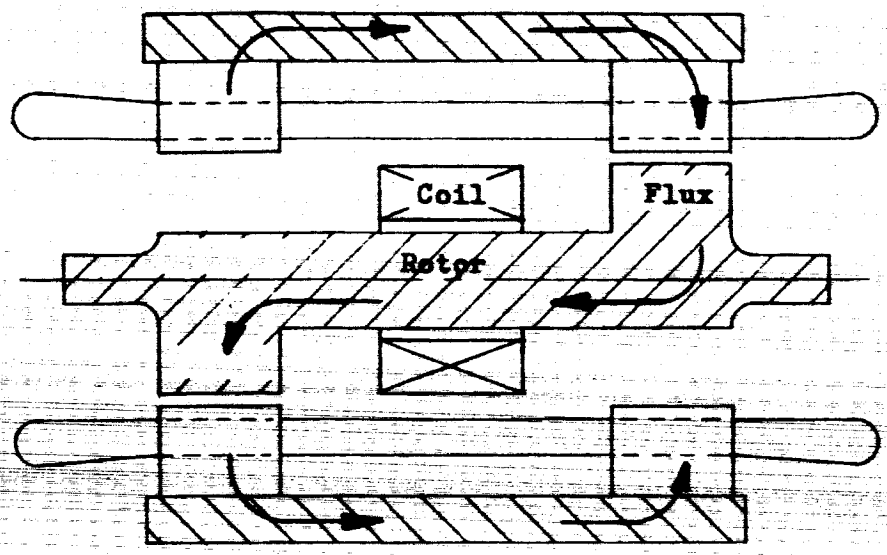
This machine is offered by Allgemeine Elktricitate Gesellshaft in Western Germany, by Siemens-Schuckertwerke, Erlangen, Germany, and is used in Russian railway service.



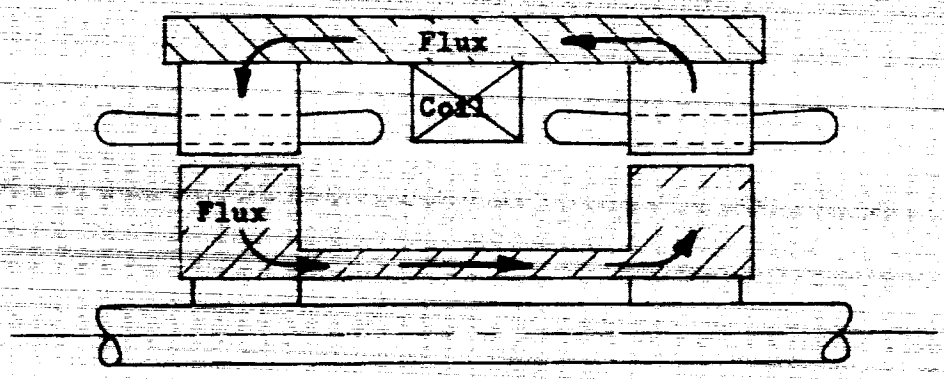
Axial Air Gap Lundell

The original Lundell patent issued in 1893 was for an axial air gap generator with a revolving output winding.

A new Lundell-type generator has no brushes and a revolving field structure. It can be made with two output stators with the field structure revolving between the stators.



Typical Construction for Small Homopolar Inductor

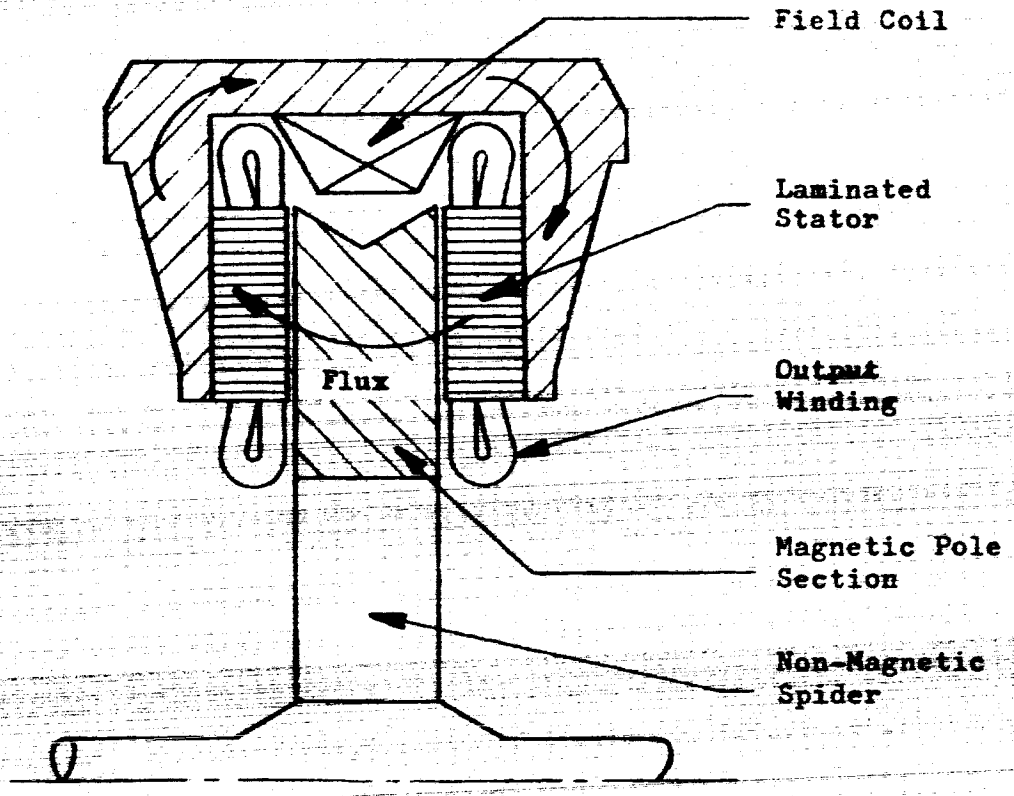


Typical Construction for Large Homopolar Inductor

Homopolar Inductor Generator

This type of generator consists of: (1) two identical stators wound with a common winding, (2) a double rotor having north poles on one end under one stator and south poles on the opposite end under the opposite stator, and (3) a field coil enclosed in the iron loop formed by the outer shell or yoke, stators, and rotor.

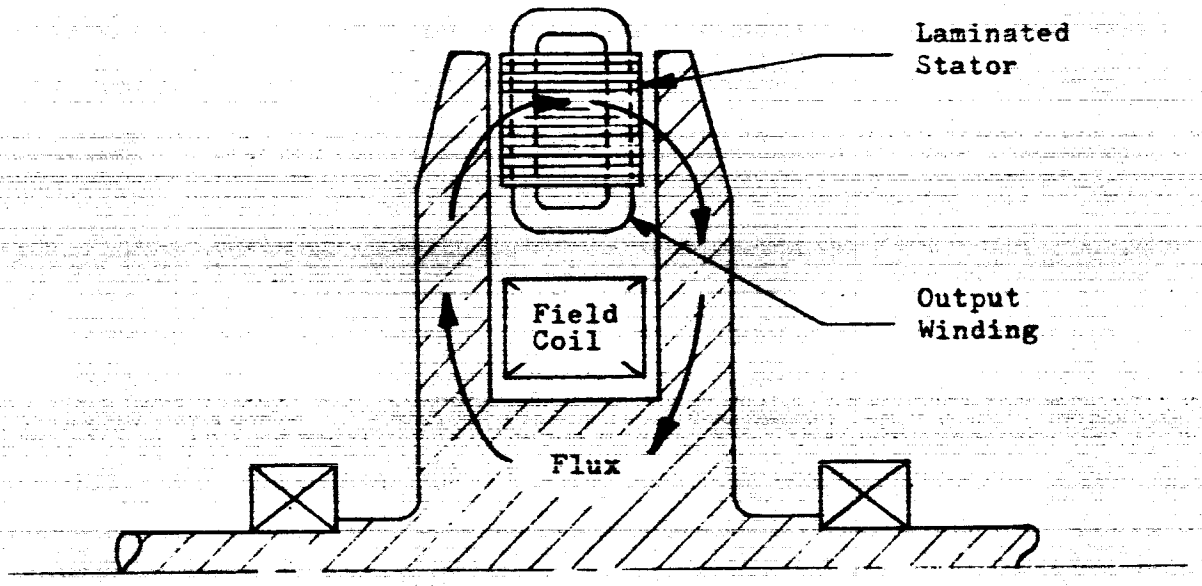
The homopolar inductor generator was widely used as a prime power source around 1900, and most patents on this type of generator were issued before 1910. Several configurations were built by Alexanderson in the 1920's for use as aircraft generators, but in recent years, it has been used almost exclusively for induction heating and welding.



Disk-Type Homopolar Inductor

This inductor generator is described in U. S. Patent No. 1369601 issued February 22, 1921, to E. F. W. Alexanderson.

It is a machine with two disk-type stators facing each other and having a rotor made of alternate magnetic and non-magnetic segments. An excitation coil and iron yoke are located around the outer periphery of the machine, and the flux path is from the yoke, through one stator, into the rotor magnetic segments, into the second stator and then back into the yoke.

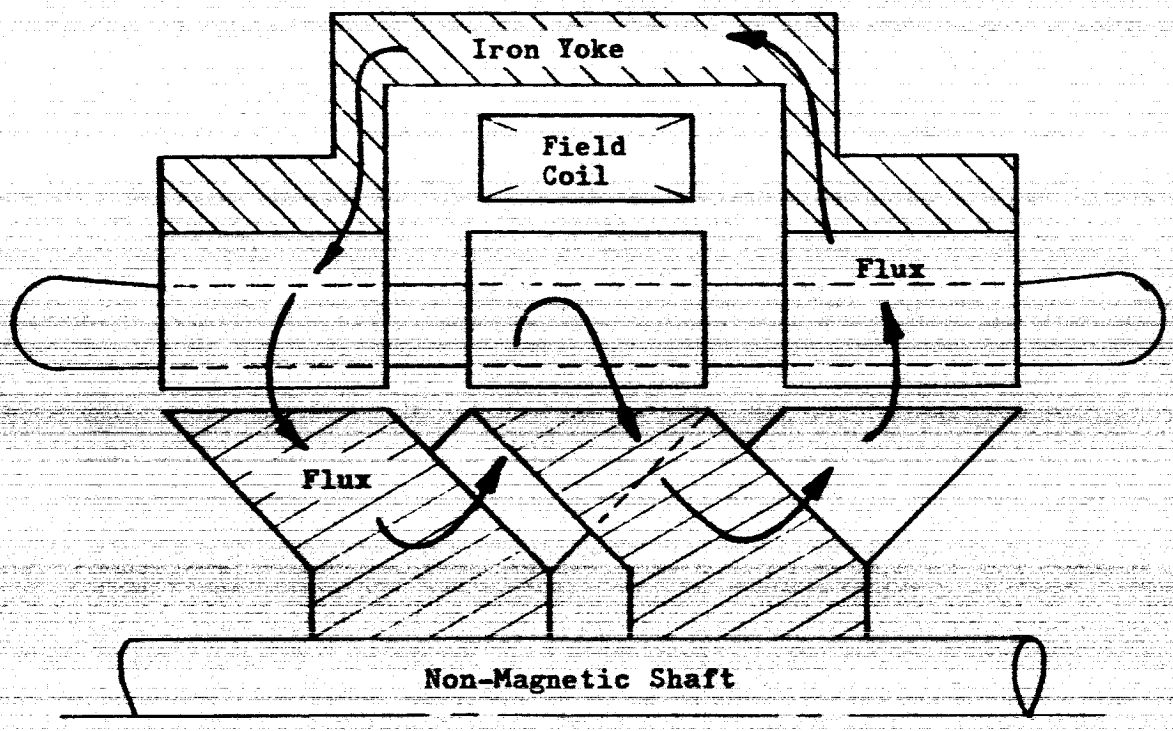


Schroeder Inductor

This is another disk-type homopolar inductor which is described in U. S. Patent Application No. 3697, dated October 7, 1960, by H. L. Schroeder.

Similar machines were built and patented by Rolls-Royce Ltd. Derby England, English Pats. 628018, 1947 and 805352, 1955 and by Nikola Teslo U. S. Pat. 447921, 1891.

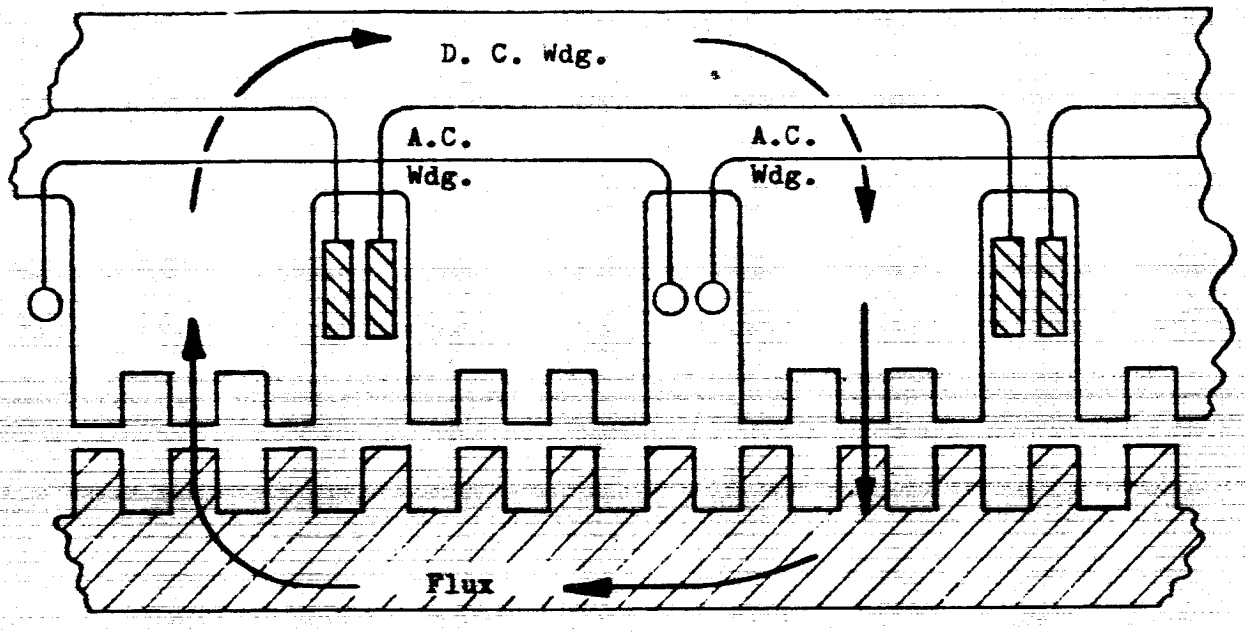
This would be an acceptable machine electrically but it is difficult to build.



The Homopolar-Inductor-Lundell

This machine, consisting of three stators and three rotor sections, was patented in 1938 by Fisher U. S. Patent No. 2, 108, 662.

Because the stator length/rotor diameter is definitely limited in both the homopolar generator and the Lundell, no advantage is had by combining the two machines. This is more fully explained in the sections describing each machine.

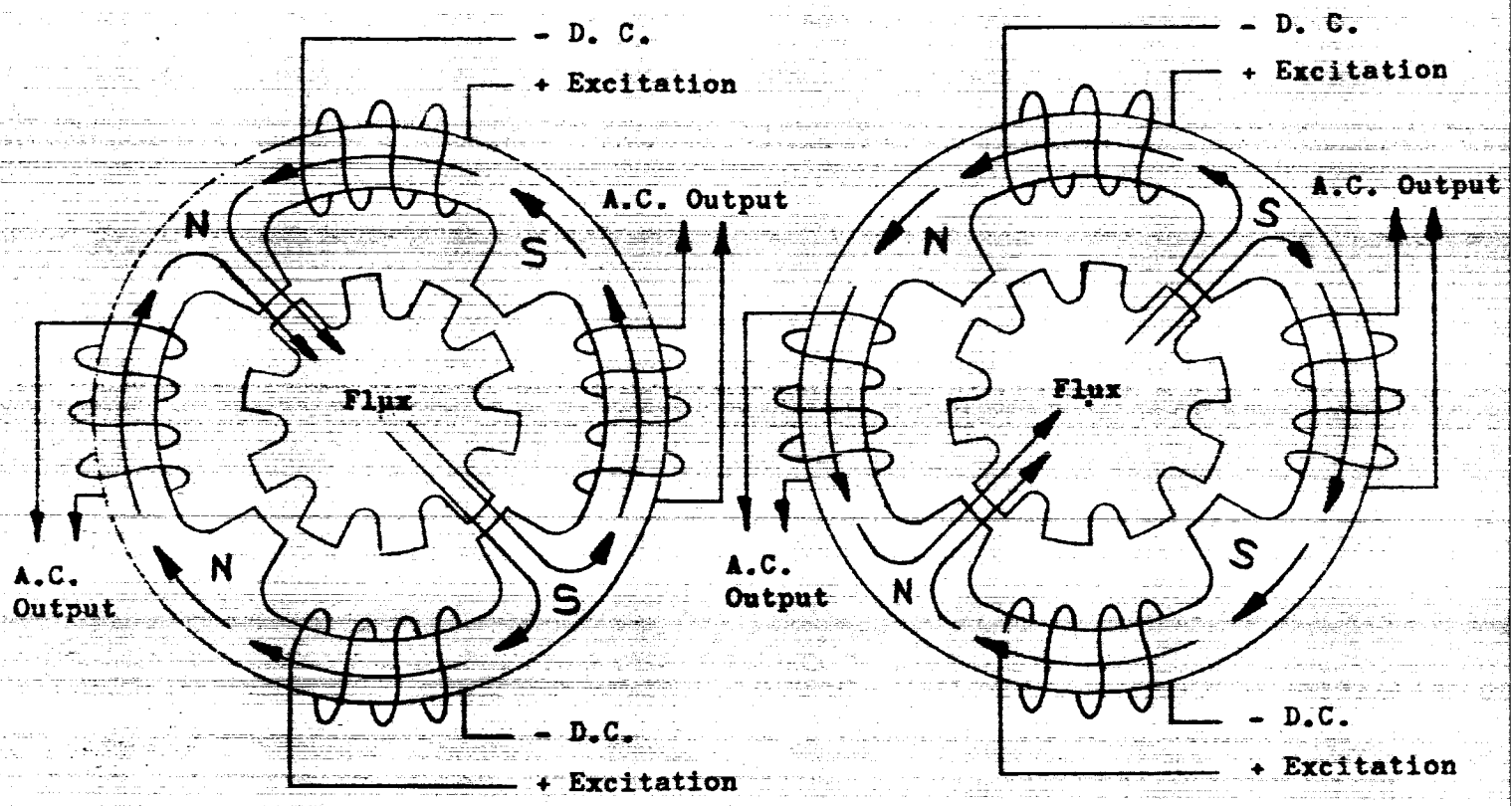


Heteropolar Inductor Generator

This machine has a single rotor with teeth similar to the teeth or poles on the homopolar inductor. The field coils are placed in stator slots and the output windings are also placed in stator slots. The two sets of windings and the stator teeth are arranged so that when the rotor moves one tooth pitch, the flux through the a-c winding reverses direction.

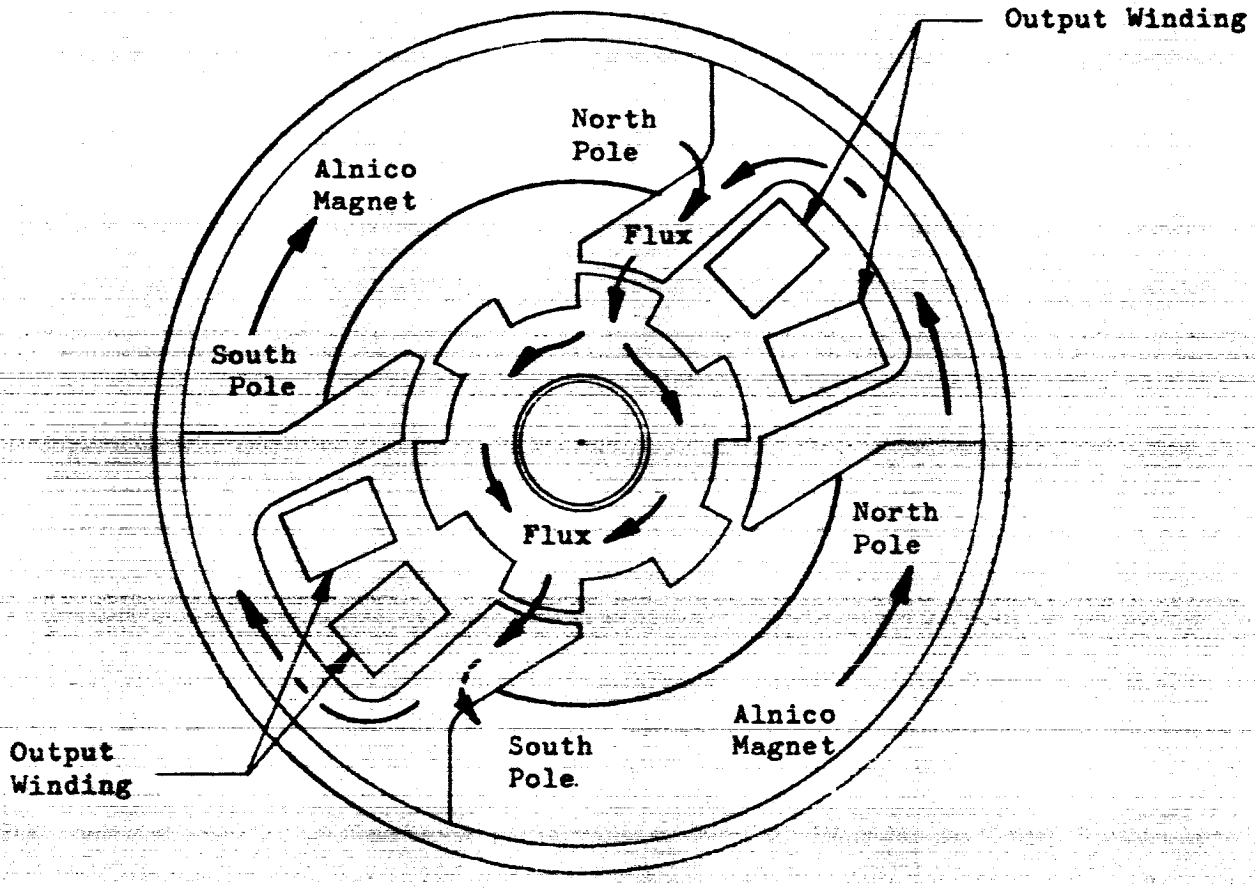
One early machine of this type was described in British Patent No. 18027 issued in 1901.

The heteropolar inductor machines can be built with more than one phase but are more commonly designed for single phase operation.



Electromagnetic Flux-Switch Alternator

The flux switch alternator is a simple version of the heteropolar inductor. It is used only where low outputs are needed and wave form is unimportant.



Permanent Magnet Generator

Permanent magnet generators use high coercive force magnets for fields. In designs that use rotating magnets, the poor mechanical qualities of the permanent magnet alloy usually limit the rotor speed. The schematic above is of a stationary magnet machine which can be used at extremely high rotor speeds.

The modern P.M. Generator designs are made possible by the development of Alnico magnet alloys. The first Alnico alloy of iron, aluminum and nickel was discovered by a Japanese metallurgist, Mishima, in 1931.

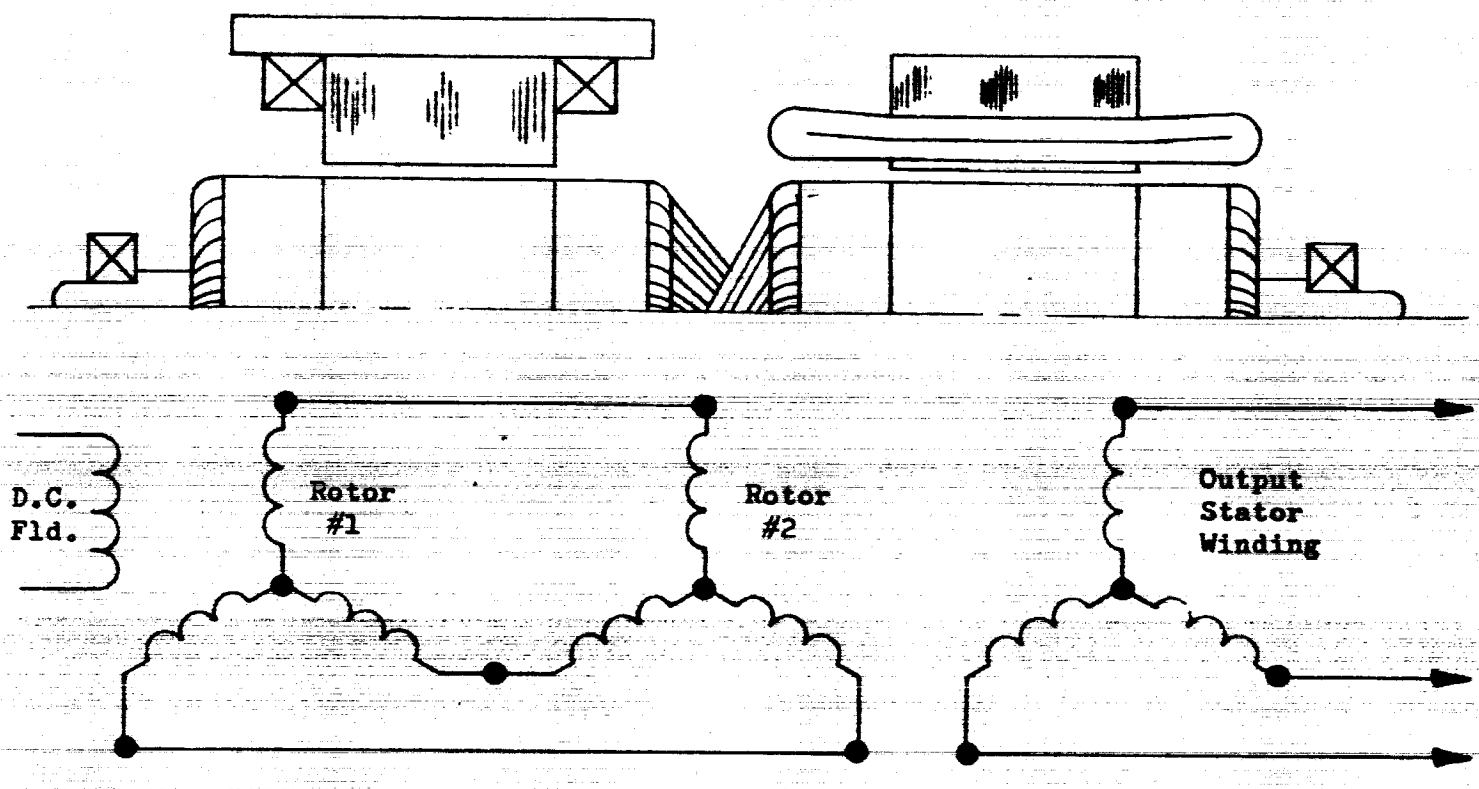
Induction Generators

The induction generator, also called an asynchronous generator, is an induction motor operating at a negative slip, or operating above synchronous speed. To operate above synchronous speed, the machine must be driven by a prime mover.

An external or auxiliary source must supply the magnetizing current of an induction generator. The induction generator can not provide reactive power even for its own magnetizing current. The same external or auxiliary capacitive power source must also supply any lagging or reactive power required by the load.

This excitation requirement is an outstanding deficiency of the induction generator because the total capacitive power requirement often exceeds the rating of the generator.

The short circuit characteristic of the induction generator is such that its generator action ceases when a short circuit occurs at its terminals.



Cascade Generators

Cascade generators can be described as consisting of two generators in series. The rotors of both generators are on a common shaft with the polyphase output windings of the first rotor feeding, with reversed phase sequence, the polyphase windings of the second rotor. The flux wave on the second rotor travels at some multiple of synchronous speed (usually twice), and produces in the output windings of the stator of the second machine, a frequency that is the same as if the poles of both machines were combined on one rotor.

The cascade machine can be thought of as a two-stage synchronous generator. Both stages, if the number of poles are equal, will absorb the same shaft power. From a control standpoint, the first stage gain will be high, of the order of 20 to 50. The second stage gain will be about 2.

OUTPUT EQUATIONS

GENERATOR VOLTAGE AND OUTPUT EQUATIONS

To begin a generator design when there is no required envelope or other size limitation, time can be saved by using an output formula that relates rotor size to output kva. The output equation is given here and then developed from the relation $E = N_c \ell v B_{max} 10^{-8}$

$$\text{Output kva} = \frac{d_r^2 \ell (\text{RPM}) A Bg}{90 \times 10^7}$$

where d_r = rotor diameter which is for practical purposes the same as the stator I.D. (inches)

ℓ = stator length in inches

A = ampere wires/inch of bore periphery

Bg = gap density in kilolines/in^2

All electromagnetic generators convert mechanical energy to electrical energy through a change of flux linking the conductors of the output winding.

The voltage generated in a single conductor is -

$$E = \ell v B_{max} 10^{-8}$$

$$e/\text{coil} = 2 \text{ Emax} \sin wt \text{ Kp}$$

$$\text{Eph} = \frac{e_{rms}}{\text{Coil}} \times \frac{\text{Coils in Series}}{\text{phase}} \times K_d$$

$$= \frac{e_{rms}}{\text{Coil}} \times \frac{\text{Total Slots } K_d}{\text{Phases x Parallels}}$$

$$= \frac{2 \ell v B_{max} 10^{-8}}{\sqrt{2}} \times \frac{QK_d}{mc} \times N_s$$

(N_s = Conductors/Slot)

$$\phi_T = Bg\,\pi\,d_r\,\ell$$

$$B_{max}\ \text{Fundamental} = C_1\ Bg$$

$$v\ B_{max}\ \text{Fund} = C_1\ \phi_T\ X\ \frac{RPM}{60}$$

$$E\ \text{phase} = C_1\ \phi_T\ \frac{RPM}{60}\ x\ \frac{K_p\ N_s\ Q\ K_d\ 10^{-8}}{\sqrt{2}\ mc}$$

$$= \frac{C_1\ \phi_t\ \frac{RPM}{60}\ Ne\ K_d\ x\ 10^{-8}}{\sqrt{2}m}$$

(Ne = total effective conductors in the stator = $\frac{Q\ N_s\ K_p}{C}$)

$$\phi_T = \frac{60\ Eph}{RPM\ Ne}\ x\ \frac{\sqrt{2}\ m}{C_1\ K_d} = \frac{60\ E_{LL}\ \sqrt{2}\ m\ 10^8}{RPM\ Ne\ C_1\ K_d\ \frac{E_{LL}}{Eph}}$$

$$C_w = \text{Winding Constant} = \frac{C_1\ K_d\ \frac{E_{LL}}{Eph}}{\sqrt{2}\ m}$$

$$\phi_T = \frac{60\ x\ 10^5\ x\ E_{LL}}{RPM\ C_w\ Ne}$$

C_w for 3 phase = $.39\ C_1$

C_w for 2 phase (90°) = $.319\ C_1$

C_w for 3 phase = $.225\ C_1$

The derived voltage equation can be found in the AIEE Paper No. 50-201 dated August, 1950, "Design Calculations for A. C. Generators" by David Ginsberg,

$$E_{LL} = \frac{\phi_T (RPM) C_w N_e}{60\ (10^5)}$$

Where ϕ_T = Hypothetical total flux in the air gap of the machine (in kilolines). This is the maximum density over the pole times the area of the stator bore.

N_e = Total effective conductors in the machine.

RPM = Revolutions per minute.

C_w = Winding Constant

$$= \frac{E_{LL}}{m\,E_{ph}} \times \frac{C_1 K_d}{\sqrt{2}} = .39\ C_1 \text{ for a 3 phase machine}$$

Where m = No. of phases

K_d = Distribution Factor = .955

C_1 = Ratio $\frac{\text{Maximum Fundamental}}{\text{Actual Maximum}}$ of the flux wave. This value is 1.0 for a sine wave and a sine wave is assumed in the formula.

Then $$KVA = \frac{I_L E_{LL} \sqrt{3}}{10^{-3}}$$

$$KVA = \left(\frac{\phi_T RPM\, C_w N_e}{60 \times 10^5}\right) \frac{I \sqrt{3}}{\times 10^{-3}}$$

$$\phi_T = B_{gap} \times \text{Area Gap}$$

$$I = \frac{A\pi d}{N_e} \quad \text{since } A = \frac{N_e I_{ph}}{\pi d} = \text{ampere wires per inch of stator bore periphery}$$

$$\underline{KVA} = \frac{B_g(\pi d\, l_c)RPM(.39 C_1)N_e \quad \sqrt{3}\, A\, \pi d}{60 \times 10^8 N_e}$$

$$= \frac{B_g\, 9.85\, d^2 l_c\, RPM\, .39\, C_1\, A\, \sqrt{3}}{60 \times 10^8}$$

$$KVA = \frac{B_g(d^2 l_c)(RPM)A}{90 \times 10^7} \qquad \text{The basic equation.}$$

If a pole embrace is used that gives other than $C_1 = 1.0$ (or if the maximum of the fundamental flux wave is not equal to the maximum of the actual flux wave), the KVA formula should be multiplied by C_1.

Note: Liwschitz-Garik and Whipple in "Electric Machinery" Vol. 2, appendix 8, pp 553-557 derived an equivalent formula for either motors or generators.

Conventional wound-rotor generators, P.M. Generators, and heteropolar inductors have no rotor length to diameter limits due to magnetic limitations. The Lundell type generators and the homopolar inductors have definite rotor length limits because all the useful flux and most of the leakage flux passes through the rotor shaft area. The outputs of the pancake or axial air gap generator are a function of the cube of the outer diameter of the pancake stator. These limitations are discussed in the section pertaining to each machine.

The limits of ampere loading will be determined for each machine and the limits of gap density will be defined for each machine in future reports.

WOUND-POLE, SALIENT-POLE GENERATOR

THE WOUND-POLE, SALIENT-POLE, A. C. GENERATOR

The salient-pole, synchronous generator with wound poles is the standard generator of the electrical industry. It has the highest electrical power output per pound per rpm of any practical electrical generator presently known. Because of its wide spread use and its superiority, all other types of electrical generators are compared to the wound-pole, salient-pole synchronous generator.

It is used on both aircraft and utility systems almost to the exclusion of any other types except non-salient pole, wound rotor, generators (or turbine generators) which are used with 1800 rpm and 3600 rpm steam turbines in central station generating plants.

In addition to its use as an electrical generator, the salient-pole, wound-pole, machine makes the best synchronous motor known. The pole heads can be designed with cage windings so that the machine can start a substantial load as an induction motor. The cage windings can be made double to give good starting characteristics and good pull-in characteristics.

Within its usable range, the wound-pole synchronous generator has no equal, but its range of usefulness is limited. Its maximum rotor peripheral speed is low because of the field windings supported by the poles and the high stresses resulting from the centrifugal loads. Its output frequency is low because the possible number of poles is restricted by electrical and mechanical limits due to the field windings, pole construction and the need for having at least one slot/phase/pole in the stator. Its maximum operating temperature is about 600° F for the copper and insulation on the rotor and 350° F for the rotating (silicon) rectifiers.

These thermal limits, plus the silicon rectifiers' susceptibility to radiation damage, have forced the need for other more rugged types of generators all of which are heavier, on a KVA/revolution basis, than the old standby wound-pole, salient-pole machine.

It is well to remember that within its application range, no other type of a-c generator can compare with the wound-pole, salient-pole machine and it should be used whenever feasible.

SALIENT POLE, WOUND POLE DESIGN CALCULATIONS

Symbol	
(1) d	punching inside diameter
(2) D	punching outside diameter
(3) l	core length
(4) K_i	stacking factor
(5) h_v	number of ventilating ducts
(6) b_v	width of ventilating ducts
(7) h_s	stator slot depth
(8) p	number of poles
(9) m	number of phases
(10) Q	number of slots
(11) b_s	stator slot width
(12)	open slots = 0203000___
	partially closed = 0203000___
(13) g_{min}	air gap length at center
(14) b_o	width of stator slot opening
(15) Y	star winding = 0203000___
(15) Δ	data winding = 0203000___
(16)	series winding =
	parallel winding =
(17) y	coil span in slots
(18) t_{sk}	skew in inches
(19) I_{ph}	current per phase
(20) N_s	conductors per slot
(21) C	number of parallel paths in winding
(22) -	stat. conductor size - dia. or width

Symbol		
(23)	-	stat. conductor size - thickness
(24)	C_1	ratio of max. to act. fundamental
(25)	E_{ph}	phase voltage
(26)	E	line voltage
(27)	g_{max}	air gap length at pole tip
(28)	b_h	width of pole head
(29)	RPM	RPM
(30)	-	steel specification
(31)	-	lamination thickness
(32)	L_E	end extension length
(33)		random wound - 0203000___ formed - 0203000___
(34)	l_{e2}	coil extension beyond core
(35)	d_b	diameter of bender pin
(36)	h_1	conductor depth in slot
(37)	X	expected coil temp. in ^{o}C
(38)	N_{ST}	number of strands/conductor in depth
(39)	h'_{ST}	distance between centerline of strand
(40)	h_{ST}	height of uninsulated strand
(41)	f	cycles per sec.
(42)	-	type slots (a) = 020300___
	-	(b) = 020300___
	-	(c) = 020300___
	-	(d) = 020300___
	-	(e) = 020300___

Symbol		
(43)	h_o	slot constants
(44)	h_2	
(45)	b_1	
(46)	b_2	
(47)	b_t	
(48)	h_t	
(49)	h_w	
(50)	b_{tm}	width of stator tooth 1/2 way down
(51)	b_p	width of pole body
(52)	l_p	length of pole body
(53)	h_f	height of pole body
(54)	h_h	height of pole head at center of pole
(55)	l_n	length of pole head
(56)	b_h	width of pole head
(57)	-	steel specification (pole) =
(58)	-	lamination thickness (pole) =
(59)	λ_b	number of damper bars/pole
(60)	-	dia. of damper bars
(61)	τ_b	bar pitch
(62)	h_{bo}	height of slot opening above damper bar
(63)	b_{bo}	width of slot opening
(64)	N_p	number of field turns per pole
(65)	-	Rot. cond. size - dia. or width
(66)	-	rot. cond. size - thickness
(67)	l_{tr}	mean length of the field turns

Symbol

(68) X_r °C	expected rotor coil temp in °C
(69) -	% load conditions to be studied
(70) -	high, ave., or low magnetization curve
(71) -	
(72) h_{bl}	height of rectangular damper bar
(73) b_{bl}	width of rectangular damper bar
(74) h_3	distance bottom to top of stator coil
(75) KVA	rated KVA
(76) P. F.	power factor
(77) b_r	width of rotor slot
(78) b_{ro}	width of slot opening in rotor slot
(79) h_b	dia. or width of rotor slot
(80) b_b	thickness of rotor slot
(81) τ_s	stator slot pitch at inside stator bore
(82) τ_b	damper bar pitch
(83) h_r	distance below surface of rotor slot
(84) l_b	damper bar length

SYM	EQUATIONS	EXPLANATION
l_s (101)	$l_s = K_i\left[l - n_v b_v\right] = (4)\left[(3) - (5)\times(6)\right]$	Solid Core Length
$2h_c$ (102)	$2h_c = D - \left[d + 2h_s\right] = (2) - \left[(1) + 2\times(7)\right]$ $h_c > .7h_s$; $(102) > 1.4(7)$; If not - STOP 1	Depth Below Slots x 2
h_c (102a)	$h_c = \frac{2h_c}{2} = \frac{(102)}{2}$	Depth Below Slot
q (103)	$q = \frac{Q}{pm} = \frac{(10)}{(8)\times(9)}$	No. Of Stator Slots Per Phase Per Pole
q_1 (103a)	$q_1 = \frac{Q}{pm} = \frac{(10)}{(8)\times(9)} \neq$ Integer = Numerator of lowest fraction	
t_s (104)	$t_s = \frac{\pi d}{Q} = \frac{\pi(1)}{(10)}$	Stator Slot Pitch
$t_{s\,1/3}$ (105)	$t_{s\,1/3} = \frac{\pi\left[d + .667h_s\right]}{Q} = \frac{\pi\left[(1) + .667\times(7)\right]}{(10)}$	Stator Slot Pitch 1/3 Way Up Tooth
K_s (106)	Transfer on input (12) to: $K_s\,(\text{OPEN}) = \frac{t_s\left[5g + b_s\right]}{t_s\left[5g + b_s\right] - b_s^2} = \frac{(104)\left[5\times(13) + (11)\right]}{(104)\left[5\times(13) + (11)\right] - (11)^2}$ Or $K_s\,(\text{CLOSED}) = \frac{t_s\left[4.44g + .75b_0\right]}{t_s\left[4.44g + .75b_0\right] - b_0^2} = \frac{(104)\left[4.44\times(13) + .75(14)\right]}{(104)\left[4.44\times(13) + .75(14)\right] - (14)^2}$	Carter Coefficient
— (107)	$= \frac{y}{mq} = \frac{(17)}{(9)\times(103)}$	% Coil Span
t_p (108)	$t_p = \frac{\pi d}{p} = \frac{\pi(1)}{(8)}$	Pole Pitch

K_{SK} (109) — Skew Factor

$$K_{SK} = \frac{\sin\left[\frac{t_{SK}\,\pi}{2\,t_p}\right]}{\frac{t_{SK}\,\pi}{2\,t_p}} = \frac{\sin\left[\frac{\pi\,(18)}{2\times(108)}\right]}{\frac{\pi\,(18)}{2\times(108)}}$$

K_d (110) — Distribution Factor

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

$$\therefore K_d = \frac{\sin[90^\circ/m]}{q\,\sin[90^\circ/mq]} = \frac{\sin[90^\circ/(9)]}{(103)\sin[90^\circ/(9)\times(103)]} \quad \text{For (103)=Integer}$$

<u>or</u>

$$K_d = \frac{\sin[N\alpha m/2]}{N\,\sin[\alpha m/2]} \quad \text{Where } N = \text{Integer} = \frac{Q}{mp}\times\text{Integer } \& \ \alpha m = \frac{180^\circ}{N\times m}$$

$$\therefore K_d = \frac{\sin[90^\circ/m]}{N\,\sin[90^\circ/Nm]} = \frac{\sin[90^\circ/(9)]}{N\,\sin[90^\circ/N\times(9)]} \quad \text{For (103)} \neq \text{Integer}$$

K_p (111) — Chord Factor

$$K_p = \sin\left[\frac{y}{mq}\times 90^\circ\right] = \sin\left[\frac{(17)}{(9)\times(103)}\times 90^\circ\right]$$

n_e (112) — Total Effective Conductors

$$n_e = \frac{Q\,n_S\,K_p\,K_{SK}}{C} = \frac{(10)\times(20)\times(111)\times(109)}{(21)}$$

a_c (113) — Strand Area

$(23) = 0$; $a_c = .25\pi\,D_{ia}^2 = .25\pi\,(22)^2$

$(23) \neq 0$; $a_c = (22)\times(23) - (.858\,r_c^2)$ Where $.858\,r_c^2$ Is Obtained By TLU As Shown

(23) ↓	(22) ≤ .188	.189 ≤ (22) ≤ .75	(22) ≥ .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

CONDUCTOR AREAS $A_c \times N_{ST}$

S (114)	$S = \frac{I_{ph}}{c\,a_c} = \frac{(19)}{(21)\times(113)}$	Current Density
α (115)	$\alpha = \frac{b_h}{t_p} = \frac{(28)}{(108)}$	Pole Embrace
C_I (116)	$(24) = 0$; If $(24) \neq 0$ Use value in (24) $C_I = \left[1.49357 \log_{10}\alpha + 1.3588\right]\left\{\left[\frac{G_{max}}{G_{min}}\right]^{-.35211}\right\}$ $C_I = \left[1.49357 \log_{10}(115) + 1.3588\right]\left\{\left[\frac{(27)}{(13)}\right]^{-.35211}\right\}$	Ratio Of Maximum To Actual Fundamental
C_W (117)	$C_W = \frac{E\,C_I\,k_d}{\sqrt{2}\,E_{ph}\,m} = \frac{(26)\times(116)\times(110)}{\sqrt{2}\times(25)\times(9)}$	Winding Constant
ϕ_T (118)	$\phi_T = \frac{6\,E\times10^9}{C_W\,n_e\,RPM} = \frac{6\times(26)\times10^9}{(117)\times(112)\times(29)}$	Total Flux
GAP AREA (119)	$\text{GAP AREA} = \pi\,d\,l = \pi\times(1)\times(3)$	Gap Area
Bg (120)	$B_g = \frac{\phi_T}{\pi\,d\,l} = \frac{(118)}{(119)}$	Gap Density
C_p (121)	$C_p = \left[\frac{G_{max}}{G_{min}}\right]^{-.41}\alpha\left\{.087271 \log_{10}\left[\frac{G_{min}}{\text{Pole Pitch}}\right] + 1.190542\right\}$ $= \left[\frac{(27)}{(13)}\right]^{-.41}\times(115)\times\left\{.087271 \log_{10}\left[\frac{(13)}{(108)}\right] + 1.190542\right\}$	Pole Density
ϕ_p (122)	$\phi_p = \frac{\phi_T\,C_p}{p} = \frac{(118)\times(121)}{(8)}$	Flux Per Pole

$b_{t\,1/3}$ (123)	$b_{t\,1/3} = t_{s\,1/3} - b_s = (105) - (11)$	Width Of Stator Tooth 1/3 From Narrowest Part
B_t (124)	$B_t = \dfrac{\phi T}{Q\, l_s\, b_{t\,1/3}} = \dfrac{(118)}{(10) \times (101) \times (123)}$	Tooth Density
B_c (125)	$B_c = \dfrac{\phi P}{2 h_c\, l_s} = \dfrac{(122)}{(102) \times (101)}$	Core Density
L_E (126)	(32) = 0: If Not Use Value In (32) Random Wound Coils: [Transfer Or (33)] $L_E = \dfrac{.5 + K_T \pi y [d + h_s]}{Q} = .5 + \dfrac{\begin{bmatrix} 1.3 \text{ If } (8)=2 \\ 1.5 \text{ If } (8)=4 \\ 1.7 \text{ If } (8)>4 \end{bmatrix} \pi (17) [(1) \times (7)]}{(10)}$ Formed Coils: [Transfer Or (33)] $L_E = 2 l_{e2} + \pi \left[\dfrac{h_1}{2} + \text{dia}\right] + y \left[\dfrac{t_s^2}{\sqrt{t_s^2 - b_s^2}}\right]$ $= 2 \times (34) + \pi \left[\dfrac{(36)}{2} + (35)\right] + (17) \left[\dfrac{(104)^2}{\sqrt{(104)^2 - (11)^2}}\right]$	End Extension Length
l_t (127)	$l_t = l + L_E = (3) + (126)$	1/2 Mean Turn
ρ (128)	$\rho = .91 \times 10^{-6} \left[\dfrac{X^\circ C + 234.5}{334.5}\right] = .91 \times 10^{-6} \left[\dfrac{(37) + 234.5}{334.5}\right]$	Resistivity At X° C
R_{ph} (129)	$R_{ph} = \dfrac{\rho\, n_s\, Q\, l_t}{m\, a_c\, C^2} = (128) \times \dfrac{(20) \times (10) \times (127)}{(9) \times (113) \times (21)^2}$	Resistance / Phase

— (130)	$EF_{TOP} = 1 + \left\{ .584 + \left[\frac{N_{st}^2 - 1}{16}\right]\left[\frac{h_{st}\, l}{h_{st}\, l_t}\right]^2 \right\} 3.35\times10^{-3} \left[\frac{h_{st}\, n_{sf}\, a_c}{b_s\, \rho \times 10^6}\right]^2$ $= 1 + \left\{ .584 + \left[\frac{(38)^2 - 1}{16}\right]\left[\frac{(39)\times(3)}{(40)\times(127)}\right]^2 \right\} 3.35\times10^{-3} \left[\frac{(40)\times(20)\times(41)\times(113)}{(11)\times(128)\times 10^6}\right]^2$	Eddy Factor Top
— (131)	$EF_{BOT} = EF_{TOP} - 1.677345 \left[\frac{h_{st}\, n_{sf}\, a_c}{b_s\, \rho \times 10^6}\right]^2 \times 10^{-3}$ $= (130) - 1.677345 \left[\frac{(40)\times(20)\times(41)\times(113)}{(11)\times(128)\times 10^6}\right]^2 \times 10^{-3}$	Eddy Factor Bottom
C_M (132)	$C_M = \frac{\alpha\pi + \sin[\alpha\pi]}{4 \sin[\alpha\pi/2]} = \frac{\pi\times(115) + \sin[\pi\times(115)]}{4 \sin[\pi\times(115)/2]}$	Demagnetizing Factor
C_q (133)	$C_q = \frac{1/2 \cos[\alpha\pi/2] + \alpha\pi - \sin[\alpha\pi]}{4 \sin[\alpha\pi/2]}$ $= \frac{1/2 \cos[\pi\times(115)/2] + \pi\times(115) - \sin[\pi\times(115)]}{4 \sin[\pi\times(115)/2]}$	Cross Magnetizing Factor
A (134)	$A = \frac{I_{ph}\, n_s\, K_p}{C_{ts}} = \frac{(19)\times(20)\times(111)}{(21)\times(104)}$	Ampere Conductors / Inch
X (135)	$X = \frac{100\, A\, K_d}{\sqrt{2}\, C_1\, B_g} = \frac{(134)\times(110)\times 10^2}{\sqrt{2}\times(116)\times(120)}$	Reactance Factor
K_x (136)	$(42) \neq \alpha: \quad K_x = 1/4\,[3y/mq + 1] = 1/4\{[3\times(17)/(9)\times(103)] + 1\}$ $(42) = \alpha: \quad K_x = 1$	Factor To Account For Difference In Phase Of Current In Coil Sides In Same Slot
C_x (136)	$C_x = K_x / [K_p^2\, K_d^2] = (136) / [(111)^2 \times (110)^2]$	Reduction Factor

— (137)	$C_x \frac{20}{mq} = \frac{(136) \times 20}{(9) \times (103)}$	—
λ_i (138)	$(42)=(a);\ \lambda_i = (137)\left[\frac{(44)}{(11)} + \frac{(36)}{3\times(11)} + \frac{(47)\times(47)}{16\times(104)\times(13)} + .35\frac{(47)}{(104)}\right]$ $(42)=(b);\ \lambda_i = (137)\left[\frac{(43)}{(14)} + \frac{2\times(48)}{(14)+(11)} + \frac{(49)}{(11)} + \frac{(36)}{3\times(11)} + \frac{(47)\times(47)}{16\times(104)\times(13)} + .35\frac{(47)}{(104)}\right]$ $(42)=(c);\ \lambda_i = (137)\left[\frac{(43)}{(14)} + \frac{2\times(48)}{(14)+(45)} + \frac{2\times(49)}{(45)+(46)} + \frac{(36)}{3\times(46)} + \frac{(47)\times(47)}{16\times(104)\times(13)} + .35\frac{(47)}{(104)}\right]$ $(42)=(d);\ \lambda_i = (137)\left[.62 + \frac{(43)}{(14)}\right]$ $(42)=(e);\ \lambda_i = (137)\left[\frac{(44)}{(11)} + \frac{(36)}{3\times(11)} + \frac{(13)}{2\times(104)} + \frac{(104)}{4\times(13)} + .6\right]$	Conductor Permeance
K_E (139)	$K_E = \frac{\text{Calculated Value Of } L_E}{\text{Value Of } L_E \text{ From Graph}} = \frac{(126)}{10^{[.10312(17)(104)+.40203]}}$ If $(1) < 8$; $K_E = [K_E \text{ Calculated Above}]^{1/2}$	Leakage Reactive Factor For End Turn
λ_E (140)	$\lambda_E = \frac{6.28\, K_E}{l\, K_d^2}\left[\frac{\phi_E\, L_E}{2n}\right]$ $= \frac{6.28\times(139)}{(3)\times(110)^2}\left[1.41 \log[10\times(107)]\times(108)\left\{\frac{1.17609 - \log[1.41 \log[10\times(107)]]}{1.90309}\right\}\right]$	End Winding Permeance
X_l (141)	$X_l = X\left[\lambda_i + \lambda_E\right] = (135)\left[(138)+(140)\right]$	Leakage Reactance

λ_a (142)	$\lambda_a = \frac{6.38\,d}{p\,g_e} = \frac{6.38 \times (1)}{(8)\times(13)\times(106)}$	Air Gap Permeance
X_{ad} (143)	$X_{ad} = X\ \lambda_a\ C_1\ C_M = (135)\times(142)\times(116)\times(132)$	Direct Axis Reactance
X_{aq} (144)	$X_{aq} = X\ C_q\ \lambda_a = (135)\times(133)\times(142)$	Quadrature Axis Reactance
— (145)	$\# = .321\ n_s\ Q\ a_c\ l_t = .321 \times (20)\times(10)\times(113)\times(127)$	Weight Of Copper
— (146)	$\# = .283\left\{b_{tm}\ Q\ l_s\ h_s + \pi\left[D - h_c\right] h_c\ l_s\right\}$ $= .283\left\{(50)\times(10)\times(101)\times(7) + \pi\left[(2) - \frac{(102)}{2}\right]\times\frac{(102)}{2}\times(101)\right\}$	Weight Of Iron

ROTOR

g_e (147)	$g_e = K_s\,g = (106)\times(13)$	Effective Air Gap
d_r (148)	$d_r = d - 2g = (1) - 2\times(13)$	Rotor Diameter
V_r (149)	$V_r = \frac{\pi\ d_r\ RPM}{12} = \frac{\pi \times (148)\times(29)}{12}$	Peripheral Speed
a_p (150)	$a_p = b_p\ l_p\ K_i = (51)\times(52)\times(4)$	Effective Area Of Pole
λ_{sl} (151)	$\lambda_{sl} = \left\{\frac{h_f}{\pi/p\left[d_r - 2h_h - .5h_f\right] - b_p}\right\}$ $= \left\{\frac{(53)}{\pi/(8)\left[(148) - 2\,(54) - .5\times(53)\right] - (51)}\right\}$	Side Leakage
λ_{el} (151)	$\lambda_{el} = \left\{\frac{2\left[l_h - 1\right] + h_f + .25\,b_p}{l}\right\} = \left\{\frac{2\left[(55)-(3)\right] + (53) + .25\times(51)}{(3)}\right\}$	End Leakage

λ_{tl} (153)	$\lambda_{tl} = \left\{ \frac{2\left[h_h + g - t_p/18\right]}{t_p - b_h} \right\} = \left\{ \frac{2\left[(54) + (13) - (108)/18\right]}{(108) - (56)} \right\}$	Tip Leakage
F_g (154)	$F_g = \frac{B_g\, g_e}{3.19} = \frac{(120) \times (147)}{3.19}$	Air Gap A.T.
F_T (155)	$F_T = h_s\left[\text{NI/in. at density } B_t\right]$ $= (7) \times \left[\text{TLU on curve spec. by (30) \& (70) using (124)}\right]$	A.T. Per Pole For Teeth
F_c (156)	$F_c = \left\{ \frac{\pi\left[D - h_c\right]}{4p} \right\} \left[\text{NI/in. at density } B_t\right]$ $= \left\{ \frac{\pi\left[(2) - (102)/2\right]}{4 \times (8)} \right\} \times \left[\text{TLU on curve spec. by (30) \& (70) using (125)}\right]$	A.T. Per Pole For Core
F_s (157)	$F_s = F_T + F_c = (155) + (156)$	Stator Ampere Turns
ϕ_l (158)	$\phi_l = .00638\left[\lambda_{sl} + \lambda_{el} + \lambda_{tl}\right]\left[F_g + F_s\right] l_p$ $= .00638\left[(151) + (152) + (153)\right] \times \left[(154) + (157)\right] \times (52)$	Leakage Flux
ϕ_{PT} (159)	$\phi_{PT} = \phi_P + \phi_l = (122) + (158)$	Total Flux Per Pole
B_P (160)	$B_P = \frac{\phi_{PT}}{a_P} = \frac{(159)}{(150)}$	Pole Density
a_{cr} (161)	Repeat steps for a_c (113)	Conductor Area
R_f (162)	$R_f = \rho \frac{N_p\, p\, l_{tr}}{a_{cr}\,(C_R)^2} = .91 \times 10^{-6}\left[\frac{(68) + 234.5}{334.5}\right] \times \left[\frac{(64) \times (8) \times (67)}{(161)}\right]$	Resistance Of Field

— (163)	$\# = .321\, N_p\, p\, l_{tr}\, a_{cr} = .321 \times (64) \times (8) \times (67) \times (161)$	Weight Of Rotor Copper
— (164)	# = DO NOT CALCULATE	Weight Of Rotor Iron
I_F (165)	I_F = (no load) $= F_{NL} \div N_p = (197) \div (64)$ (rated load) $= F_{FL} \div N_p = (207) \div (64)$ (overload) $= F_{OL} \div N_p = (209) \div (64)$	Field Current
E_F (166)	$E_F = I_F \times R_f = (165) \times (162)$ ↳ (For three values of I_F)	Field Voltage
— (167)	$= I_F \div a_{cr} = (165) \div (161)$ ↳ (For three values of I_F)	Amps/In.^{2}
λ_F (168)	$\lambda_F = 4.25\left[\lambda_{sl} + 1.5\lambda_{tl}\right] + 6.38\lambda_{el} = 4.25\left[(151) + 1.5 \times (153)\right] + 6.38 \times (152)$	Rotor Leakage Permenance
X_F (169)	$X_F = X_{ad}\left[1 - \dfrac{[C_l/C_M]}{2C_p + \dfrac{4\lambda_F}{\pi\lambda_a}}\right] = (143)\left[1 - \dfrac{[(116)/(132)]}{2 \times (121) + \dfrac{4 \times (168)}{\pi \times (142)}}\right]$	Field Leakage Permenance
L_f (170)	$L_f = N_p^2\, p\, l_p \left[C_p \dfrac{\pi}{2} \lambda_a + \lambda_F\right] \times 10^{-8}$ $= (64)^2 \times (8) \times (52) \times \left[\dfrac{\pi}{2} \times (121) \times (142) + (168)\right] \times 10^{-8}$	Field Self Inductance
— (171)	$(72) = 0$; $h_{bl}/3b_{bl} = .62$ $(72) \neq 0$; $h_{bl}/3b_{bl} = (72)/3 \times (73)$	———

λ_b (172)	$\lambda_b = 6.38\left[\frac{h_{bo}}{b_{bo}} + \frac{h_{bi}}{3b_{bi}} + .5\right] = \left[\frac{(62)}{(63)} + (171) + .5\right]$	Permeance Of Damper Bar Embedded In Iron
λ_{pt} (173)	$\lambda_{pt} = 6.38\left\{\frac{b_h - t_b[n_b - 1]}{3g_e}\right\} = 6.38\left\{\frac{(56) - (61)\times[(59)-1]}{3\times(147)}\right\}$	Permeance Of End Portion Of Damper Bars
λ_{Dd} (174)	$\lambda_{Dd} = \left\{\cos\left[\frac{[n_b-1]\,t_b\,\pi}{2t_p}\right]\right\}\left\{\frac{[\lambda_b+\lambda_{pt}]\,\lambda_F}{\lambda_b+\lambda_{pt}+\lambda_F}\right\}$ $= \left\{\cos\left[\frac{[(59)-1]\times(61)\times\pi}{2\times(108)}\right]\right\}\left\{\frac{[(72)+(73)]\times(68)}{(72)+(73)+(68)}\right\}$	Permeance In Direct Axis
X_{Dd} (175)	$X_{Dd} = \mathbb{X}\,\lambda_{Dd} = (135)\times(174)$	Leakage Reactance In Direct Axis
λ_{Dq} (176)	$\lambda_{Dq} = \frac{20\,t_b}{t_p}\left[\frac{h_{bo}}{b_{bo}} + \frac{h_{bi}}{3b_{bi}} + .5 + \frac{g}{t_b}\right]$ $= \frac{20\times(61)}{(108)}\left[\frac{(62)}{(63)} + (171) + .5 + \frac{(13)}{(61)}\right]$	Permeance In Quadrature Axis
X_{Dq} (177)	$X_{Dq} = \mathbb{X}\,\lambda_{Dq} = (135)\times(176)$	Leakage Reactance In Quadrature Axis

REACTANCES & TIME CONSTANTS

X_d (178)	$X_d = X_l + X_{ad} = (41) + (43)$	Syn. Reactance In Direct Axis
X_q (179)	$X_q = X_l + X_{ad} = (41) + (44)$	Syn. Reactance In Quadrature Axis
X'_{du} (180)	$X'_{du} = X_l + X_F = (41) + (69)$	Unsat. Trans. Reactance

X'_d (181)	$X'_d = .88 X'_{du} = .88 \times (180)$	Sat. Trans. Reactance
X''_d (182)	$X''_d = X_l + X_{Dd} = (141)+(175)$ If $(59) \neq 0$ $X''_d = X'_d = (181)$ If $(59) = 0$	Subtrans Reactance In Direct Axis
X''_q (183)	$X''_q = X_l + X_{Dq} = (141)+(177)$ If $(59) \neq 0$ $X''_q = X_q = (179)$ If $(59) = 0$	Subtrans Reactance In Quadrature Axis
X_2 184	$X_2 = .5\left[X''_d + X''_q\right] = .5\left[(182)+(183)\right]$	Neg. Seq. Reactance
K_{xo} (185)	$K_{xo} = 1$; If $(20) = 1$ $K_{xo} = \frac{3y}{mq} - 2 = \frac{3\times(17)}{(9)\times(103)} - 2$; If $(20) \neq 1$ If $(20) = 0$, Make $\lambda_{BO} = 0$ And Skip To x_o	———
K_x (186)	If $(20) = 1$; $K_x = 1$ If $(20) \neq 1$ $K_x = \left[\frac{3y}{4mq} + \frac{1}{4}\right] = \left[\frac{3\times(17)}{4\times(9)\times(103)} + .25\right]$ If $(107) \geq .667$ $K_x = \left[\frac{3y}{4mq} + \frac{1}{4}\right] = \left[\frac{3\times(17)}{4\times(9)\times(103)} - .25\right]$ If $(107) < .667$	———
λ'_{BO} (187)	$\lambda'_{BO} = \frac{K_{xo}}{K_x} \times \lambda_{Dq} = \frac{(185)}{(186)} \times (176)$	———
λ_{BWO} (188)	$\lambda_{BWO} = \frac{K_{xo}}{K_p^2}\left[.07\,\lambda_a\right] = \frac{(185)}{(111)^2}\left[.07\times(142)\right]$	———

λ_{BO} (189)	$\lambda_{BO} = \lambda_{BWO} = (188)$; If $(59) = 0$ $\lambda_{BO} = \dfrac{\lambda'_{BO} + \lambda_{BWO}}{(\lambda'_{BO})(\lambda_{BWO})} = \dfrac{(187)+(188)}{(187)\times(188)}$; If $(59) \neq 0$	———
X_0 (190)	Transfer on (15): If Δ ; $X_0 = 0$ If Y ; $X_0 = X\left\{\dfrac{K_{X0}}{K_X}\left[\lambda_i + \lambda_{BO}\right] + \dfrac{1.667\left[h_1 + 3h_3\right]}{m\,q\,K_p^2\,K_d^2\,b_s} + .2\lambda_E\right\}$ $= (135)\left\{\dfrac{(185)}{(186)}\left[(138)+(189)\right] + \dfrac{1.667\left[(36)+3\times(74)\right]}{(9)\times(103)\times(111)^2\times(110)^2\times(11)} + .2\times(140)\right\}$	Zero Sequence Reactance
T'_{do} (191)	$T'_{do} = \dfrac{L_F}{R_F} = \dfrac{(170)}{(162)}$	Open Circuit Time Constant
r_a (192)	$r_a = \dfrac{m\,I_{ph}^2\,R_{ph}}{\text{Rated KVA}} = \dfrac{(9)\times(19)^2\times(129)}{(75)\times 10^{-3}}$	———
T_a (193)	$T_a = \dfrac{X_2}{200\pi f r_a} = \dfrac{(184)}{200\times\pi\times(41)\times(192)}$	Armature Time Constant
T_d' (194)	$T_d' = \dfrac{X_d'}{X_d}\,T'_{do} = \dfrac{(181)}{(178)}\times(191)$	Transient Time Constant
T_d'' (195)	If $(41) = 60$, $T_d'' = .035$; If $(41) = 400$, $T_d'' = .005$	Subtrans. Time Constant

SATURATION

F_R (196)	$F_R = \left[h_f + h_h\right]\left[\text{NI/in at density } B_P\right]$ $= \left[(53)+(54)\right]\left[\text{TLU on curve spec. by (57) \& (70) using (160)}\right]$	Pole Ampere Turns

F_{NL} (197)	$F_{NL} = F_g + F_S + F_R = (154) + (157) + (196)$	No Load Ampere Turns
– (198)	$\theta = \cos^{-1}[\text{Power Factor}]$; Assume θ & Iterate Till $\cos\theta = \frac{(76)}{100} \pm 10^{-5}$	Power Factor Angle
Ψ (199)	$\Psi = \tan^{-1}\left[\frac{\sin\theta + X_q}{\cos\theta}\right] = \tan^{-1}\left[\frac{\sin(198) + (179)/100}{\cos(198)}\right]$	———
ϵ (200)	$\epsilon = \Psi - \theta = (199) - (198)$	Generator Power Angle
e_d (201)	$e_d = \cos\epsilon + X_d \sin\Psi = \cos(200) + \frac{(178)}{100}\sin(199)$	Nominal Voltage
ϕ_{PL} (202)	$\phi_{PL} = \phi_P\left[e_d - .0093 X_{ad} \sin\Psi\right] = (122)\left[(201) - \frac{.0093 \times (143)}{100}\sin(199)\right]$	Load Flux Per Pole
ϕ_{ll} (203)	$\phi_{ll} = \phi_l\left\{\frac{e_d F_g + [1 + \cos\theta] F_T + F_c}{F_g + F_T + F_c}\right\}$ $= (158)\left\{\frac{(201) \times (154) + [1 + \cos(198)] \times (155) + (156)}{(154) + (157)}\right\}$	Leakage Flux / Pole At Load
ϕ_{Ptl} (204)	$\phi_{Ptl} = \phi_{Pl} + \phi_{ll} = (202) + (203)$	Load Total Flux / Pole
B_{PL} (205)	$B_{PL} = \frac{\phi_{Ptl}}{a_P} = \frac{(204)}{(150)}$	Flux Density At Base Of Pole
F_{PL} (206)	$F_{PL} = [h_f + h_h]$ [NI/In^2 At Density Of B_{PL}] $= [(53) + (54)]$ [TLU On Curve Spec By (57) & (70) Using (205)]	Ampere Turns / Pole At Load

F_{FL} (207)	$F_{FL} = e_d F_g + [1+\cos\theta] F_T + F_C + F_{PL}$ $= (201) \times (154) + [1+\cos(76)] \times (155) + (156) + (206)$	Rated Load Ampere Turns
— (208)	Change factor 100 in (199) (201) (202) to 75	———
F_{OL} (209)	Repeat (199) to (207)	Overload Ampere Turns
F_{SC} (210)	$F_{SC} = X_d F_g = \frac{(178)}{100} \times (154)$	Short Circuit Ampere Turns
SCR (211)	$SCR = \frac{F_{NL}}{F_{SC}} = \frac{(197)}{(210)}$	Short Circuit Ratio
	LOSSES & EFFICIENCY	
F&W (212)	$F\&W = 2.52 \times 10^{-6} \times d_r^{2.5}\, l_h\, RPM^{1.5}$ $= 2.52 \times 10^{-6} \times (148)^2 \times (29)^{1.5} \times (55)$	Friction & Windage
K_Q (213)	$K_Q = k\left[\frac{B_t}{77.4}\right]^2 = [\text{Watts/lb. loss at density } B_t]$ $= [\text{TLU on curve spec. by (30) \& (41) using (124)}]$	Watts Per Pound Loss
W_{TNL} (214)	$W_{TNL} = .453[t_{s1/3} - b_s]\, Q\, l_s\, h_s\, k_Q$ $= .453[(115) - (11)] \times (10) \times (100) \times (7) \times (213)$	No Load Stator Tooth Losses
W_C (215)	$W_C = 1.42[D - h_c]\, h_c\, l_s\, k_Q$ $= 1.42\left[(2) - \frac{(102)}{2}\right] \times \frac{(102)}{2} \times (100) \times \left[\begin{array}{l}\text{TLU on curve spec. by} \\ \text{(30) \& (41) using (125)}\end{array}\right]$	Stator Core Losses
K_1 (216)	$K_1 = 10^{[4.91901 \times (58) - .06791]}$	———
K_2 (217)	$K_2 = f\, B_g = 6.1 \times 10^{-5} \times (120)^{2.5} = 6.1 \times 10^{2.5 \log(120)} \times 10^{-5}$	———

K_3 (218)	$K_3 = f_n[F_T] = 1.5147 \times 10^{-5} \times \left[\frac{(29)}{60} \times (10)\right]^{1.74}$ $= 1.5147 \times 10^{\{1.74 \log [(29)/60] \times (10)\}} \times 10^{-5}$	———
K_4 (219)	$K_4 = f_n[t_s] = .81 \times (104)^{1.285} = .81 \times 10^{[1.285 \log (104)]}$; $t_s \leqq .9$ $= .79 \times 10^{[1.145 \log (104)]}$; $.9 \leqq t_s \leqq 2.0$ $= .92 \times 10^{[.79 \log (104)]}$; $t_s > 2.0$	———
K_5 (220)	$K_5 = f_n[B_0/g] = [\ B_0/g \leqq 1.7\ ] = .3 \times 10^{[2.31 \log (14)/(13)]}$ $[1.7 < B_0/g \leqq 3] = .35 \times 10^{[2.0 \log (14)/(13)]}$ $[3 < B_0/g \leqq 5\ ] = .625 \times 10^{[1.4 \log (14)/(13)]}$ $[\ B_0/g > 5\ ] = 1.38 \times 10^{[.965 \log (14)/(13)]}$	———
K_6 (221)	$K_6 = f_n[C_1] = 10^{[.9323 (116) - 1.60596]}$	———
— (222)	$= \pi d l = \pi \times (1) \times (3)$	Bore Area
W_{NPL} (223)	$W_{NPL} = K_1 \times K_2 \times K_3 \times K_4 \times K_5 \times K_6 \times \pi d l$ $= (216) \times (217) \times (218) \times (219) \times (220) \times (221) \times (222)$	No Load Pole Face Losses
K_r (224)	Repeat (106) using b_r (77) in place of b_s (11) and b_{ro} (78) in place of b_o (14)	Rotor Slot Carters Coefficient
K_g (225)	$K_g = K_s = (106)$	Total Carter Coefficient
λ_t (226)	$\lambda_t = f_n\left[\frac{b_r}{g K_g}\right] = f_n\left[\frac{(77)}{(13) \times (125)}\right] = -.558 \log \left[\frac{(77)}{(13) \times (125)}\right] + .59$	———
f_{s1} (227)	$f_{s1} = 2 g m f = 2 \times (13) \times (9) \times (41)$	———
f_{s2} (228)	$f_{s2} = 2 f_{s1} = 2 \times (227)$	———

ρ		Damper Bar Restivity
δ_1 (230)	$\delta_1 = .32\sqrt{\frac{f_{s1}}{\rho}} \times h_b = .32 \times \left[\frac{(227)}{(229)}\right]^{1/2} \times (79)$	
δ_2 (231)	$\delta_2 = .32\sqrt{\frac{f_{s2}}{\rho}} \times h_b = .32 \times \left[\frac{(228)}{(229)}\right]^{1/2} \times (79)$	
K_{f1} (232)	$K_{f1} = f_n[\delta_1] = .208\delta_1 - .232 = .208 \times (230) - .232$; If $(230) > 1.5$ $= 10^{[\text{Log}.025 + 2.875\ \text{Log}(230)]}$; If $(230) \leq 1.5$	
K_{f2} (233)	Repeat (232) Using (231) In Place Of (230)	
λ_c (234)	If $(60) \neq 0$ Or $(60) = 0$ And $(72) = (73)$; $\lambda_c = .75/K_{f1} = .75/(232)$ If $(60) = 0$ And $(72) \neq (73)$; $\lambda_c = \frac{h_{b1}}{3b_{b1}\ K_{f1}} = \frac{(79)}{3 \times (80) \times (232)}$	
λ_s (235)	$\lambda_s = \frac{h_r}{b_r} + \lambda_t + \lambda_c = \frac{(83)}{(77)} + (226) + (234)$	
λ_g (236)	$\lambda_g = \frac{\tau_b}{K_g g} = \frac{(82)}{(225) \times (13)}$	

K_p (237)	$K_p = 1 - \dfrac{1}{\sqrt{1+\left[\dfrac{b_o}{2g}\right]^2}} = 1 - \dfrac{1}{\left\{1+\left[\dfrac{(11)}{2\times(13)}\right]^2\right\}^{1/2}}$	———
K_{W1} (238)	$K_{W1} = f_n\left[b_o/\tau_s\right] = f_n\left[(11)/(81)\right]$ $= .17 \sin\left[2.5\pi\dfrac{(11)}{(81)} - .875\pi\right] + .88$	———
K_{W2} (239)	$K_{W2} = f_n\left[b_o/\tau_s\right] = f_n\left[(11)/(81)\right]$ $= .23 \sin\left[3.33\pi\dfrac{(11)}{(81)} - .667\pi\right] + .23$	———
$K_{\phi 1}$ (240)	$K_{\phi 1} = f_n\left[\tau_b/\tau_s\right] = f_n\left[(82)/(81)\right]$ $= \sin\left[2\pi\dfrac{(82)}{(81)} - \dfrac{\pi}{2}\right] + 1$	———
$K_{\phi 2}$ (241)	$K_{\phi 2} = f_n\left[\tau_b/\tau_s\right] = f_n\left[(82)/(81)\right]$ $= \sin\left[4\pi\dfrac{(82)}{(81)} - \dfrac{\pi}{2}\right] + 1$	———
W_{DNL} (242)	$W_{DNL} = \dfrac{1.246\, p\, n_b\, l_p\, \rho}{a_b \times 10^3}\left[\tau_s B_g K_p K_g\right]^2 \times \left\{K_{f1}\left[\dfrac{K_{W1}}{2\lambda_s + \left[\lambda_g/K_{\phi 1}\right]}\right]^2 + K_{f2}\left[\dfrac{K_{W2}}{2\lambda_s + \left[\lambda_g/K_{\phi 2}\right]}\right]^2\right\}$ $= \dfrac{1.246\times(8)\times(59)\times(84)\times(229)}{a_b \times 10^9}\left[(81)\times(120)\times(237)\times(225)\right]^2$ $\times\left\{(232)\left[\dfrac{(238)}{2\times(235)+\left[(236)/(240)\right]}\right]^2 + (233)\left[\dfrac{(239)}{2\times(235)+\left[(236)/(241)\right]}\right]^2\right\}$ where $a_b = .25\pi \times (60)^2$; if $(60) \neq 0$ $= (72)\times(73)$; if $(60) = 0$	No Load Damper Loss

I^2R_S (243)	$I^2R_S = m\, I^2_{ph}\, R_{ph} \times \left[\%\ \text{Load}\right]^2 = (9) \times (19)^2 \times \left[\%\ \text{Load}\right]^2 \times (129)$	Stator I^2R
Eddy (244)	$\text{Eddy Loss} = \left[\dfrac{\text{Eddy Factor Top} + \text{Eddy Factor Bottom}}{2} - 1\right] I^2R_S$ $= \left[\dfrac{(130)+(131)}{2} - 1\right] \times (143)$	Eddy Loss
I^2R_R (245)	$I^2R = I_f^2\ R_f = (165)^2_{\text{No Load}} \times (162)$	Rotor I^2R
— (246)	$= F\&W + W_{TNL} + W_C + W_{PNL} + W_{DNL} + I^2R_{SNL} + \text{Eddy}_{NL} + I^2R_{RNL}$ $= (212)+(214)+(215)+(223)+(242)+(243)+(244)+(245)$	Sum Of Losses
KVA (247)	$\text{KVA} = E \times \sqrt{3} \times I_{ph} \times \%\text{Load} \times \text{P.F.} = (26)\times(19)\times(76)\times\sqrt{3} \times \%\ \text{Load}$	Rating
— (248)	$= \text{Rating} + \sum\text{Losses} = (247) + (246)$	Rating Plus Losses
— (249)	$\%\ \text{Loss} = \sum\text{Losses} \div \text{Rating} + \sum\text{Losses} = \left[(246) \div (248)\right] \times 100$	Percent Loss
— (250)	$\%\ \text{Efficiency} = 100\% - \%\ \text{Loss} = 100 - (249)$	Percent Efficiency
— (251)	$\text{Watts/In}^2 = \dfrac{W_{TNL} + W_C + \text{Stator } I^2R + \text{Eddy Loss}}{\pi D l}$ $= \dfrac{\left[(214)+(215)+(243)+(244)\right]}{\pi \times (2) \times (3)}$	Stator Watts Per Sq Inch
— (252)	$\text{Watts/In}^2 = \dfrac{\left[W_{PNL} + W_{DNL} + I^2R_R\right]}{\pi_{dr}\, l_p}$ $= \dfrac{\left[(223)+(242)+(245)\right]}{\pi \times (148) \times (52)}$	Rotor Watts Per Sq Inch

W_{TL} (253)	$W_{TL} = \left\{2\left[.27\,X_d\right]^{1.8}+1\right\} W_{TNL} = \left\{2\left[.27 \times \frac{(178)}{100} \times \%\ \text{load}\right]^{1.8}+1\right\}(214)$ Repeat for % load = .25, .50, .75, 1.00, 1.25, 1.50, 2.00	Stator Tooth Loss/Load
K_{SC} (254)	$K_{SC} = f\left[b_0/g\right] = f\left[(11)/(13)\right]$ $= 10^{\{.11022 - .17369 \log[[(11)/(13)]-1]\}}$; if $b_0/g \geq 3.75$ $= 10^{\{.17815 - .33419 \log[[(11)/(13)]-1]\}}$; if $b_0/g < 3.75$	———
— (255)	$= \left[\frac{K_{SC}\, I_{ph}\, n_s}{c\, F_g}\right]^2 + 1 = \left[\frac{(254) \times (19) \times \%\ \text{load} \times (20)}{(21) \times (154)}\right]^2 + 1$ Repeat for % load = .25, .50, .75, 1.00, 1.25, 1.50, 2.00	———
W_{PL} (256)	$W_{PL} = \left\{\left[\frac{K_{SC}\, I_{ph}\, n_s}{c\, F_g}\right]^2 + 1\right\} W_{PNL} = (255) \times (223)$ Repeat for each value of (255) above	Pole Face Loss/Load
W_{DL} (257)	$W_{DL} = \left\{\left[\frac{K_{SC}\, I_{ph}\, n_s}{c\, F_g}\right]^2 + 1\right\} W_{DNL} = (255) \times (242)$ Repeat for each value of (255) above	Damper Loss/Load
— (258)	Change factor 100 in (199) (201) (202) to 400, 200, 133, 80, 67, 50 & repeat (199) to (207) for each factor	———
I_{FL} (259)	$I_{FL} = \frac{\text{Load Ampere Turns}}{N_p}$ $= \frac{(207)_{\text{for each value of (258)}}}{(64)}$	Field Amps/Load
— (260)	Repeat (243) to (252) using values of (253), (255), (256), (257), (259) & % load for each load condition	———

NO LOAD SATURATION

— (261)	Volts $= E_{ph} \times \sqrt{3} \times \% = (25) \times \sqrt{3} \times \%$ [Original Set At .80]	Volts
F_g (262)	$F_g = (154) \times \%$	Air Gap A.T.
B_t (263)	$B_t = (124) \times \%$	Tooth Density
F_t (264)	$F_t =$ Repeat (155) Using Density (263)	A.T. Per Pole For Tooth
B_c (265)	$B_c = (125) \times \%$	Core Density
F_c (266)	$F_c =$ Repeat (156) Using Density (265)	A.T. Per Pole For Coil
— (267)	$F_g + F_s = F_g + F_t + F_c = (262) + (264) + (266)$	Stator Ampere Turns
ϕ_l (268)	$\phi_l = 6.38 \times [(151) + (152) + (153)] \times (267) \times (52)$	Leakage Flux
ϕ_{pt} (269)	$\phi_{pt} = [\% \times (122)] + (268)$	Total Flux Per Pole
B_p (270)	$B_p = (269)/(150)$	Pole Density
F_p (271)	$F_p = F_R =$ Repeat (196) Using Density (270)	Pole Ampere Turns
— (272)	$= F_g + F_s + F_R = (267) + (271)$	No Load Ampere Turns
— (273)	Repeat Steps (261) thru (272) Using % Of .9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6.	_____
— (274)	Repeat Steps (155), (156), (196) Using Opposite Extreme Of Saturation Curve And Then Repeat Steps (261) thru (273).	_____

SALIENT POLE SYNCHRONOUS DESIGN SHEET

STATOR

Punching I.D.	7.25
Punching O.D.	9.25
Core Length	3.0
[illegible] x 2	1.132
Slots	96
Size Slots	.122 x .434
Carter Coeff.	1.082
Type Wdg.	ser. Y
Throw	83.3% 1 - 11
Skew & Dist. Fact.	.995 .958
Chord Fact.	.966
Cond. Per Slot	2
Total Eff. Cond.	184.8
Cond. Size	.075 x .162 SGHF
Cond. Area	.01194
Current Density	6970
Wdg. Const.	.397 C1 1.018
Total Flux	3550
Gap Area	68.4
Gap Density	52.0
Pole Const.	.650
Flux Per Pole	288
Tooth Pitch	.238
Tooth Density	107
Core Density	92
Grade Of Iron	M 22 29 ga.
1/2 Mean Turn	6.99
Res. Per Ph. At	300°F .0391
Eddy Fact. Top	1.185
Eddy Fact. Bottom	1.026
Demag. Fact. Cm	.84 Cq .52
Amp. Cond. Per In.	676
React. Factor	.867
Cond. Perm.	3.56
End Perm.	5.45
Leakage React.	7.8
Air Gap Perm.	152.5
React. Of Arm. Xad	113 Xaq 68.7
Wt. Of Copper	
Wt. Of Iron	

ROTOR

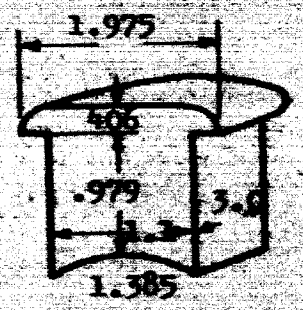
Single Gap	.035 g° .0379
Rotor Diameter	7.18
Peripheral Speed	
Pole Pitch	2.84 α .71
Pole Area	3.12
Side Leakage	.809
End Leakage	.419
Tip Leakage	.655
Leakage Flux	26
Pole Density	99.1
Grade Of Iron	M 36 22 ga.
No. Damper Bars	5
Bar Size	.156 dia.
Bar Pitch	.403 h_o .038 b_o .040
Turns Per Pole	68
Cond. Size	#14 .071 dia.
Cond. Area	SGSF .00322
Mean Turn	10.13
Res. At	300f 1.79
Wt. Of Copper	
Wt. Of Iron	

% Load	0	100	
Amps.	11.6	24.6	
Volts 300°F	20.8	44.0	
Amps/In.^{2}	3600	7650	

Field Leak. React.	14.1
Field Self Induct.	.184
Damp. Leak. XDd	4.30 XDq 5.35

REACT.-TIME CONST.

Synch. Xd	121.0 Xq 76.7
Unsat. Trans.	22.1
Sat. Trans.	19.5
Subtrans. X''d	12.30 X''q 13.35
Neg. Sequence	12.8
Zero Sequence	3.5
Open Circ. Time Con.	300° F .103
Arm. Time Con.	.00234
Trans. Time Con.	.0166
Subtrans. Time Con.	.0065



SATURATION

Air Gap A.T.	618
Stator A.T.	104
Pole A.T.	67
No Load A.T.	789
Rated Load A.T.	1675
Overload A.T.	-
Short Circ. A.T.	748
Short Circ. Ratio	1.055

LOSSES-EFFICIENCY

% Load	0	100	
F & W	137	137	
Sta. Teeth	131	166	
Sta. Core	310	310	
Pole Face	109	131	
Damper	4	5	
Sta. I^2R	-	815	(300°F)
Eddy		87	(300° F)
Rot. I^2R	239	1082	
Σ Losses		2732	
Rating		22500	
Rtg.+Loss		25232	
% Loss		10.8	
% Eff.		89.2	

Stator Watts/In.^{2}	15.8
Rotor Watts/In.^{2}	18.0

Type Cooling Air

30 KVA 75 % PF 208 Volts 83.4 Amps. 3 Ph. 320 Cycles 4800 RPM

Salient Pole A.C. Generator Coding Sheet

1. AAA = 031 for open slots; 038 for partially closed slots.
   BBB = 331 for type a slots; 347 for b; 368 for c; 391 for d; 396 for e.
   CCC = 214 for Δ connection; 216 for Y.
   DDD = 214 for random wound coils; 231 for formed.
   EEE = .5 for 60° belt; .433 for 120° belt.
   FFF = Number of loads.
2. Code all unspecified information as 0.

\# It is not necessary to specify C_1 and L_E unless desired.

* If t_{sk} = 0, use .0001.

p	8
m	3
f	320
RPM	4800
KVA	30
E	208
E_{ph}	120
I_{ph}	83.3
P. F.	.75
% Load	0
	100
	200
FFF	3
d	7.25
D	9.25
l	3.0
K_i-Stat.	.92
watts/lb	15.0
B	77.4
K_i-Rot.	.97

K_1	1.17
AAA	.038
BBB	347
Q	96
b_o	.06
b_1	--
b_2	--
b_s	.122
b_{tm}	.130
h_o	.020
h_1	.364
h_2	--
h_3	--
h_s	.434
h_t	0
h_w	.030
EEE	.5
CCC	216
Std.Dia.or width - s	.075
h_{st}	.162

DDD	231
C_{stator}	1
y_d	10
* t_{sk}	.0001
N_s	2
# C_1	1.018
^oC-S	150
# LE	--
l_{e2}	.25
d_b	.25
N_{st}	1
h'_{st}	.192
b_h	1.975
b_p	1.10
g	.035
gmax	.047
h_f	.979
h_h	.406
l_h	3.0
l_p	3.0
α	.711

b_{bo}	.038
b_{bl}	--
h_{bo}	.040
Bar Dia.or h_{bl}	.156
l_b	3.0
N_b	5
t_b	.403
$p_{damper\ bars}$	1.04
C_{rotor}	1
Cond.Dia. or width-R	.0641
Cond.Thickness-R	--
l_{tr}	10.13
N_p	68
^oC-R	150

Stator - MS 6003 Lower

Rotor - MS 6002 Lower

L-S	2H-C	Q	K-S	CSPAN	K-S-K
$\bar{5}127600000$	$\bar{5}111320000$	$\bar{5}140000000$	$\bar{5}110819184$	$\bar{5}083333333$	$\bar{5}110000000$
K-D	K-P	N-E	A-C	S	C-1
$\bar{5}095766228$	$\bar{5}096592582$	$\bar{5}318545775$	$\bar{4}911357250$	$\bar{5}473345220$	$\bar{5}110180000$
C-W	O-T	GAP-A	B-G	C-P	O-P
$\bar{5}039829606$	$\bar{5}435198354$	$\bar{5}268329800$	$\bar{5}251512449$	$\bar{5}064506489$	$\bar{5}328381527$
T-S	B-T	B-C	L-T	P-PH	EDFTP
$\bar{5}023725625$	$\bar{5}310650982$	$\bar{5}290840653$	$\bar{5}176234816$	$\bar{4}944936752$	$\bar{5}111665678$
EDFBM	C-M	C-Q	A	X	LAM-I
$\bar{5}110237587$	$\bar{5}084061346$	$\bar{5}061960000$	$\bar{5}367826765$	$\bar{5}087586776$	$\bar{5}135308538$
LAM-E	X-L	LAM-A	XAD	XAQ	WT-CU
$\bar{5}154285781$	$\bar{5}178472775$	$\bar{5}315268843$	$\bar{5}311444287$	$\bar{5}282862127$	$\bar{5}153362083$
WT-FE					
$\bar{5}216291560$					
AP	LAMSL	LAMEL	LAMTL	OL	RF
$\bar{5}132010000$	$\bar{5}081010762$	$\bar{5}041800000$	$\bar{5}064863496$	$\bar{5}226681990$	$\bar{5}117862531$
ACR	WTRCU	XF	LF	XDD	XDQ
$\bar{4}832270592$	$\bar{5}157084774$	$\bar{5}213689221$	$\bar{5}018306463$	$\bar{5}143506836$	$\bar{5}156025170$
XD	XQ	X1DU	X1D	X2D	X2Q
$\bar{5}312229014$	$\bar{5}290709404$	$\bar{5}221536498$	$\bar{5}218952118$	$\bar{5}212197961$	$\bar{5}213449794$
X2	XO	T1DO	TA	T1D	T2D
$\bar{5}212823877$	$\bar{5}138050721$	$\bar{5}010248526$	$\bar{4}983412055$	$\bar{4}915882823$	$\bar{4}850000000$
ELL	RPM	PF			
$\bar{5}320800000$	$\bar{5}448000000$	$\bar{5}075000000$			
BT	BC	FG	OL	BP	FNL
$\bar{5}310650982$	$\bar{5}290840653$	$\bar{5}361148253$	$\bar{5}226681990$	$\bar{5}297000081$	$\bar{5}382913190$
RAMPS	RVOLT	ASQIN	F+W	STATH	SCORE
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PLOAD	IPH				
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SI	ED	OLL	OPL	BPL	FFL
5264445009	5120235302	5251562235	5330178991	5311038804	5417205019
FSC	SCR				
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RAMPS	RVOLT	ASQIN	F+W	STATH	SCORE
5225301498	5245194879	5478404195	5334729156	5323477044	5339801866
PFACE	DAMPR	SISQR	EDDY	RISQR	TLOSS
5312684223	5138273880	5393543353	5289018848	5411434981	5432787006
RATNG	RT+LS	PLOSS	PEFF	SWSIN	RWSIN
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PLOAD	IPH				
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SI	ED	OLL	OPL	BPL	FFL
5273145620	5131912234	5277210584	5332752915	5312644165	5428741649
FSC	SCR				
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RAMPS	RVOLT	ASQIN	F+W	STATH	SCORE
5242267130	5275499791	5513097723	5334729156	5335943291	5339801866
PFACE	DAMPR	SISQR	EDDY	RISQR	TLOSS
5319317758	5158290174	5437417341	5335607539	5431911593	5485927182
RATNG	RT+LS	PLOSS	PEFF	SWSIN	RWSIN
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481	0354851898	1899898883	0203000530	3898896000	2883000000	3817000885
487	1897734000	3876000000	1877000898	3883875000	1898000898	1875878000
493	4898000000	3846000884	1000885852	4000842886	9000886603	9002951601
499	0005628501	0203000607	3874630853	1898000887	3854875892	0203000505

505	4881000893	0481700701	3907909899	9000909898	0480898899	0481565570
511	0480882887	0481563564	0480892893	0203000534	0000000000	3984984892
517	3984788898	3554974000	1000898000	3000991898	2000892000	4898000000
523	3803000892	0203000305	9002854555	3555909555	3556909556	1899556899
529	0203000475	9000833554	3554909554	3751554898	0203000484	0500550887
535	0203000214	3630948876	9000820603	0005628030	0203000926	6989000543
541	9000742863	0203000404	0203000544	0203000516	3000899000	4000993000
547	4000993000	0203000051	4863800000	4881997899	3000993856	0203000218
553	4200000000	5144400000	0000000000	0000000000	4157000000	5341546253
559	5341544553	5341546353	5653000000	5946000000	4662430000	6243590000
565	6249000000	4544000000	5653530000	5657530000	4257530000	4646530000
571	5941635547	5963105362	5753566262	5745464600	6266624955	5966624955
577	5746414345	4441545759	6249625859	4544446800	5949625859	6353566262
583	5941545762	5965565363	4162584955	4610660000	6263416348	6243565945
589	4263000000	4243000000	4647000000	5653000000	4257000000	4655530000
595	4553530000	5957540000	5746000000	5033419000	5017815000	0000000000
601	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
607	2603601000	0201632609	9000742606	2606603000	0201615612	1606737606
613	0600602005	0203000610	0205623616	2616207160	2312160230	0005261621
619	9160232616	0441000026	1605410000	4901012000	2606603000	4000737629
625	2604605000	3000629000	2604000630	0203000000	0000000000	0000000000
631	0000000000	0481553553	0480603603	0480628628	0000000000	0205001696
637	3216435000	0011163760	0010141637	6170054716	3700120049	0101200000
643	0000051105	5111351120	5112751135	5114751156	5117051185	5120051220
649	5124051265	5129051320	5135051390	5143551490	5155551630	5172051830
655	5198052115	5214052175	5222552310	5244052640	5288053115	5315053185
661	5322553270	5332053370	5341553470	5352053590	5365000000	0000000000
667	0000000000	0000000000	0000000000	0000000000	0000051225	5126051280

673	5130051320	5133551360	5138051410	5143051460	5149051530	5157051610
679	5165051710	5177051840	5191052100	5211052124	5213852155	5217852205
685	5224052285	5234552430	5256052750	5310253133	5317053218	5326453315
691	5337053430	5351053600	0000000000	0000000000	0000000000	3216372000
697	0032164010	0000491637	0000000000	5753564144	4957480000	4143590000
703	6663594364	6746000000	5346000000	6744440000	6744580000	6744000000
709	6758000000	6771446400	6771440000	6772440000	6772580000	6772000000
715	6756000000	6371445600	6341000000	6371440000	6372440000	5120000000
721	5050000000	5131415926	5025000000	5218000000	4831900000	5140000000
727	5163800000	5323450000	5333450000	4491000000	5032100000	5115000000
733	5142500000	5110000000	4310000000	5062000000	5130000000	5220000000
739	5088000000	5066700000	4970000000	0000000000	5116670000	5020000000
745	5410000000	5115707963	5320000000	4935000000	4850000000	5310000000
751	4893000000	4525200000	5125000000	4661000000	5045300000	5114200000
757	4615147000	5116500000	5260000000	5090000000	5112850000	5081000000
763	5079000000	5111450000	5092000000	5117000000	5150000000	5030000000
769	5123100000	5035000000	5062500000	5114000000	5113800000	5096500000
775	5023200000	5093230000	5116059600	5135000000	5210000000	5055800000
781	5059000000	5011022000	5032000000	5128750000	4925000000	5015000000
787	0000000000	5075000000	5316300000	5110500000	5023000000	5210461503
793	5120954423	4812460000	5117320508	5027000000	5118000000	5137500000
799	5017369000	0000000000	0000000000	0000000000	0000000000	0000000000
805	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
811	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
817	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
823	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
829	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
835	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000

841	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
847	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
853	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
859	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
865	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
871	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
877	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
883	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
889	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
895	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
901	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
907	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
913	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
919	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
925	0000000000	9002946601	0203000607	0000000000	0000000000	0000000000
931	0000000000	0000000000	0000000000	0000000000	0000000000	6990000336
937	2987985000	0203000335	0000000000	0000000000	0000000000	0000000000
943	0000000000	0000000000	0000000000	5313200000	6434000000	0000000000
949	0000000000	0000000000	5312600000	6714000000	0000000000	0000000000
955	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
961	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
967	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
973	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
979	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
985	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
991	0000000000	0000000000	0000000000	0000000000	0000000000	0000000000
997	0000000000	0000000000	6249550000			

$\bar{0}10$ $\bar{6}9890000014$ $\bar{9}000742853$ $\bar{9}000742852$ $\bar{0}203000106$ $\bar{6}985000079$ $\bar{9}000736899$
$\bar{0}16$ $\bar{0}203000081$

$\bar{0}01$ $\bar{6}886000004$ $\bar{9}000742890$ $\bar{0}203000145$ $\bar{2}804740000$ $\bar{0}201128131$ $\bar{0}203000128$

$\bar{0}20$ $\bar{2}893030000$ $\bar{0}201025022$ $\bar{3}779893000$ $\bar{0}352000000$ $\bar{0}203000309$ $\bar{3}893031000$
$\bar{0}26$ $\bar{1}000032893$ $\bar{0}203000311$ $\bar{9}000359884$ $\bar{0}203000365$ $\bar{5}065000000$ $\bar{5}026600000$
$\bar{0}32$ $\bar{5}032270000$ $\bar{5}037000000$

TABLE 2 – VALUES OF K_{dn} FOR INTEGRAL SLOT 3φ WINDINGS

n	K_{dn} – HARMONIC DISTRIBUTION FACTORS									
q=	2	3	4	5	6	7	8	9	10	∞
1	.966	.960	.958	.957	.957	.957	.956	.955	.955	.955
3	.707	.667	.654	.646	.644	.642	.641	.640	.639	.636
5	.259	.217	.205	.200	.197	.195	.194	.194	.193	.191
7	−.259	−.177	−.158	−.149	−.145	−.143	−.141	−.140	−.140	−.136
9	−.707	−.333	−.270	−.247	−.236	−.229	−.225	−.222	−.220	−.212
11	−.966	−.177	−.126	−.110	−.102	−.097	−.095	−.093	−.092	−.087
13	−.966	.217	.126	.102	.092	.086	.083	.081	.079	.073
15	−.707	.667	.270	.200	.172	.158	.150	.145	.141	.127
17	−.259	.960	.158	.102	.084	.075	.070	.066	.064	.056
19	.259	.960	−.205	−.110	−.084	−.072	−.066	−.062	−.060	−.059
21	.707	.667	−.654	−.247	−.172	−.143	−.127	−.118	−.112	−.091
23	.966	.217	−.958	−.149	−.092	−.072	−.063	−.057	−.054	−.041
25	.966	−.177	−.958	.200	.102	.075	.063	.056	.052	.038
27	.707	−.333	−.654	.646	.236	.158	.127	.111	.101	.071
29	.259	−.177	−.205	.957	.145	.086	.066	.056	.050	.033
31	−.259	.217	.158	.957	−.197	−.097	−.070	−.057	−.050	−.031
33	−.709	.667	.270	.696	−.644	−.229	−.150	−.118	−.101	−.058
35	−.966	.960	.126	.200	−.957	−.143	−.083	−.062	−.052	−.027
37	−.966	.960	−.126	−.149	−.957	.195	.095	.066	.054	.026
39	−.707	.667	−.270	−.247	−.644	.642	.225	.145	.112	.049
41	−.259	.217	−.158	−.110	−.197	.957	.141	.081	−.060	.023
43	.259	−.177	.205	.102	.145	.957	−.194	−.093	−.064	−.022
45	.707	−.333	.654	.200	.236	.642	−.641	−.222	−.141	−.042
47	.966	−.177	.958	.102	.102	.195	−.956	−.140	−.079	−.020
49	.966	.217	.958	−.110	−.092	−.143	−.956	.194	.092	.019
51	.707	.667	.654	−.247	−.172	−.229	−.641	.640	.220	.038
53	.259	.960	.205	−.149	−.084	−.097	−.194	.955	.140	.018
55	−.259	.960	−.158	.200	.084	.086	.141	.955	−.193	−.017
57	−.707	.667	−.270	.646	.172	.158	.225	.640	−.639	−.033
59	−.966	.217	−.126	.957	.092	.075	.095	.194	−.955	−.016
61	−.966	−.177	.126	.957	−.102	−.072	−.083	−.140	−.955	.016
63	−.707	−.333	.270	.646	−.236	−.143	−.150	−.222	−.639	.030
65	−.259	−.177	.158	.200	−.145	−.072	−.070	−.093	−.193	.015

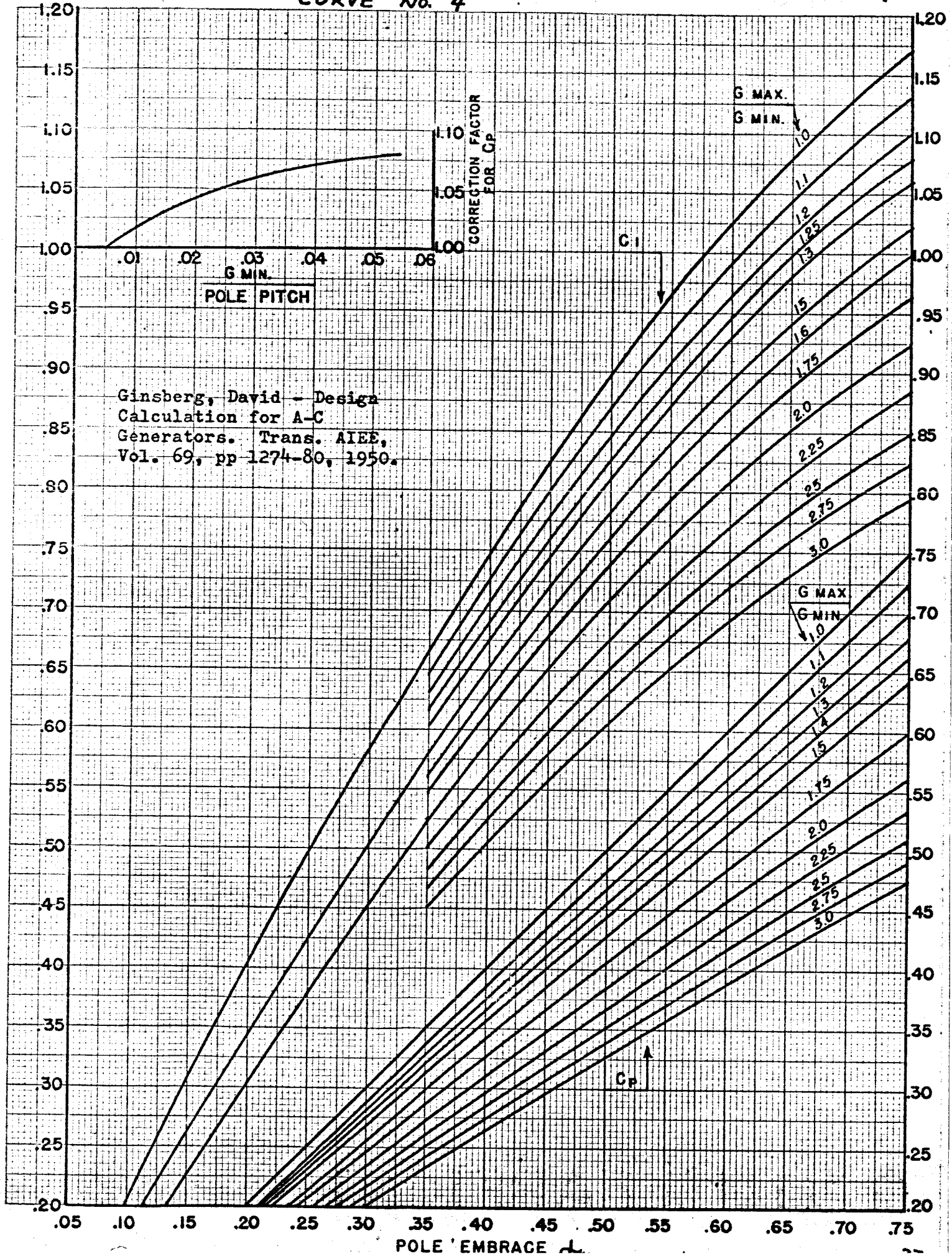
Chord Factors K_p For Harmonics At Different Pitches — Table I.

P_n																																				
P_m													9/mg																							
1	3/3																														2/3					
2	6/6															5/6															4/6					
3	9/9											8/9								7/9											6/9					
4	12/12							11/12								10/12							9/12								8/12					7/12
5	15/15						14/15							13/15					12/15						11/15						10/15				9/15	
6	18/18					17/18							16/18				15/18				14/18					13/18					12/18					
7	21/21				20/21				19/21					18/21				17/21						16/21				15/21			14/21					
8	24/24			23/24				22/24				21/24				20/24				19/24					18/24				17/24			16/24		15/24		14/24
9	27/27		26/27				25/27				24/27				23/27		22/27				21/27				20/27					19/27			18/27		17/27		16/27
10	30/30	29/30				28/30				27/30			26/30			25/30			24/30				23/30			22/30					21/30	20/30	19/30			18/30	
P_m	1.0	957	914	959	952	945	934	926	917	905	903	889	875	867	857	852	833	815	810	800	792	777	767	762	750	741	729	722	712	709	705	700	667	639	630	625	600	592	584
1	1.0	999	998	998	997	996	995	993	991	989	988	985	981	978	975	973	966	958	956	951	947	940	935	931	927	918	914	906	901	897	894	891	866	837	835	831	809	800	793
3	1.0	983	935	981	975	966	951	940	929	901	891	865	831	809	732	766	707	643	623	583	556	500	454	434	383	342	309	259	222	195	174	156	0.0	156	174	195	309	342	383
5	1.0	966	958	947	931	906	866	835	793	733	707	643	559	500	434	376	259	116	075	0.0	065	174	259	342	383	447	500	574	623	660	690	707	866	966	974	982	1.0	993	993
7	1.0	943	918	897	866	819	743	686	609	500	454	342	177	105	0.0	053	259	449	500	583	659	766	837	866	924	958	978	996	1.0	998	993	988	866	629	583	559	309	225	139
9	1.0	897	866	831	782	707	588	500	383	223	156	0.0	191	304	434	500	707	866	901	951	981	1.0	998	975	924	866	804	707	623	556	500	454	0.0	356	407	462	500	755	875
11	1.0	834	802	750	680	574	407	287	131	075	156	342	556	660	782	795	966	998	989	951	897	766	669	583	383	231	105	087	222	321	396	454	866	977	974	931	809	721	618
13	1.0	777	727	659	563	423	208	058	131	365	454	643	831	914	975	993	966	802	733	583	442	174	052	148	383	550	669	818	901	947	973	988	866	371	291	195	309	459	598
15	1.0	707	643	556	434	259	0.0	174	383	624	707	866	981	1.0	975	940	707	342	223	0.0	195	500	707	782	921	981	1.0	996	907	831	766	707	0.0	696	760	831	1.0	982	930
17	1.0	629	550	442	295	087	208	396	609	826	891	985	981	914	782	685	259	231	365	588	752	940	999	997	924	802	669	423	222	065	058	156	866	940	818	831	309	100	113
19	1.0	545	449	321	149	087	407	597	793	956	903	985	831	669	434	287	259	727	826	951	998	940	777	690	383	116	105	423	623	752	835	891	866	072	017	174	809	952	989
21	1.0	454	342	195	0.0	259	588	766	924	1.0	988	866	556	309	0.0	174	707	985	1.0	951	831	500	156	0.0	383	643	804	966	1.0	981	940	891	0.0	881	935	981	809	628	402
23	1.0	358	231	064	149	423	743	894	991	956	891	643	195	105	434	597	966	918	826	583	321	174	545	688	924	998	978	819	623	442	287	156	866	792	696	555	309	566	778
25	1.0	258	116	064	295	574	866	973	991	826	707	342	195	500	782	894	966	550	365	0.0	321	766	966	997	924	727	500	087	222	442	597	707	866	061	383	555	1.0	951	809
27	1.0	170	0.0	195	434	707	951	1.0	924	624	454	0.0	556	809	975	1.0	707	0.0	223	558	831	1.0	847	782	383	0.0	305	707	901	981	1.0	928	0.0	983	1.0	981	309	025	356
29	1.0	052	116	321	563	819	995	973	743	365	156	342	831	978	975	894	259	550	733	951	948	766	398	148	383	727	914	996	901	752	597	454	866	569	412	194	809	965	945
31	1.0	052	231	442	680	906	995	894	109	075	156	643	981	978	782	597	259	918	989	951	752	174	398	503	924	998	914	574	222	065	287	454	866	517	673	831	809	525	162
33	1.0	156	342	556	782	966	951	766	383	223	454	866	981	807	434	174	707	985	901	588	195	500	891	975	924	643	309	259	623	831	940	988	0.0	992	940	831	309	666	910
35	1.0	259	449	659	866	996	865	597	131	500	707	985	831	500	0.0	287	966	727	500	0.0	942	940	966	866	383	116	500	936	1.0	947	835	707	866	294	017	194	1.0	905	637
37	1.0	358	550	750	931	996	743	396	131	793	891	935	556	105	434	686	966	231	075	588	897	940	545	575	383	802	978	906	623	321	058	156	866	855	834	981	309	150	577
39	1.0	454	643	831	975	966	588	174	383	901	988	866	195	309	782	940	707	342	623	951	981	500	156	434	924	985	809	259	222	556	766	891	0.0	909	780	555	805	990	939
41	1.0	545	727	897	997	906	407	058	609	981	988	643	195	669	975	933	259	802	956	951	659	174	777	931	924	550	105	574	901	998	973	841	866	010	264	555	809	414	088
43	1.0	629	802	947	997	819	208	287	793	989	891	342	556	914	975	795	259	918	956	588	065	766	947	931	383	231	669	996	901	660	346	156	866	916	990	981	309	754	984
45	1.0	707	866	987	925	707	0.0	500	924	901	707	0.0	831	1.0	782	500	707	866	623	0.0	556	1.0	707	434	383	866	1.0	707	222	145	500	707	0.0	739	523	194	1.0	844	262
47	1.0	777	918	998	931	574	208	686	991	733	454	342	901	914	434	058	966	449	075	588	947	766	052	275	924	958	669	087	623	847	993	988	866	312	575	831	305	273	762
49	1.0	834	958	998	866	423	407	835	991	500	156	643	981	669	0.0	376	966	116	500	951	947	174	629	866	224	597	105	819	1.0	847	690	454	866	994	979	831	809	1.0	823
51	1.0	891	985	981	782	259	588	940	924	223	156	866	831	309	434	766	707	643	901	951	556	500	988	975	383	342	809	966	623	195	174	454	0.0	501	203	194	805	297	333
53	1.0	934	998	947	680	087	743	993	793	075	454	985	556	105	782	973	259	958	989	588	065	940	839	583	383	918	978	423	222	660	894	988	866	585	818	981	309	721	997
55	1.0	966	998	897	563	087	866	993	605	365	707	985	195	500	975	973	259	958	733	0.0	659	940	259	148	924	918	500	423	901	998	894	707	866	979	853	555	1.0	771	187
57	1.0	988	985	831	434	255	951	940	383	624	891	866	195	809	975	766	707	643	223	588	981	500	454	782	924	342	309	966	901	556	174	156	0.0	215	141	555	309	407	899
59	1.0	999	958	756	295	423	995	835	131	826	988	643	556	978	782	396	966	116	365	951	897	174	934	997	383	597	914	819	222	321	698	891	866	863	965	981	809	994	777
61	1.0	995	978	659	149	574	995	686	131	956	983	342	831	978	434	058	966	449	826	951	442	766	934	680	383	958	914	087	623	947	993	891	866	872	625	194	809	175	557
63	1.0	989	866	556	0.0	707	051	500	383	1.0	891	0.0	981	809	0.0	500	707	866	1.0	588	195	1.0	454	0.0	924	866	309	707	1.0	831	500	156	0.0	691	468	831	309	894	947
65	1.0	966	802	442	149	814	866	207	609	956	707	342	981	500	434	795	259	998	826	0.0	752	766	259	680	924	231	500	996	623	065	346	707	866	946	997	831	1.0	689	063

Round Copper Wire

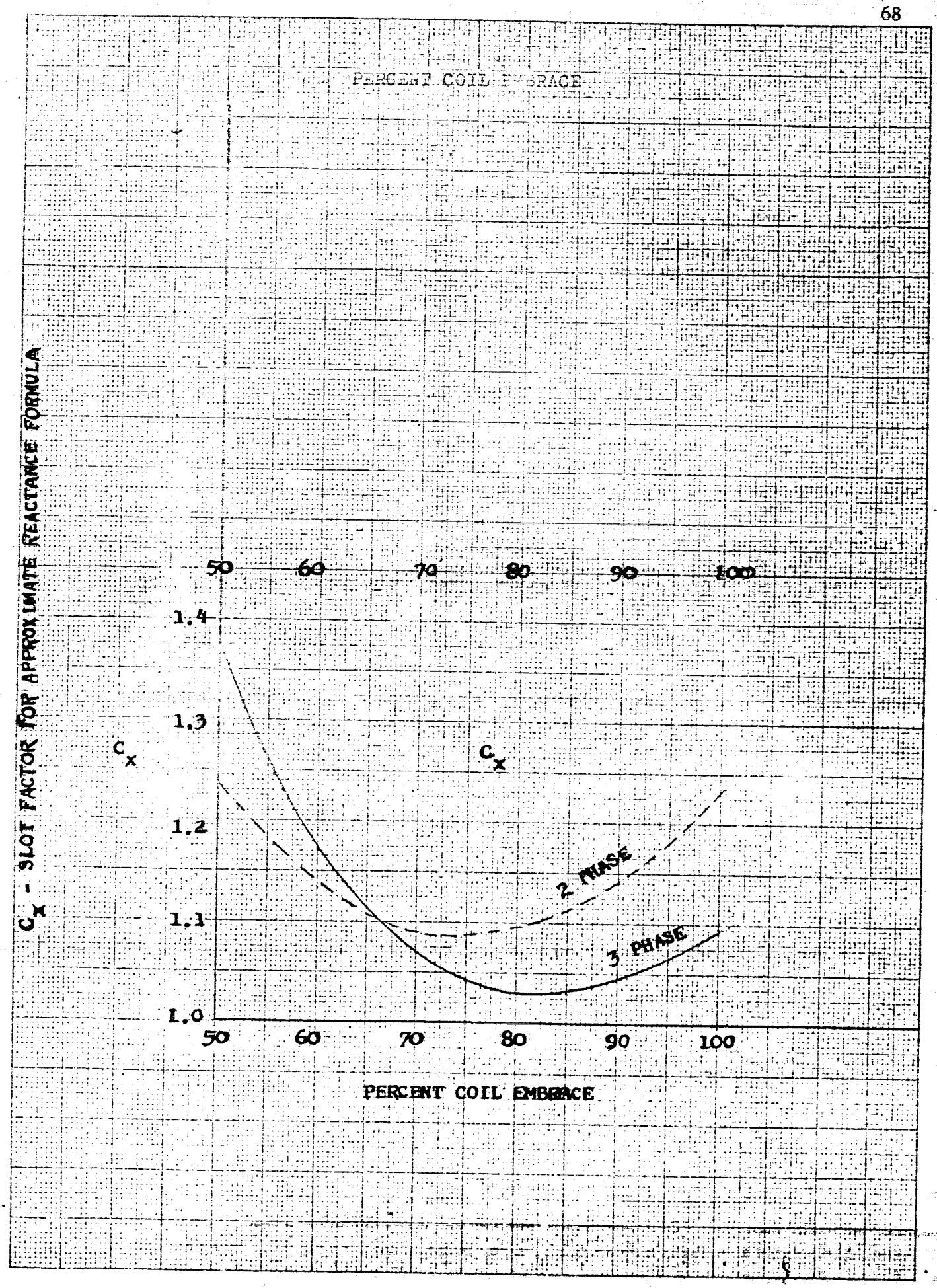
Size AWG	Bare Diameter	Area □"	Ω/1000' @25°C	Single Formvar	Heavy Formvar	Single Glass Formvar	Bare Wt. #/1000'	Single Glass Silicone	Double Glass Silicone
36	.0050	.0000196	424	.0056	.0060		.0757		
35	.0056	.0000246	338	.0062	.0066		.0949		
34	.0063	.0000312	266	.0070	.0074		.1201		
33	.0071	.0000396	210	.0079	.0084		.1526		
32	.0080	.0000503	165	.0088	.0094	.0121	.1937		
31	.0089	.0000622	134	.0097	.0104	.0130	.2398		
30	.0100	.0000785	106	.0108	.0116	.0142	.3025	.0132	.0152
29	.0113	.000100	83.1	.0122	.0130	.0156	.3866	.0145	.0165
28	.0126	.000125	66.4	.0135	.0144	.0169	.4806	.0158	.0178
27	.0142	.000158	52.6	.0152	.0161	.0186	.6101	.0174	.0194
26	.0159	.000199	41.7	.0169	.0179	.0203	.7650	.0191	.0211
25	.0179	.000252	33.0	.0190	.0200	.0224	.970	.0211	.0231
24	.0201	.000317	26.2	.0213	.0223	.0263	1.223	.0251	.0276
23	.0226	.000401	20.7	.0238	.0249	.0289	1.546	.0276	.0301
22	.0254	.000507	16.4	.0266	.0277	.0317	1.937	.0303	.0328
21	.0285	.000638	13.0	.0299	.0310	.0349	2.459	.0335	.0360
20	.0320	.000804	10.3	.0334	.0346	.0384	3.099	.0370	.0395
19	.0360	.00102	8.14	.0374	.0386	.0424	3.900	.0409	.0434
18	.0403	.00126	6.59	.0418	.0431	.0468	4.914	.0453	.0478
17	.0453	.00159	5.22	.0469	.0482	.0519	6.213	.0503	.0528
16	.0508	.00204	4.07	.0524	.0538	.0575	7.812	.0558	.0583
15	.0571	.00255	3.26	.0588	.0602	.0639	9.87	.0621	.0646
14	.0641	.00322	2.58	.0659	.0673	.0710	12.44	.0691	.0716
13	.072	.00407	2.04	.0738	.0753	.0789	15.69	.0770	.0795
12	.0808	.00515	1.61	.0827	.0842	.0877	19.76	.0858	.0883
11	.0907	.00650	1.28	.0927	.0942	.0977	24.90	.0957	.0982
10	.102	.00817	1.02	.1039	.1055	.1089	31.43	.1069	.1094
9	.114	.0102	.814	.1165	.1181	.1225	39.62	.1204	.1254
8	.129	.0131	.634	.1306	.1323	.1366	49.98	.1345	.1395
7	.144	.0163	.510	.1465	.1482	.1525	63.03	.1503	.1553
6	.162	.0206	.403	.1643	.1661	.1703	79.44	.1680	.1730
5	.182	.0260	.319	.1842	.1861	.1902	100.2	.1879	.1929
4	.204	.0327	.254				126.3	.2103	.2153
3	.229	.0412	.202				159.3		
2	.258	.0523	.159				200.9		
0	.325	.0830	.100						
2/0	.365	.105	.0791						
4/0	.460	.166	.0500						

CURVE No. 4

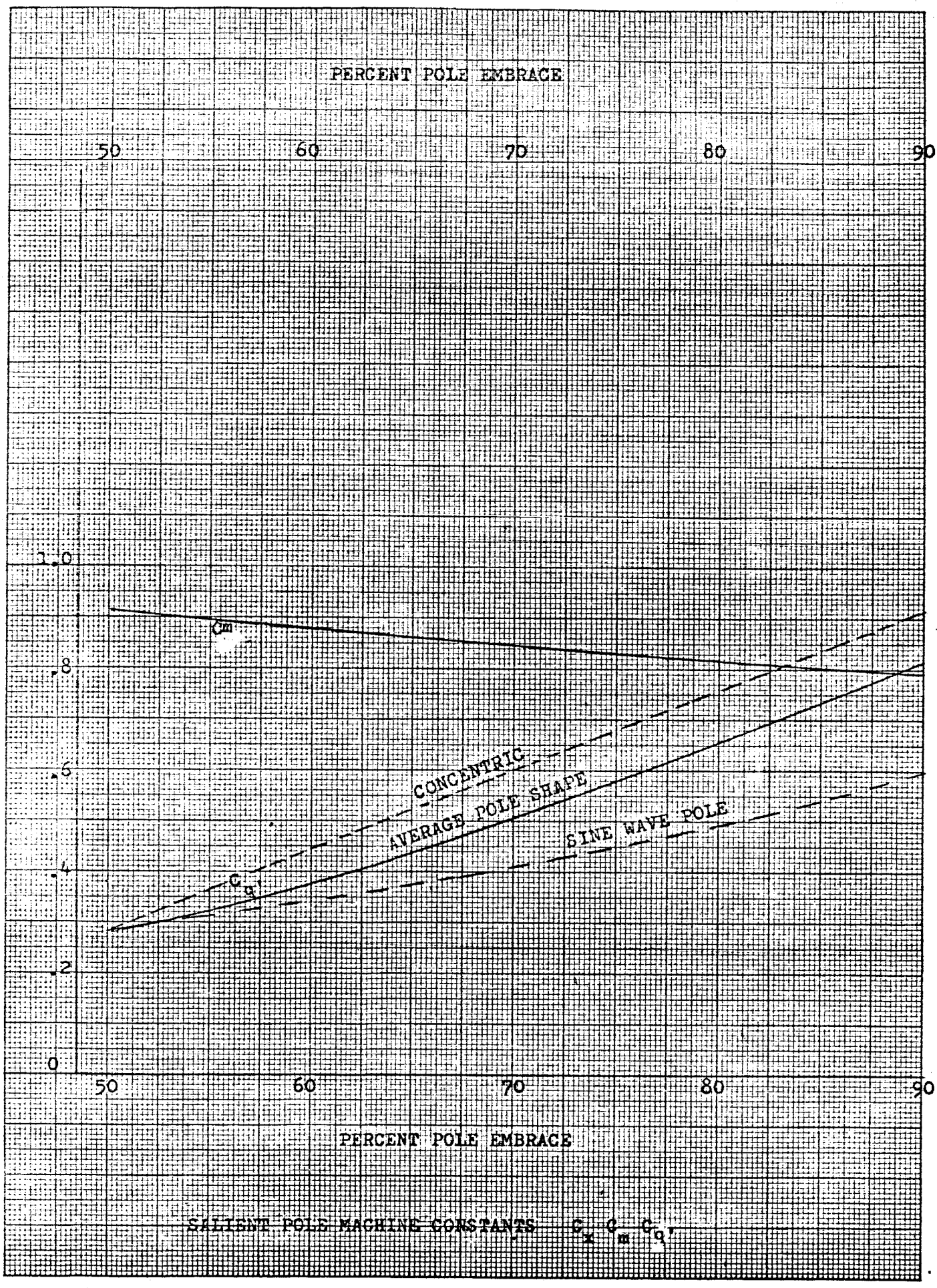


Ginsberg, David – Design Calculation for A-C Generators. Trans. AIEE, Vol. 69, pp 1274-80, 1950.

E. K. ELLIOTT COMPANY PITTSBURGH. DETROIT. CLEVELAND
"PRECISION" TRADE MARK
NO. 7 20 X 20 TO 1 INCH



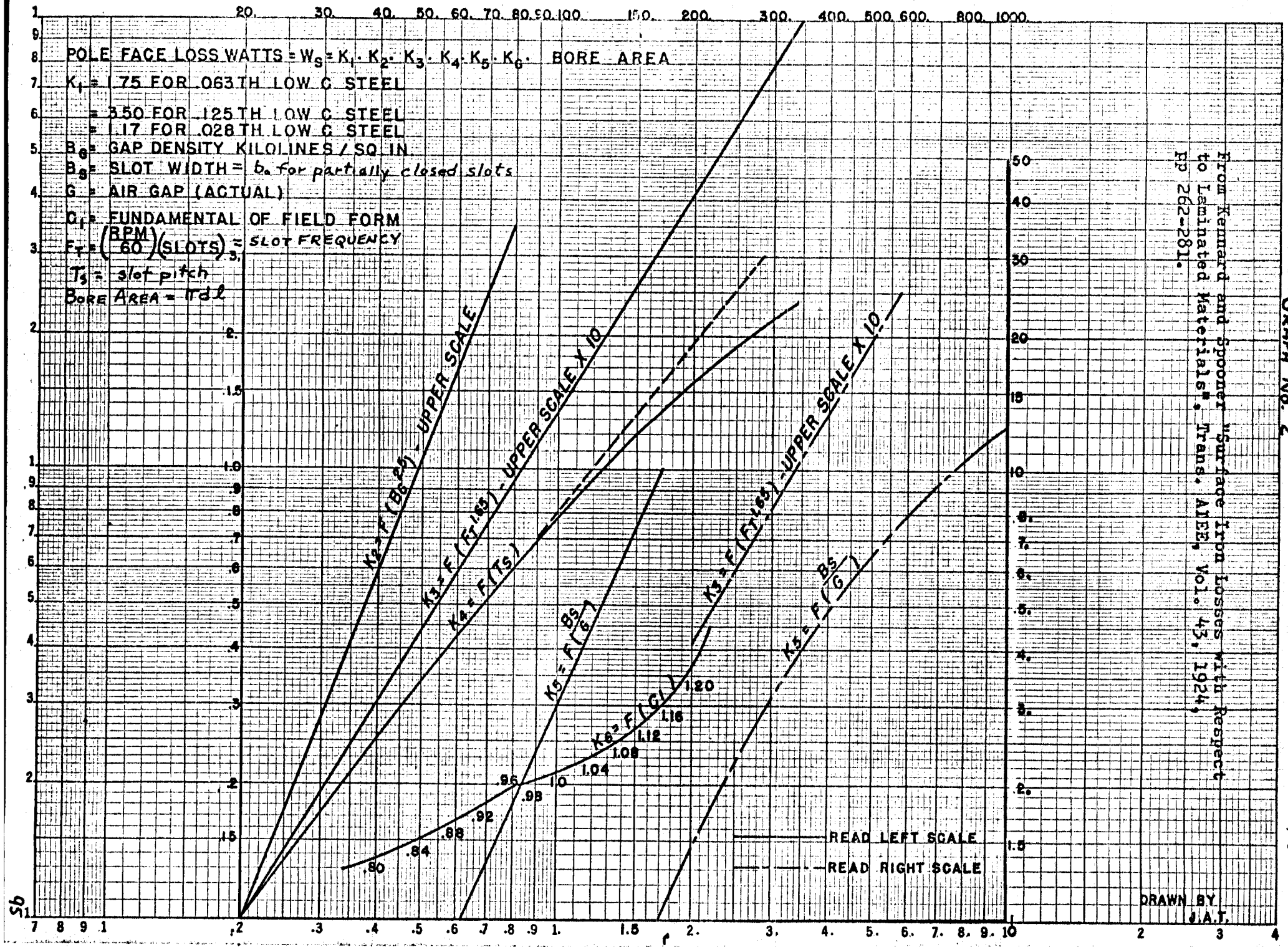
K&E 10 X 10 TO THE CM. 359-14 KEUFFEL & ESSER CO. MADE IN U.S.A.



SALIENT POLE MACHINE CONSTANTS C_x C_m $C_{q'}$

K&E 10 X 10 TO THE CM. 359-14 KEUFFEL & ESSER CO. MADE IN U.S.A.

KEUFFEL & ESSER CO., N. Y. NO. 359-111
Logarithmic, 2¾ × 2 Cycles.
MADE IN U. S. A.



From Kennard and Spooner "Surface Iron Losses with Respect to Laminated Materials", Trans. AIEE, Vol. 43, 1924, pp 262-281.

GRAPH No. 2

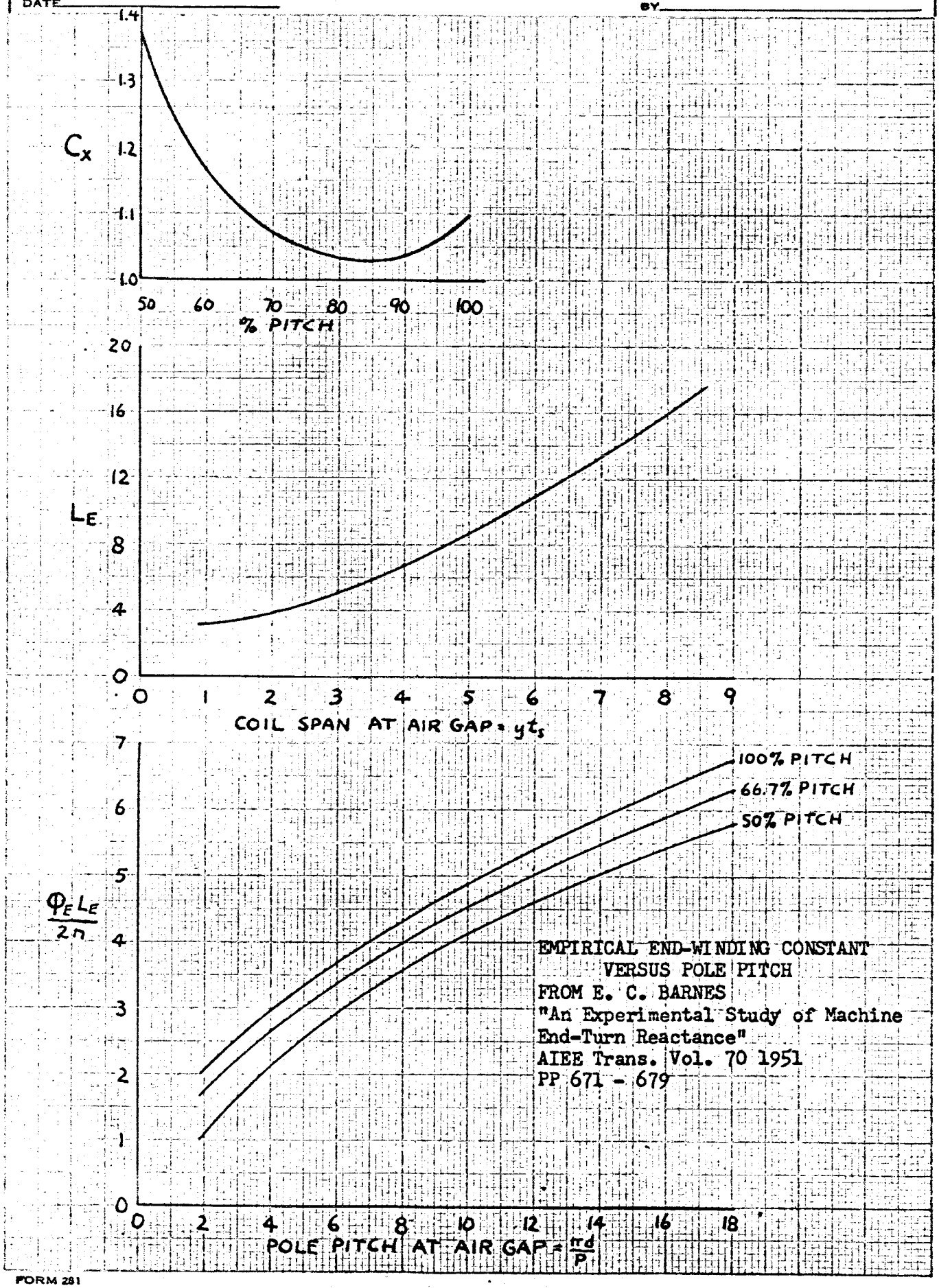
GRAPH NO. 1

E. W. O. REP'T NO.

SHOWING

DATE

BY



EMPIRICAL END-WINDING CONSTANT VERSUS POLE PITCH
FROM E. C. BARNES
"An Experimental Study of Machine End-Turn Reactance"
AIEE Trans. Vol. 70 1951
PP 671 - 679

FORM 281

NO LOAD DAMPER LOSS

$$D.L. = \frac{1.246 P n_b l_b \rho}{10^6 a_b}\left[\tau_s B_g K_p K_g\right]^2\left[K_{f1}\left(\frac{K_{w1}}{2\lambda_s + \frac{\lambda_g}{K_{\phi 1}}}\right)^2 + K_{f2}\left(\frac{K_{w2}}{2\lambda_s + \frac{\lambda_g}{K_{\phi 2}}}\right)^2\right]$$

= LOSS IN KW

$$\lambda_s = \frac{h_r}{b_r} + \lambda_t + \lambda_c$$

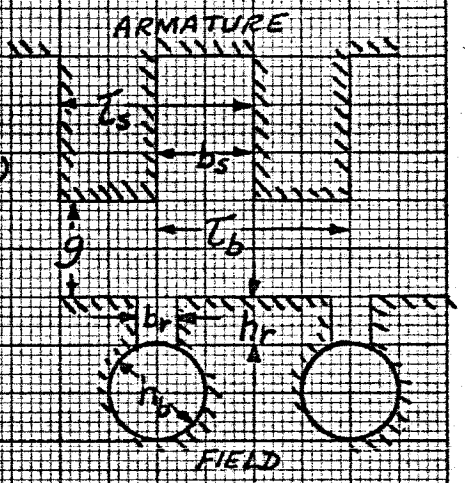
$$\lambda_g = \frac{\tau_b}{K_g g} = \frac{\tau_b}{g'}$$

a_b = BAR AREA IN SQ IN.
n_b = BARS/POLE
P = NO. POLES
l_b = LENGTH BAR IN.

K_g = CARTER'S COEFFICIENT (TOTAL)
$K_p = f_n(b_s/g)$, CURVE (a) ($b_s = b_o$ for partially closed slots)
K_{f1} AND $K_{f2} = f_n(f_s/\rho)$ CURVE (b)
ρ = DAMPER BAR RESISTIVITY (MICROHMS PER CU. IN.)

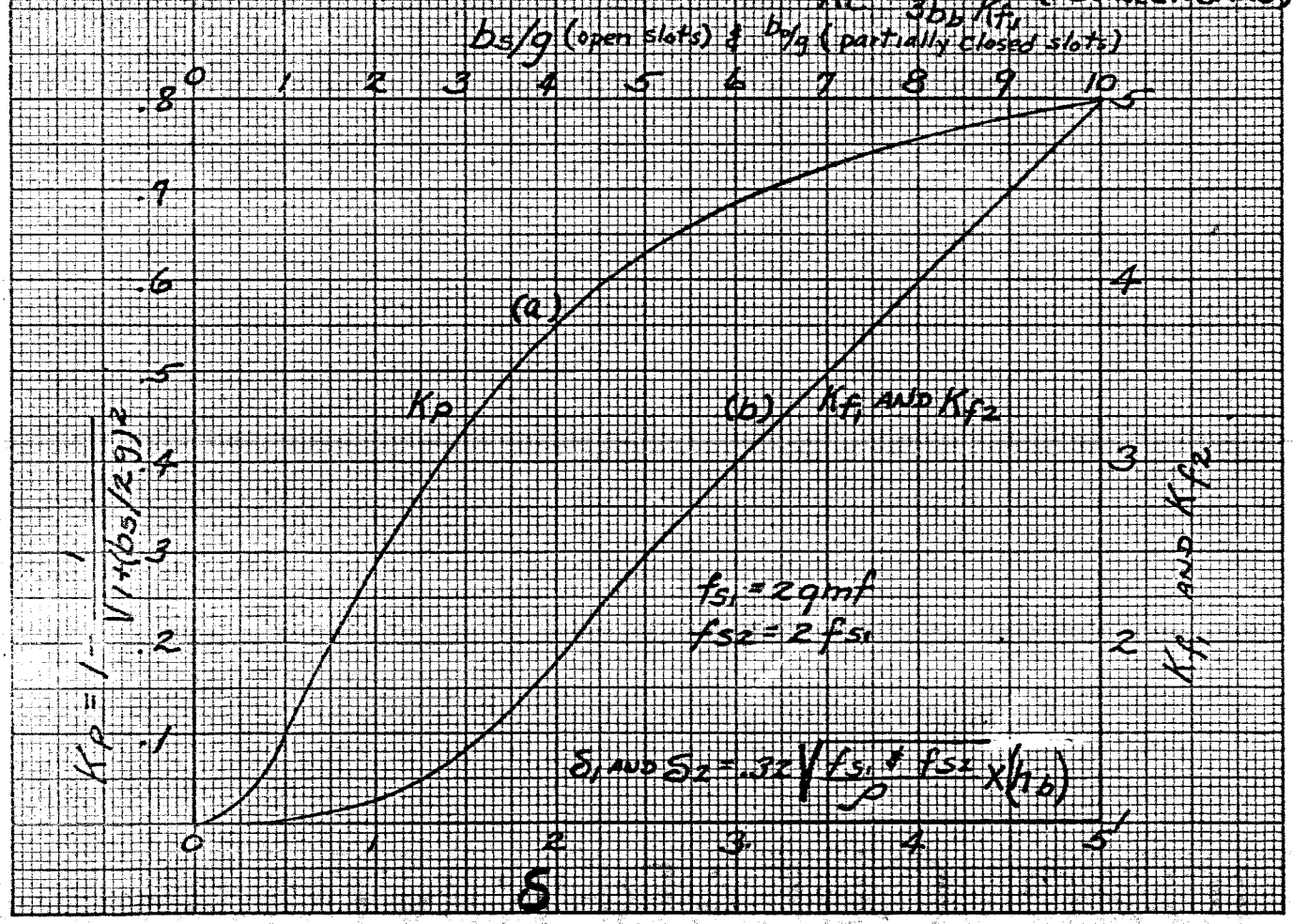
K_{w1} AND $K_{w2} = f_n(b_s/\tau_s)$, CURVE (c_1) AND (c_2)
$K_{\phi 1}$ AND $K_{\phi 2} = f_n(\tau_b/\tau_s)$, CURVE ($d_1$) AND ($d_2$)

$\lambda_t = f_n(b_r/g K_g)$ CURVE (e)
B_g IS IN KILOLINES PER SQ INCH



$$\lambda_c = \frac{.75}{K_{f1}} \text{ (FOR ROUND OR SQ. BARS)}$$

$$\lambda_c = \frac{h_b}{3 b_b K_{f1}} \text{ (FOR RECT. BARS)}$$

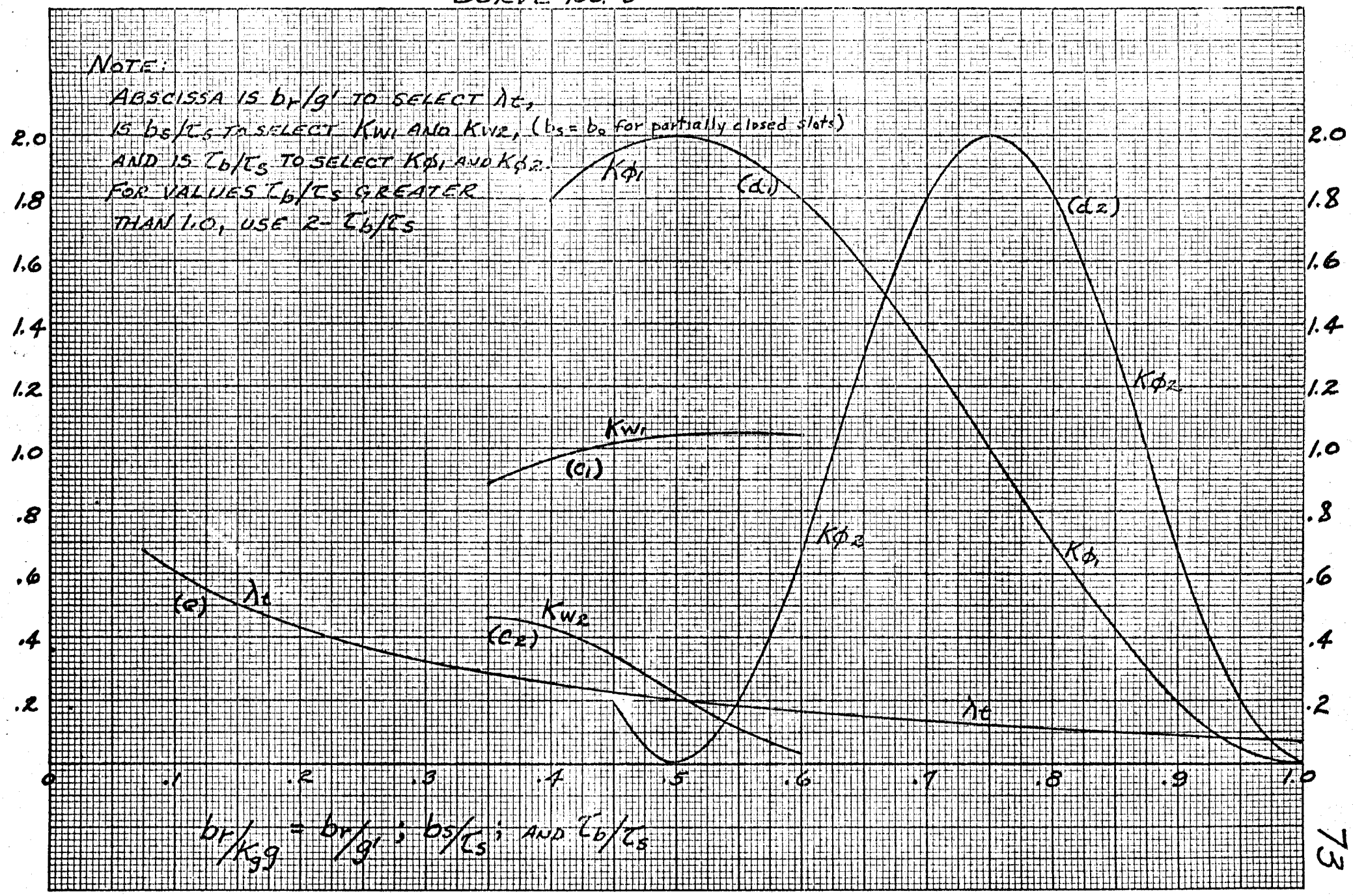


From E. I. Pollard "Calculation of No-Load Damper Winding Loss in Synchronous Machines", AIEE Vol. 51, 1932, pp 477-81.

KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 X 10 to the ½ inch, 5th lines accented
MADE IN U.S.A.

KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 × 10 to the ½ inch, 5th lines accented
MADE IN U. S. A.

CURVE NO. 8



STATOR

PUNCHING I. D. --(d) The inside diameter of the stator punchings.

PUNCHING O. D. --(D) The outside diameter of the stator punchings.

CORE LENGTH -(ℓ) The overall length of the stator iron. Also record on this line the solid core length (ℓ_s). The solid length is the overall length times the stacking factor (K_i). The stacking factor allows for the coating on the punchings, the burrs due to slotting, and the deviations in flatness. Approximate values of K_i are given in the table below.

THICKNESS OF LAMINATIONS (INCHES)	GAGE	K_i
.014	29	0.92
.018	26	0.93
.025	24	0.95
.028	23	0.97
.063	--	0.98
.125	--	0.99

If ventilating ducts are used their length must be subtracted from the overall length also.

DEPTH BELOW SLOTS x 2--($2h_c$) The depth of the stator core below the slots times 2.

$$2h_c = D = (d+2h_s)$$

Due to mechanical strength reasons h_c should never be less than 70% of h_s.

SLOTS--(Q) The number of stator slots. Write Q as a product of poles (p) times phases (m) times slots per phase per pole (q). Thus pmq = Q. In general fractions of q close to 1/3 and 2/3 should be avoided, because these fractions are inclined toward producing force poles that cause excessive noise and vibration. In three phase machines fractions of q with thirds or any multiple of three in the denominator should be avoided because with these values a balanced winding cannot be obtained.

SIZE SLOTS--(b_s and h_s) The width of the stator slot (b_s) and the depth of the stator slot (h_s).

CARTER COEFFICIENT--(K_s) The Carter coefficient for the stator slots.

$$K_s = \frac{t_s(5g+b_s)}{t_s(5g+b_s)-b_s^2} \quad \text{(for open slots)}$$

$$K_s = \frac{t_s(4.44g+.75b_o)}{t_s(4.44g+.75b_o)-b_o^2} \quad \text{(for partially closed slots)}$$

TYPE WINDING-- Record whether star or delta (Y or Δ), and whether series or parallel.

THROW--(y) The coil span in slots. Record the percent span (y/mq) and designate the slots in which the coil is placed (1 + y).

SKEW AND DISTRIBUTION FACTORS--(K_{sk} and K_d) The skew factor (K_{sk}) is the ratio of the voltage induced in the coils to the voltage that sould be induced if there was no skew.

OR $$K_{sk} = \frac{\sin \frac{t_{sk}\pi}{2t_p}}{\frac{t_{sk}\pi}{2t_p}}$$

The distribution factor (K_d) is the ratio of the voltage induced in the coils to the voltage that would be induced if the winding was concentrated in a single slot

$$K_d = \frac{\sin(q\alpha_{s/2})}{q \sin\alpha_{s/2}} \quad \text{(for integral slot machines)}$$

$$K_d = \frac{\sin(N\alpha\, m/2)}{N \sin\alpha\, m/2} \quad \text{(for fractional slot machines)}$$

See table 2 in the non-salient pole manual for a compilation of distribution factors for the various harmonics. See "Grouping of Fractional Slot Windings" and "Distribution Factor" sections of the non-salient pole manual for an explanation of K_d for fractional slot machines.

CHORD FACTOR--(K_p) The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil.

$$K_p = \sin\left(\frac{Y}{mq} \times 90^\circ\right)$$

See Table 1 in the non-salient pole manual for a compilation of the pitch factors for the various harmonics.

CONDUCTORS PER SLOT--(n_s) The actual number of conductors per slot. For random wound slots use a space factor of 80% to 85% when determining the permissable number.

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

$$n_e = \frac{Qn_s K_p K_{sk}}{C}$$

CONDUCTOR SIZE-- Record the number of strands making up each conductor and their bare and insulated sizes. Indicate also the type of strand insulation.

CONDUCTOR AREA--(a_c) 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.

$$a_c = (\text{width of cond.})\text{x}(\text{thickness of cond.}) - .858r_c^2$$

Corner Radii			
Thickness	Width		
	.751 & Up	.187 - .750	Up to .188
.689 & up	3/16	3/16	--
.688 - .439	1/8	3/32	--
.438 - .226	3/32	1/16	--
.225 - .166	1/16	3/64	3/64
.165 - .126	1/16	1/32	1/32
.125 - .073	Rounded edge	1/32	1/64
.072 - .051	Rounded edge	Rounded edge	1/64
.050 & under	Rounded edge	Rounded edge	Rounded edge

Corner	$.858r_c^2$
1/64	.00021
1/32	.00084
3/64	.00189
1/16	.00335
3/32	.00754
1/8	.0134
3/16	.0302

Square wire .072 and under has a radius of .012. A rounded edge is produced by rolling round wire to the specified size.

CURRENT DENSITY--(s) The amperes per square inch of conductor.

$$s = \frac{I_{ph}}{Ca_c}$$

WINDING CONSTANT--(C_w) 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.

$$C_w = \frac{EC_1K_d}{\sqrt{2}\,E_{ph}m}$$

Assuming $K_d = .955$, $C_w = .225\,C_1$ for three phase delta machines and $C_w = .390C_1$ for three phase star ones. C_1 is the ratio of the maximum fundamental of the field form to the actual maximum of the field form. For pole heads with more than one radius the field form is determined from a flux plot of the air gap flux at no load, neglecting saturation, and C_1 is then obtained by Fourier analysis. For pole heads with only one radius, C_1 is obtained from curve #4. The graphical flux plotting method of determining C_1 is explained in the section titled "Derivations."

TOTAL FLUX--(ϕ_T) The total flux that would exist in the gap if the density was uniform and equal to the maximum gap density.

$$\phi_T = \frac{6000E10^6}{C_w n_e RPM}$$

GAP AREA-- The area of the gap surface at the stator bore = $\pi d \ell$

GAP DENSITY--(B_g) The maximum flux density in the air gap.

$$B_g = \frac{\phi_T}{\pi d \ell}$$

POLE CONSTANT--(C_p) The ratio of the average to the maximum value of the field form. For pole heads with more than one radius C_p is calculated from the same field form that was used to determine C_1, and this method is described in the second part of the manual. For pole heads with only one radius C_p is obtained from curve #4. Note the correction factor at the top of the curve.

FLUX PER POLE--(ϕ_p) The total flux per pole.

$$\phi_p = \frac{\phi_T C_p}{p}$$

TOOTH PITCH--(t_s and $t_{s\frac{1}{3}}$) The stator slot pitch on the inside stator bore, and the stator slot pitch at a distance a third of the way up the tooth.

$$t_s = \frac{\pi d}{Q} \qquad t_s 1/3 = \frac{\pi(d + \frac{2}{3} h_s)}{Q}$$

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

$$B_t = \frac{\phi_T}{Q \ell_s b_{t\,1/3}} \quad \text{where } b_{t\,1/3} = t_{s\,1/3} - b_s$$

CORE DENSITY--(B_c) The flux density in the stator core.

$$B_c = \frac{\phi_p}{2h_c \ell_s}$$

GRADE OF IRON-- Alloy identification and lamination thickness of stator iron.

1/2 MEAN TURN--(ℓ_t) The average length of one conductor.

$$\ell_t = \ell + L_E$$

where L_E = the end extension length

For random wound coils

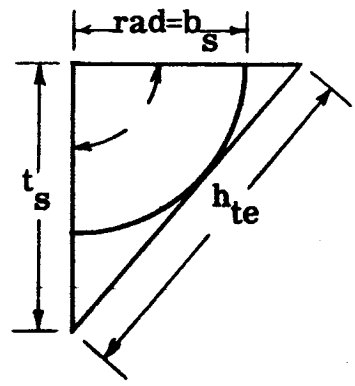
$$L_E = .5 + \frac{K_t \pi y(d+h_s)}{Q}$$

where K_t = constant depending on the number of poles

K_t = 1.3 for 2 poles; 1.5 for 4 poles; and 1.7 for 6 poles and up

For formed coils

$$L_E = 2\ell_{e2} + \pi\left(\frac{h_1}{2} + d_b\right) + yh_{te}$$



where d_b = diameter of bender pin

h_{te} = is obtained from the diagram as shown

ℓ_{e2} = straight part of the coil extension beyond the core

RESISTANCE PER PHASE AT__^{o}--(R_{ph}) The resistance per phase calculated at the expected coil temperature.

$$R_{ph} = \frac{n_s Q \ell_t R_{1000}}{12000\, C^2 m} \times \frac{235 + X^{o}C}{260} = \rho \frac{n_s Q \ell_t}{m a_c C^2}$$

where ρ = resistivity at $X^{o}C$ = $.91 \times 10^{-6}$ $100^{o}C$

R_{1000} = resistance per 1000 ft. of conductor at $25^{o}C$

$X^{o}C$ = expected coil temperature in ^{o}C

EDDY FACTOR TOP-- The eddy factor of the top coil. Calculate this value at the expected operating temperature of the machine.

$$\text{EF Top} = 1 + \left[.584 + \left(\frac{N_{st}^2 - 1}{16}\right)\left(\frac{h'_{st}\ell}{n_{st}\ell_t}\right)^2\right]\frac{3.35}{1000}\left[\frac{h_{st} n_s f a_c}{b_s \rho'}\right]^2$$

where $\rho' = \rho \times 10^6$

N_{st} = number of strands per conductor in depth

h'_{st} = distance between centerline of strands in depth

h_{st} = height of uninsulated strand

EDDY FACTOR BOTTOM-- The eddy factor of the bottom coil at the expected operating temperature of the machine. Use same equation as E. F. top except use .0833 in place of .584.

DEMAGNETIZING FACTOR--(C_M and C_q) The ratio of the field ampere turns to the maximum sine wave stator ampere turns required to force

the same fundamental flux across the gap. The demagnetizing factor in the direct axis is

$$C_M = \frac{\alpha\pi + \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$$

and the cross magnetizing factor in the quadrature axis is

$$C_q = \frac{1/2\cos\frac{\alpha\pi}{2} + \alpha\pi - \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$$

The above factors can be read directly from curve #9 and calculation by the above formulas is thus unnecessary.

AMPERE CONDUCTORS PER INCH--(A) 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.

$$A = \frac{I_{ph} n_s K_p}{Ct_s}$$

REACTANCE FACTOR--(X) 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.

$$X = \frac{100AK_d}{\sqrt{2}\,C_1 B_g}$$

CONDUCTOR PERMEANCE--(λ_i) 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.

$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_2}{b_s} + \frac{h_1}{3b_s} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right] \qquad b_t = \text{tooth width at gap}$$

(b) For partially closed slots with constant slot width.

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

(c) For partially closed slots with constant tooth width.

$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_o}{b_o} + \frac{2h_t}{b_o + b_1} + \frac{2h_w}{b_1 + b_2} + \frac{h_1}{3b_2} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right]$$

(d) For round slots.

$$\lambda_i = C_X \frac{20}{mq}\left[.62 + \frac{h_o}{b_o}\right]$$

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

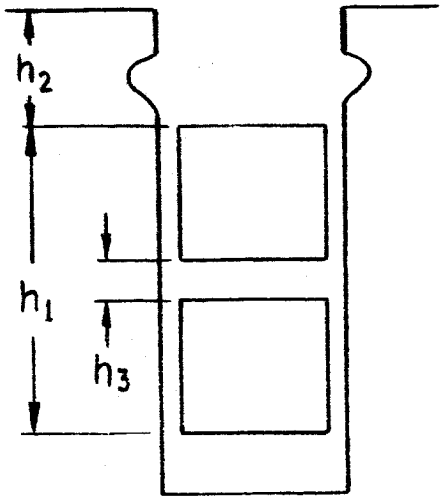
$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_2}{b_s} + \frac{h_1}{3b_s} + .6 + \frac{g}{2t_s} + \frac{t_s}{4g}\right] \qquad \left(C_X = \frac{1}{K_p^2 K_d^2}\right) \quad (K_X = 1)$$

In all of the above formulas C_X is a reduction factor that is dependent upon the pitch and distribution of the winding.

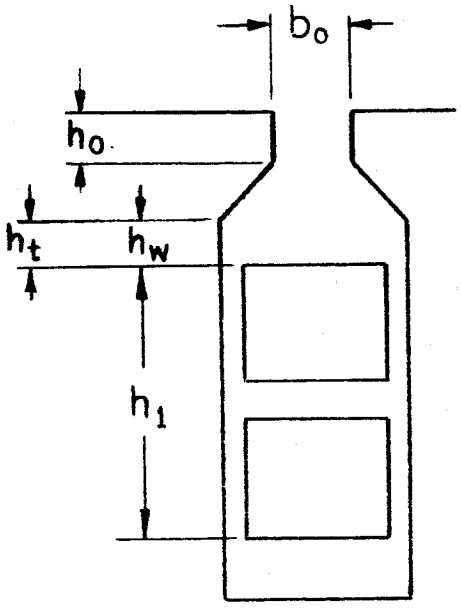
$$C_X = \frac{K_X}{K_p^2 K_d^2} \qquad \text{where } K_X = \frac{1}{4}\left(\frac{3y}{mq} + 1\right) \text{ for 3 phase}$$

$$K_X = \frac{y}{mq} \text{ for 2 phase}$$

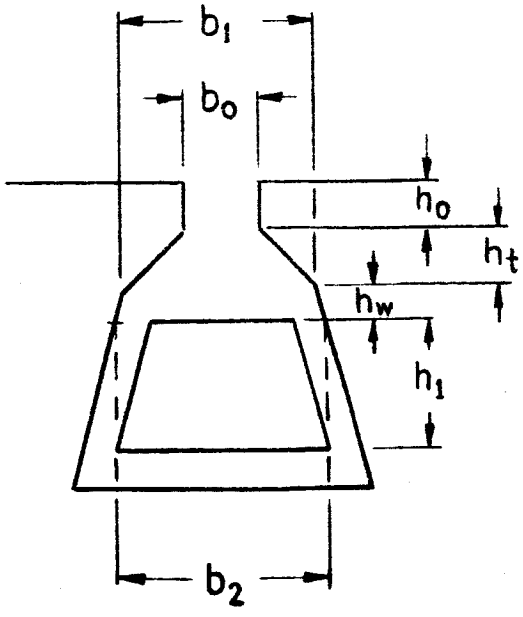
(a) Open Slots



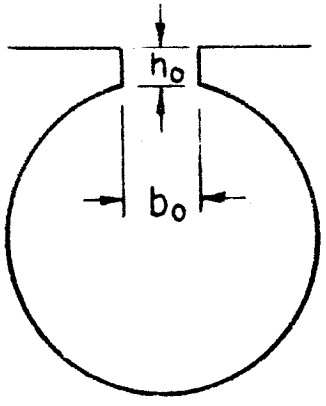
(b) Constant Slot Width



(c) Constant Tooth Width



(d) Round Slots



Values of C_X versus percent pitch for three phase windings are plotted on Graph #1. These values assume a distribution factor of .955. See Graph #1.

END WINDING PERMEANCE--(λ_E) The specific permeance for the end extension portion of the stator winding.

$$\lambda_E = \frac{6.28}{\ell K_d^2}\left[\frac{\phi_E L_E}{2n}\right] K_E$$

(Obtain the value of $\phi_E L_E$ from Graph #1

$$K_E = \frac{\text{Calculated valve of } L_E}{\text{Value of } L_E \text{ from Graph \#1}} \quad \text{(for machines of } d > 8'')$$

$$K_E = \sqrt{\frac{\text{Calculated value of } L_E}{\text{Value of } L_E \text{ from Graph \#1}}} \quad \text{(for machines of } d < 8'')$$

LEAKAGE REACTANCE--($X\ell$) The leakage reactance of the stator for steady state conditions

$$X_\ell = X(\lambda_i + \lambda_E)$$

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.

$$\lambda_B = \frac{.1d}{pg_e}\left[\frac{\sin \frac{3y}{mq} \times 90^o}{K_p}\right]$$

$$X_\ell = X(\lambda_i + \lambda_E + \lambda_B) \qquad \text{where } \lambda_b = 0 \text{ for 3 phase machines.}$$

AIR GAP PERMEANCE--(λ_a) The specific permeance of the air gap.

$$\lambda_a = \frac{6.38d}{pg_e}$$

REACTANCE OF ARMATURE REACTION--(X_{ad} and X_{aq}) The "fictituous reactance" due to armature reaction. In the direct axis

$$X_{ad} = X \lambda_a C_1 C_M$$

and in the quadrature axis

$$X_{aq} = X C_q \lambda_a$$

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

$$\# = .321\, n_s Q a_c \ell_i$$

WEIGHT OF IRON-- The weight in lbs. of the stator iron.

$$\# = .238 \left[b_{tm} Q \ell_s h_s + \pi (D-h_c) hc\, \ell_s \right]$$

ROTOR

SINGLE GAP--(g) The single air gap. Also record the effective air gap (g_e)

$$g_e = K_s g$$

ROTOR DIAMETER--(d_r) The outside diameter of the rotor.

$$d_r = d - 2g$$

PERIPHERAL SPEED--(V_r) The velocity of the rotor surface in feet per minute.

$$V_r = \frac{\pi \, d_r RPM}{12}$$

POLE PITCH--(t_p) The pole pitch measured at the inside diameter of the stator.

$$t_p = \frac{\pi d}{p}$$

Also record the ratio of the pole arc to the pole pitch (α).

$$\alpha = \frac{b_n}{t_p}$$

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

$$a_p = b_p \ell_p K_i$$

Values of K_i are obtained from chart in Stator Section.

SIDE LEAKAGE--($\lambda_{s\ell}$) The side leakage permeance of the field. The unit for this factor is flux per pole per inch of core length for unit ampere turns.

$$\lambda_{s\ell} = \left[\frac{h_f + t_{p/10}(1 - 10/p)}{\pi/p(d_r - 2h_h - .4h_f) - b_p}\right]$$

END LEAKAGE--($\lambda_{e\ell}$) The end leakage permeance of the field.

$$\lambda_{e\ell} = \left[\frac{2(\ell_n - \ell) + h_f + .25b_p}{\ell}\right]$$

TIP LEAKAGE--($\lambda_{t\ell}$) The tip leakage permeance of the field.

$$\lambda_{t\ell} = \left[\frac{2(h_n + g - t_{p/18})}{t_p - b_h}\right]$$

LEAKAGE FLUX--(ϕ_ℓ) The total field leakage flux.

$$\phi_\ell = 6.38\,(\lambda_{s\ell} + \lambda_{e\ell} + \lambda_{t\ell})\,(F_g + F_s)\,\ell_p$$

Record also the total flux per pole in the rotor

$$\phi_{pt} = \phi_p + \phi_\ell$$

POLE DENSITY--(B_p) The apparent flux density at the base of the pole.

$$B_p = \frac{\phi_{pt}}{a_p}$$

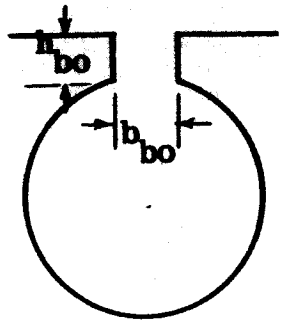
No provision is made in this manual for calculating the density in the spider section. It is therefore important to remember not to restrict the flux area through this section.

GRADE OF IRON-- Alloy and thickness of rotor iron laminations.

NUMBER OF DAMPER BARS--(n_b) The number of damper bars per pole.

BAR SIZE-- The size of the damper bars.

BAR PITCH--(t_b) The damper bar pitch. This is the distance between the centerlines of adjacent damper bars. Also indicate the height of the slot opening above the damper bar (h_{bo}) and the width of this opening (b_{bo}).



TURNS PER POLE--N_p) The number of field turns per pole.

CONDUCTOR SIZE-- The bare and insulated sizes of the field conductors. Also indicate the type of strand insulation.

CONDUCTOR AREA--(a_{cr}) The actual area of the conductor taking into account the corner radius. See stator area of conductor for typical corner radii values.

$$a_{cr} = (\text{cond. width x cond. thick.} - .858r_c^2)$$

MEAN TURN--(ℓ_{tr}) The mean length of the field turns. This value can be estimated from a layout of the field winding or from data on a previous machine.

RESISTANCE AT___ ^{o}--(R_f) The resistance of the field winding at the expected operating temperature.

$$R_f = \rho \frac{N_p P \ell_{tr}}{a_{cr}} \quad \text{where } \rho = .91 \times 10^{-6} @ 100^oC$$

WEIGHT OF COPPER-- The weight in lbs. of the field winding.

$$\# = .321\, N_p\, P\, \ell_{tr}\, a_{cr}$$

WEIGHT OF IRON-- The weight in lbs. of the rotor iron exclusive of the shaft.

% LOAD-- Space is provided for field voltage and current values at three load conditions. These loads will preferably be taken as no load, rated load, and guaranteed overload (usually 5 minutes).

FIELD AMPS--(I_f) The field current at the various load conditions.

FIELD VOLTS--(E_f) The field voltage drop across the collector rings at the various load and temperature conditions.

AMPS./SQ. IN. -- The current density of the field copper at the various load conditions.

FIELD LEAKAGE REACTANCE--(X_F) The effective leakage reactance of the field winding.

$$X_F = X_{ad}\quad 1 - \frac{(C_l/C_M)}{2C_p + \frac{4\lambda_F}{\pi\lambda_a}}$$

$$\lambda_F = \lambda_{FS} + \lambda_{FE}$$

$$\lambda_{FS} = 4.25\,(\lambda_s \ell + 1.5\,\lambda_t \ell)$$

$$\lambda_{FE} = 6.38\,\lambda_e \ell$$

FIELD SELF INDUCTANCE--(L_f) The total self inductance of the field winding.

$$L_f = \frac{N_p^2 \, p \, \ell_p}{10^8} \left[C_p \frac{\pi}{2} \lambda_a + \lambda_F \right]$$

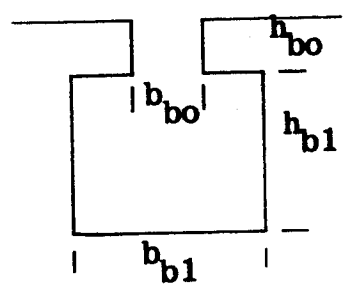
DAMPER LEAKAGE REACTANCE--(X_{Dd} and X_{Dq}) The leakage reactance of the damper winding. In the direct axis the dimensions corresponding to the end bar next to the pole tip are used.

For rectangular square damper bars

$$\lambda_b = 6.38 \left(\frac{h_{bo}}{b_{bo}} + \frac{h_{b1}}{3b_{b1}} + .5 \right)$$

$$\lambda_{pt} = 6.38 \left[\frac{b_n - t_b (n_b - 1)}{3g_e} \right]$$

$$\lambda_{Dd} \left[\cos \left\{ \frac{(n_b - 1) t_b \pi}{2t_p} \right\} \right] \frac{(\lambda_b + \lambda_{pt}) \lambda_F}{\lambda_b + \lambda_{bt} + \lambda_F}$$



$$X_{Dd} = X \lambda_{Dd}$$

In the quadrature axis the dimensions corresponding to the bar in the center of the pole is used.

For rectangular square bars

$$\lambda_{Dq} = \frac{20 t_b}{t_r} \left[\frac{h_{bo}}{b_{bo}} + \frac{h_{b1}}{3b_{b1}} + .5 + \frac{g}{t_b} \right]$$

$$X_{Dq} = X \lambda_{Dq}$$

For round damper bars use the constant 0.62 in place of $h_{b1}/3b_{b1}$ in the above formulas.

REACTANCES AND TIME CONSTANTS

SYNCHRONOUS REACTANCE--(X_d and X_q) The steady state short circuit reactance. In the direct axis

$$X_d = X_\ell + X_{ad}$$

and in the quadrature axis

$$X_q = X_\ell + X_{aq}$$

UNSATURATED TRANSIENT REACTANCE--(X'_{du}) The transient reactance due to the field winding assuming unsaturated conditions.

$$X'_{du} = X_\ell + X_F$$

SATURATED TRANSIENT REACTANCE--(X'_d) The transient reactance due to the field winding assuming normally saturated conditions.

$$X'_d = .88\, X'_{du}$$

SUBTRANSIENT REACTANCE--(X''_d and X''_q) The subtransient reactance due to the damper winding. In the direct axis

$$X''_d = X_\ell + X_{Dd}$$

and in the quadrature axis

$$X''_q = X_\ell + X_{Dq}$$

If the machine does not have a damper winding

$$X_d'' = X_d'$$

$$X_q'' = X_q$$

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

$$X_2 = .5(X_d'' + X_q'')$$

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

$$X_o = X\left[\frac{K_{Xo}}{K_X}(\lambda_i + \lambda_{Bo}) + \frac{20(h_1 + 2h_3)}{12mqK_p^2K_d^2b_s} + .2\ \lambda_E\right]$$

$$\lambda_{Bo}' = \frac{K_{Xo}}{K_X}\lambda_{Dq}$$

$$\lambda_{BWO} = \frac{K_{Xo}}{K_p^2}(.07\ \lambda_a)$$

for machines with damper windings

$$\lambda_{Bo} = \frac{\lambda_{Bo}' + \lambda_{BWo}}{(\lambda_{Bo}')(\lambda_{BWo})}$$

and for machines without damper windings

$$\lambda_{Bo} = \lambda_{BWo}$$

and

$$K_{Xo} = \frac{3y}{mq} - 2$$

$$K_X = \left(\frac{3y}{4mq} + \frac{1}{4}\right) \quad \text{for pitches of 66 2/3\% to 100\%}$$

$$K_X = \left(\frac{3y}{2mq} - \frac{1}{4}\right) \quad \text{for pitches of 33 1/3\% to 66 2/3\%}$$

for a one conductor per slot winding

$$K_{Xo} = K_X = 1$$

OPEN CIRCUIT TIME CONSTANT--(T'_{do}) The time constant of the field winding with the stator open circuited and with negligible external resistance and inductance in the field circuit.

$$T'_{do} = \frac{L_F}{R_F} \text{ second}$$

ARMATURE TIME CONSTANT--(T_a) The time constant of the DC component.

$$T_a = \frac{X_2}{(2)\,(100 \quad f\,r_a)} \text{ seconds}$$

$$r_a = \frac{\text{Stator } I^2 \text{ R(KW)}}{\text{Rated KVA}}$$

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

$$T'_d = \frac{X'_d}{X_d} T'_{do}$$

SUBTRANSIENT TIME CONSTANT--(T''_d) The time constant of the subtransient component of the alternating wave. This value has been determined empirically from tests on large machines and

T''_d = .035 second at 60 cycles.

T''_d = .005 second at 400 cycles.

SATURATION

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

$$F_g = \frac{B_g g_e}{3.19}$$

STATOR AMPERE TURNS--(F_s) The ampere turns per pole required to force the flux through the stator iron when operating at no load with rated voltage.

$$F_s = F_T + F_C$$

F_T is the ampere turns per pole for the teeth. It is calculated as the product of h_s and the NI per inch at a density of B_t.

F_C is the ampere turns per pole required for the core. It is calculated as the product of $\left[\frac{\pi(D - h_c)}{4_p}\right]$ and the NI per inch at a density of B_C.

Use sat curves from USS Electrical Steel Sheets Manual.

POLE AMPERE TURNS--(F_R) The ampere turns per pole required to force the flux through the pole and spider at no load rated voltage. In general the spider density is kept fairly low and its ampere turns can be neglected. The no load pole ampere turns per pole are calculated as the product of ($h_f + h_h$) times the NI per inch at the density B_p.

Use sat curves from USS Steel Sheets Manual.

NO LOAD AMPERE TURNS--(F_{NL}) The total ampere turns per pole required to produce rated voltage at no load.

$$F_{NL} = (F_g + F_s + F_R)$$

RATED LOAD AMPERE TURNS--(F_{FL}) The total ampere turns per pole required to produce rated voltage at rated load. The values of X_d, X_{ad}, X_q etc. in the following calculations must be expressed in per unit.

$$F_{FL} = e_d F_g + (1 + \cos\theta) F_T + F_e + F_{PL}$$

$$\tan\psi = \frac{\sin\theta + X_q}{\cos\theta}$$

$$\epsilon = \psi - \theta$$

$$e_d = \cos\epsilon + X_d \sin\psi$$

$$\phi_{PL} = \phi_P \left[e_d - .93 X_{ad} \sin\psi \right]$$

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

$$\phi_{pt\ell} = \phi_{PL} + \phi_{\ell\ell}$$

$$B_{PL} = \frac{\phi_{pt}\ell}{a_p}$$

F_{PL} is then calculated as the product of $(h_f + h_h)$ times the NI/inch at the density B_{PL}.

OVERLOAD AMPERE TURNS--(F_{OL}) The total ampere turns per pole required to produce rated voltage at the overload condition of operation. This is determined in the same manner as described in F_{FL} by using the proper per unit values for X_d, X_{ad}, X_q, etc.

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

X_d in per unit

$$F_{SC} = X_d F_g$$

SHORT CIRCUIT RATIO--(SCR) The ratio of the field current required 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.

$$SCR = \frac{F_{NL}}{F_{SC}}$$

LOSSES AND EFFICIENCY

PERCENT LOAD-- Space is provided for three conditions of loading and these are preferably taken as no load, full rated load, and overload.

FRICTION AND WINDAGE--(F & W) There is no known calculation method that will give reasonable accuracy for this loss, and so data from a previous machine will have to be used. 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.

STATOR TEETH--(W_{TNL}, W_{TFL}, W_{TOL}) 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.

$$W_{TNL} = .453\,(t_{s\,1/3} - b_s)\,Q\,\ell_s\,h_s\,K_Q$$

K_Q = Watts per pound loss from USS Electrical Steel Sheets Manual at a density B_t.

The stator tooth loss under load (W_{TFL} & W_{TOL}) is increased because of the parasitic fluxes caused by the ripple due to the rotor damper bar slot openings.

$$W_{TFL} = \left[2(.27\,X_d)^{1.8} + 1\right] W_{TNL};\ (X_d \text{ in per unit})$$

For W_{TOL} use X_d corresponding to the overload condition.

STATOR CORE--(W_C) 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.

$$W_C = 1.42\,(D - h_c)\,h_c\,\ell_s K_Q$$

K_Q = Watts per pound loss from USS Electrical Steel Sheets Manual at a density of B_C.

POLE FACE--(W_{PNL}, W_{PFL}, W_{POL}) The pole surface losses are due to the 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}) is calculated from Graph #2. Graph #2 is plotted on the basis of open slots and thus B_s on the curve equals b_o for partially closed ones. The pole face loss under load (W_{PFL}, W_{POL}) is calculated as

$$W_{PFL} = \left[\left(\frac{K_{sc}\,I_{ph}\,n_s}{c\,F_g}\right)^2 + 1\right] W_{PNL}$$

K_{sc} is obtained from Graph #3. (Page 96 non-salient pole manual.)

For W_{POL} use I_{ph} corresponding to the overload phase current.

DAMPER--(W_{DNL}, W_{DFL}, W_{DOL}) The loss produced by the slot ripple in the damper winding. At no load this loss is calculated from curves #7 and #8. The damper loss under load (W_{DFL}, and W_{DOL}) for <u>polyphase</u> machines is calculated as

$$W_{DFL} = \left[\left(\frac{K_{sc}\,I_{ph}\,n_s}{c\,F_g}\right)^2 + 1\right] W_{DNL}$$

K_{sc} is obtained from Graph #3.

For W_{DOL} use I_{ph} corresponding to the overload phase current.

STATOR I^2R-- The copper loss based on the DC resistance of the winding. Calculate for the maximum expected operating temperature.

$$I^2R = m\, I_{ph}^2\, R_{ph}$$

EDDY-- The stator I^2R loss due to skin effect.

$$\text{Eddy Loss} = \left[\left(\frac{\text{Eddy Factor Top} + \text{Eddy Factor Bottom}}{2}\right) - 1\right] \text{Stator } I^2R$$

ROTOR I^2R-- The copper loss in the field winding.

$$I^2R = I_f^2\, R_f$$

SUM OF THE LOSSES-- The total losses at the various loads.

RATING-- The kilowatt rating of the generator.

RATING + LOSS-- The sum of the total losses and the KW rating.

PERCENT LOSS-- The total loss divided by the rating plus total loss.

PERCENT EFFICIENCY-- (100% - % loss)

STATOR WATTS/SQ. IN. -- The stator watts loss per sq. in. of stator periphery.

$$\text{Watts/in}^2 = \frac{\text{Stator (Tooth Loss + Core Loss + } I^2R \text{ + Eddy Loss)}}{\pi D \ell}$$

ROTOR WATTS/SQ. IN. -- The rotor watts loss per sq. in. of rotor periphery.

$$\text{Watts/in}^2 = \frac{\text{Pole Face Loss + Damper Loss + Rotor } I^2R}{\pi d_r \ell_p}$$

DIRECT AXIS COMPONENT OF ARMATURE REACTION

When the air gap under the pole is constant the field produced by the direct axis armature reaction MMF wave A will have the approximate shape B insofar as its reaction on the field pole is concerned. Since this MMF produces very little demagnetizing effect in the interpolar region it is sufficient to consider only the fundamental of the effective part of the MMF curve (the part which lies under the pole). The amplitude of this fundamental is given by the equation

$$A_1 = \frac{1}{\pi}\int_0^{2\pi} f(x) \sin x \, d x$$

If the ratio of the pole arc to the pole pitch is designated as α then

$$f(x) = 0 \text{ from } x = 0 \text{ to } x = \left(\frac{1-\alpha}{2}\right)\pi$$

$$f(x) = F_{DM} \sin x \text{ from } \left(\frac{1-\alpha}{2}\right)\pi \text{ to } \left[\left(\frac{1-\alpha}{2}\right)\pi + \alpha\pi\right] = (1+\alpha)\frac{\pi}{2}$$

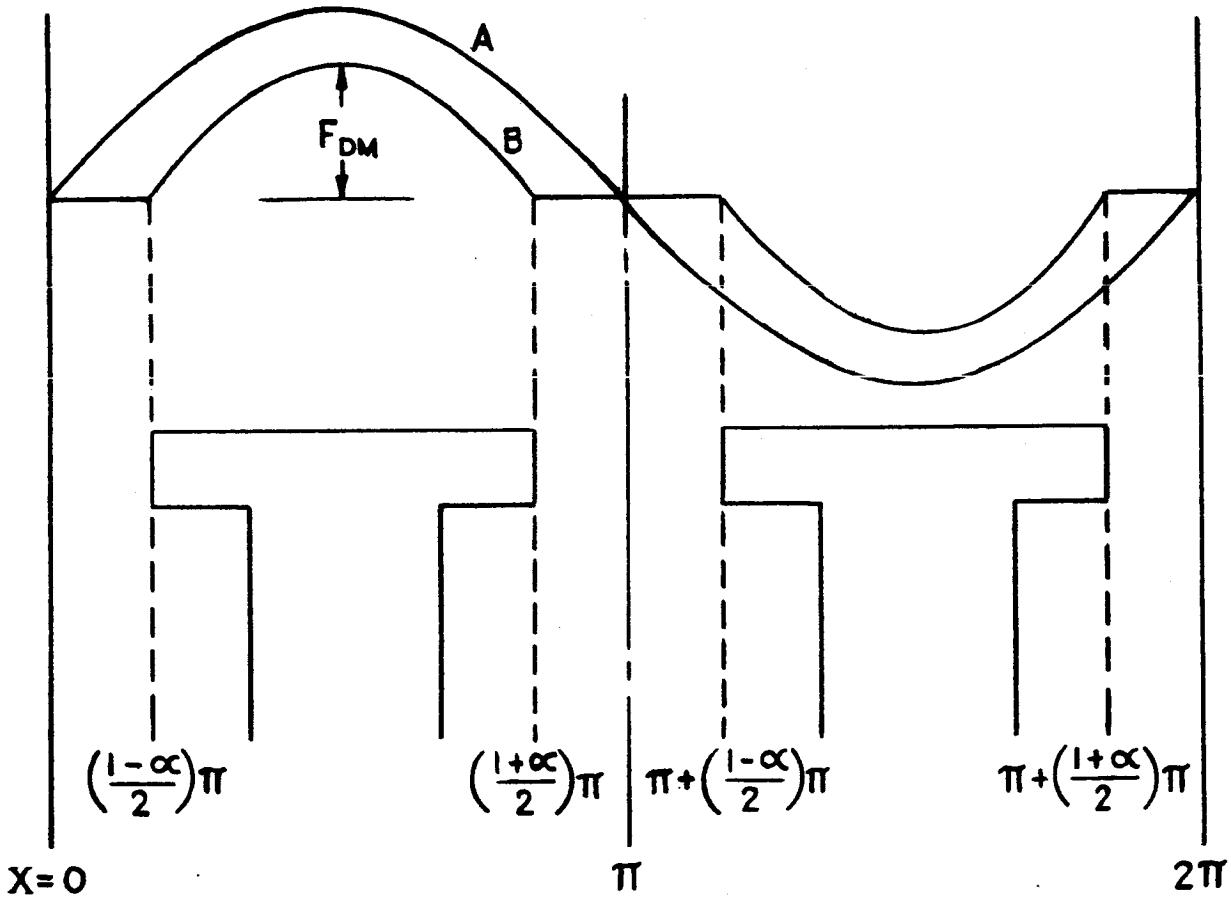
$$f(x) = 0 \text{ from } \left(\frac{1+\alpha}{2}\pi\right) \text{ to } \pi + \left(\frac{1-\alpha}{2}\right)\pi$$

$$f(x) = F_{DM} \sin x \text{ from } \pi + \left(\frac{1-\alpha}{2}\right)\pi \text{ to } \pi + (1+\alpha)\frac{\pi}{2}$$

$$A_1 = \frac{1}{\pi}\left[\int_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} F_{DM} \sin^2 x \, d x + \int_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}} F_{DM} \sin^2 x \, d x\right]$$

$$\int \sin^2 x \, d x = \frac{1}{2}x - \frac{1}{4}\sin 2x$$

$$A_1 = \frac{F_{DM}}{\pi}\left[\left(\frac{1}{2}x - \frac{1}{4}\sin 2x\right)_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} + \left(\frac{1}{2}x - \frac{1}{4}\sin 2x\right)_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}}\right]$$


A
B
F_{DM}
$\left(\frac{1-\alpha}{2}\right)\pi$
$\left(\frac{1+\alpha}{2}\right)\pi$
$\pi+\left(\frac{1-\alpha}{2}\right)\pi$
$\pi+\left(\frac{1+\alpha}{2}\right)\pi$
X=0
π
2π

$$A_1 = \frac{F_{DM}}{\pi}\left[(1+\alpha)\frac{\pi}{4} - \frac{1}{4}\sin(\pi+\alpha\pi) - (1-\alpha)\frac{\pi}{4} + \frac{1}{4}\sin(\pi-\alpha\pi) + \frac{\pi}{2} + (1+\alpha)\frac{\pi}{4}\right.$$

$$\left. - \frac{1}{4}\sin(2\pi+\pi+\alpha\pi) - \frac{\pi}{2} - (1-\alpha)\frac{\pi}{4} + \frac{1}{4}\sin(2\pi+\pi-\alpha\pi)\right]$$

$$\sin(x+y) = \sin x \cos y + \cos x \sin y$$

$$\sin(\pi+\alpha\pi) = -\sin\alpha\pi$$

$$\sin(3\pi+\alpha\pi) = -\sin\alpha\pi$$

$$\sin(\pi-\alpha\pi) = +\sin\alpha\pi$$

$$\sin(3\pi-\alpha) = +\sin\alpha\pi$$

$$A_1 = \frac{F_{DM}}{\pi}\left[\frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4}\sin\alpha\pi - \frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4}\sin\alpha\pi + \frac{\pi}{2} + \frac{\pi}{4} + \frac{\alpha\pi}{4} + \right.$$

$$\left. \frac{1}{4}\sin\alpha\pi - \frac{\pi}{2} - \frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4}\sin\alpha\pi\right]$$

$$A_1 = \frac{F_{DM}}{\pi}\left[\alpha\pi + \sin\alpha\pi\right]$$

The amplitude of the fundamental of the field MMF will be

$$A_{1f} = \frac{1}{\pi}\int_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} N_f I_f \sin x\, dx + \int_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}} N_f I_f \sin x\, dx$$

$$A_{1f} = \frac{N_f I_f}{\pi}\left[(-\cos x)_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} + (-\cos x)_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}}\right]$$

$$A_{1f} = \frac{N_f I_f}{\pi}\left[-\cos\left(\frac{\pi}{2} + \frac{\pi\alpha}{2}\right) + \cos\left(\frac{\pi}{2} - \frac{\pi\alpha}{2}\right) - \cos\left(\frac{3\pi}{2} + \frac{\pi\alpha}{2}\right) + \right.$$

$$\left. \cos\left(\frac{3\pi}{2} - \frac{\pi\alpha}{2}\right)\right]$$

QUADRATURE AXIS COMPONENT OF ARMATURE REACTION

For all practical purposes the armature MMF in the quadrature axis will have the shape indicated insofar as its reaction on the field is concerned. If the assumption (justified by practice) is made that the magnitude of the constant part over the interpolar space is equal to 1/8 F_{DM}, the fundamental of this wave will then be found by the equation

$$A_1 = \frac{1}{\pi}\int_0^{2\pi} f(x)\cos x\,dx$$

$$f(x) = \frac{1}{8}F_{DM} \text{ from } y = 0 \text{ to } x = (1-\alpha)\frac{\pi}{2}$$

$$f(x) = F_{DM}\cos x \text{ from } (1-\alpha)\frac{\pi}{2} \text{ to } (1+\alpha)\frac{\pi}{2}$$

$$f(x) = -\frac{1}{8}F_{DM} \text{ from } (1+\alpha)\frac{\pi}{2} \text{ to } \pi + (1-\alpha)\frac{\pi}{2}$$

$$f(x) = F_{DM}\cos x \text{ from } \pi + (1-\alpha)\frac{\pi}{2} \text{ to } \pi + (1+\alpha)\frac{\pi}{2}$$

$$f(x) = \frac{1}{8}F_{DM} \text{ from } \pi + (1+\alpha)\frac{\pi}{2} \text{ to } 2\pi$$

$$A_1 = \left[\begin{array}{l} \frac{1}{\pi}\int_0^{(1-\alpha)\frac{\pi}{2}} \frac{F_{DM}}{8}\cos x\,dx + \frac{1}{\pi}\int_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} F_{DM}\cos^2 x\,dx \\ -\frac{1}{\pi}\int_{(1+\alpha)\frac{\pi}{2}}^{\pi+(1-\alpha)\frac{\pi}{2}} \frac{F_{DM}}{8}\cos x\,dx + \frac{1}{\pi}\int_{\pi+(1-\alpha)\frac{\pi}{2}}^{\pi+(1+\alpha)\frac{\pi}{2}} F_{DM}\cos^2 x\,dx \\ +\frac{1}{\pi}\int_{\pi+(1+\alpha)\frac{\pi}{2}}^{2\pi} \frac{F_{DM}}{8}\cos x\,dx \end{array}\right]$$

$$\cos(x + y) = \cos x \cos y - \sin x \sin y$$

$$\cos\left(\frac{\pi}{2} + \frac{\pi\alpha}{2}\right) = -\sin\frac{\pi\alpha}{2}$$

$$\cos\left(\frac{3\pi}{2} + \frac{\pi\alpha}{2}\right) = -\sin\frac{\pi\alpha}{2}$$

$$\cos\left(\frac{\pi}{2} - \frac{\pi\alpha}{2}\right) = \sin\frac{\pi\alpha}{2}$$

$$\cos\left(\frac{3\pi}{2} - \frac{\pi\alpha}{2}\right) = \sin\frac{\pi\alpha}{2}$$

$$A_{1f} = \frac{N_f I_f}{\pi}\left[\sin\frac{\pi\alpha}{2} + \sin\frac{\pi\alpha}{2} + \sin\frac{\pi\alpha}{2} + \sin\frac{\pi\alpha}{2}\right] = \frac{N_f I_f}{\pi}\left(4\sin\frac{\pi\alpha}{2}\right)$$

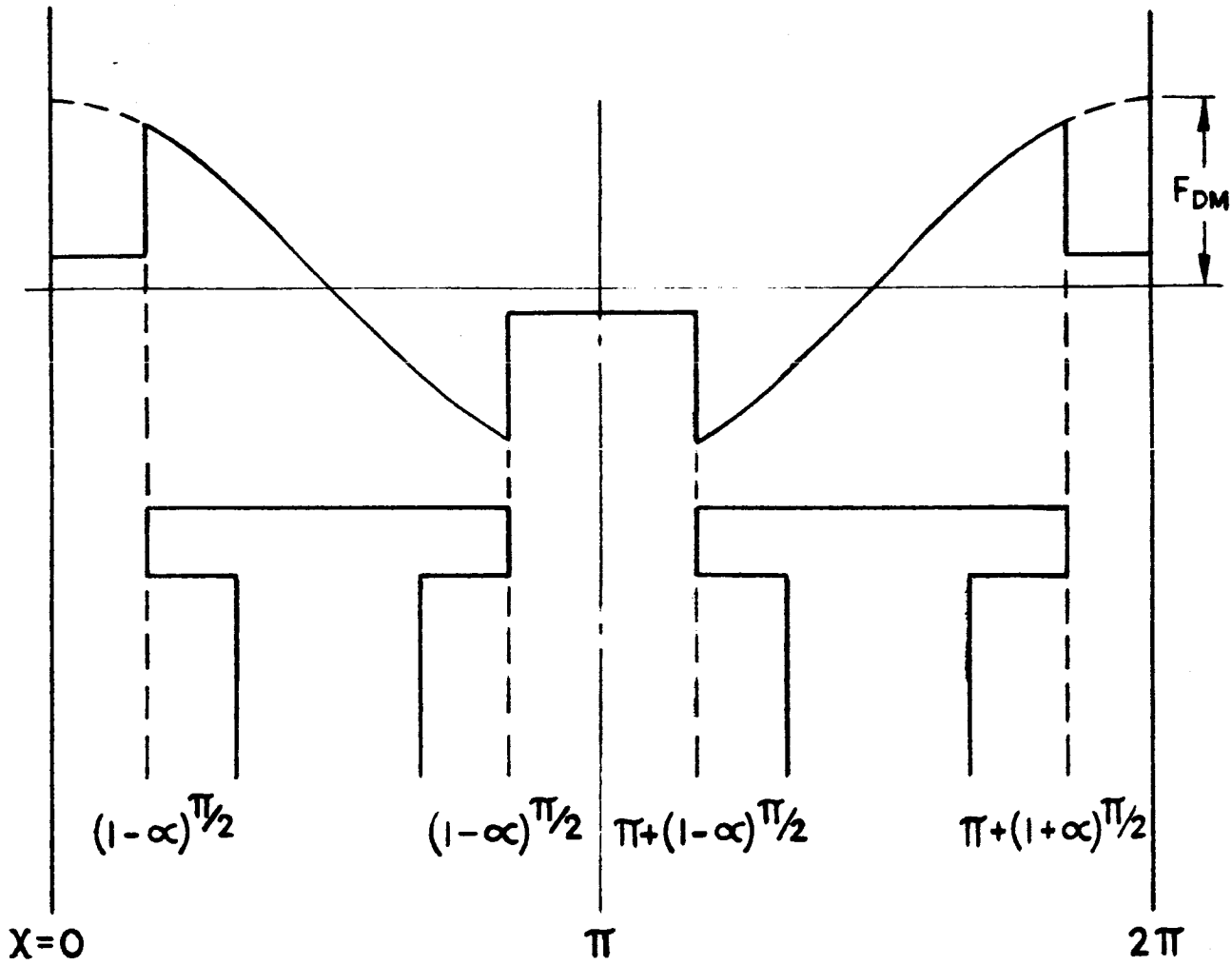
The demagnetizing factor in the direct axis is found by equating A_1 and A_{1f}

$$\frac{N_f I_f}{\pi}\left(4\sin\frac{\pi\alpha}{2}\right) = \frac{F_{DM}}{\pi}(\alpha\pi + \sin\alpha\pi)$$

$$N_f I_f = \frac{F_{DM}}{\pi}(\alpha\pi + \sin\alpha\pi)\frac{\pi}{4\sin\frac{\pi\alpha}{2}} = C_M F_{DM}$$

where $C_M = \dfrac{\alpha\pi + \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$

Although this derivation has been based on the assumption that the air gap under the pole is constant, the formula is much more accurate than might appear. The formula has been checked by flux plots over a wide range of pole shapes from 4 to 88 poles and found to be reasonably accurate.


F_{DM}
$(1-\alpha)\pi/2$
$(1-\alpha)\pi/2$
$\pi+(1-\alpha)\pi/2$
$\pi+(1+\alpha)\pi/2$
$X=0$
π
2π

$$\int \cos x \, dx = \sin x$$

$$\int \cos^2 x \, dx = \frac{1}{2} x + \frac{1}{4} \sin 2x$$

$$A_1 = \frac{F_{DM}}{8\pi} \left[(\sin x)_0^{(1-\alpha)\frac{\pi}{2}} - (\sin x)_{(1+\alpha)\frac{\pi}{2}}^{\pi + (1-\alpha)\frac{\pi}{2}} + (\sin x)_{\pi + (1+\alpha)\frac{\pi}{2}}^{2\pi} \right]$$

$$+ \frac{F_{DM}}{\pi} \left[\left(\frac{1}{2} x + \frac{1}{4} \sin 2x\right)_{(1-\alpha)\frac{\pi}{2}}^{(1+\alpha)\frac{\pi}{2}} + \left(\frac{1}{2} x + \frac{1}{4} \sin 2x\right)_{\pi + (1-\alpha)\frac{\pi}{2}}^{\pi + (1+\alpha)\frac{\pi}{2}} \right]$$

$$A_1 = \frac{F_{DM}}{8\pi} \left[\sin\left(\frac{\pi}{2} - \frac{\pi\alpha}{2}\right) - \sin\left(\frac{3\pi}{2} - \frac{\pi\alpha}{2}\right) + \sin\left(\frac{\pi}{2} + \frac{\pi\alpha}{2}\right) - \sin\left(\frac{3\pi}{2} + \frac{\pi\alpha}{2}\right) \right] + \frac{F_{DM}}{\pi} \left[\frac{\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4} \sin(\pi + \alpha\pi) - \frac{1}{4} \right.$$

$$+ \frac{\alpha\pi}{4} - \frac{1}{4} \sin(\pi - \alpha\pi) + \frac{3\pi}{4} + \frac{\alpha\pi}{4} + \frac{1}{4} \sin(3\pi + \alpha\pi)$$

$$\left. - \frac{3\pi}{4} + \frac{\alpha\pi}{4} - \frac{1}{4} \sin(3\pi - \alpha\pi) \right]$$

$$\sin(x + y) = \sin x \cos y + \cos x \sin y$$

$$\sin(x - y) = \sin x \cos y - \cos x \sin y$$

$$\sin\left(\frac{\pi}{2} - \frac{\pi\alpha}{2}\right) = \cos\frac{\pi\alpha}{2} \qquad \sin\left(\frac{3\pi}{2} - \frac{\pi\alpha}{2}\right) = -\cos\frac{\pi\alpha}{2}$$

$$\sin\left(\frac{\pi}{2} + \frac{\pi\alpha}{2}\right) = \cos\frac{\pi\alpha}{2} \qquad \sin\left(\frac{3\pi}{2} + \frac{\pi\alpha}{2}\right) = -\cos\frac{\pi\alpha}{2}$$

$$\sin(\pi + \alpha\pi) = -\sin\alpha\pi \qquad \sin(\pi - \alpha\pi) = \sin\alpha\pi$$

$$\sin(3\pi + \alpha\pi) = -\sin\alpha\pi \qquad \sin(3\pi - \alpha\pi) = \sin\alpha\pi$$

$$A_1 = \frac{F_{DM}}{8\pi}\left[\cos\frac{\pi\alpha}{2} + \cos\frac{\pi\alpha}{2} + \cos\frac{\pi\alpha}{2} + \cos\frac{\pi\alpha}{2}\right] + \frac{F_{DM}}{\pi}\left[\frac{\pi}{4} + \frac{\alpha\pi}{4}\right.$$

$$- \sin\frac{\alpha\pi}{4} - \frac{\pi}{4} + \frac{\alpha\pi}{4} - \sin\frac{\alpha\pi}{4} + \frac{3\pi}{4} + \frac{\alpha\pi}{4} - \sin\frac{\alpha\pi}{4} - \frac{3\pi}{4}$$

$$\left. + \frac{\alpha\pi}{4} - \sin\frac{\alpha\pi}{4}\right]$$

$$A_1 = \frac{F_{DM}}{2\pi}\left(\cos\frac{\pi\alpha}{2}\right) + \frac{F_{DM}}{\pi}(\alpha\pi - \sin\alpha\pi) = \frac{F_{DM}}{\pi}\left(\frac{1}{2}\cos\frac{\pi\alpha}{2} + \alpha\pi - \sin\alpha\pi\right)$$

The amplitude of the fundamental of the field MMF was derived in the determination of C_M and

$$A_{1f} = \frac{N_f I_f}{\pi} 4 \sin\frac{\alpha\pi}{2}$$

The demagnetizing factor in the quadrature axis is found by equating A_1 and A_{1f}

$$\frac{N_f I_f}{\pi} 4 \sin\frac{\pi\alpha}{2} = \frac{F_{DM}}{\pi}\left(\frac{1}{2}\cos\frac{\pi\alpha}{2} + \alpha\pi - \sin\alpha\pi\right)$$

$$N_f I_f = F_{DM}\left[\frac{\frac{1}{2}\cos\frac{\pi\alpha}{2} + \alpha\pi - \sin\alpha\pi}{4\sin\frac{\pi\alpha}{2}}\right] = F_{DM}\, C_q$$

where

$$C_q = \frac{\frac{1}{2}\cos\frac{\pi\alpha}{2} + \alpha\pi - \sin\alpha\pi}{4\sin\frac{\pi\alpha}{2}}$$

VECTOR DIAGRAM AND CALCULATION OF LOAD EXCITATION OF A SALIENT POLE GENERATOR

The vector diagram for a salient pole generator is as shown. OA is the terminal voltage E_{ph} and OB is the phase current I_{ph} drawn at the proper power factor angle θ. AC is the effective resistance drop $I_{ph}\, r_e$ and C_D is the leakage reactance drop $I_{ph}\, X_\ell$. The stator current is divided into a direct axis component I_d and a quadrature axis component I_q, and $I_d\, X_{ad}$ will thus be the voltage induced in the stator by the direct axis flux ϕ_q and $I_q\, X_{aq}$ will be the voltage induced in the stator by the cross flux ϕ_q. The voltage $I_q\, X_{aq}$ will be in quadrature with ϕ_q and it is represented by DE.

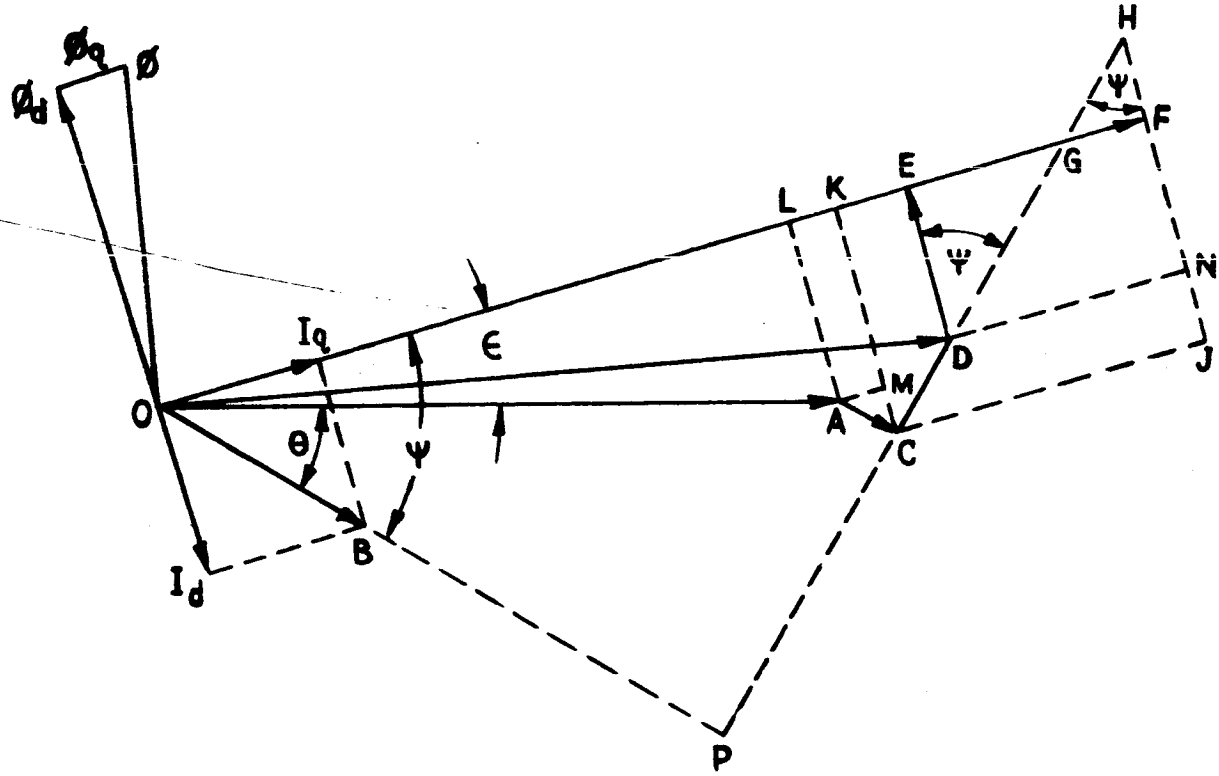
Likewise, the voltage $I_d\, X_{ad}$ will be in quadrature with ϕ_d and it is represented by EF. The voltage OF is the voltage that would exist at no load with excitation corresponding to rated load, neglecting saturation, and this voltage is represented by the symbol e_d.

Consider the triangle $OI_q\, B$ and

$$\sin \psi = \frac{I_d}{OB} = \frac{I_d}{I_{ph}} \; ; \; I_d = I_{ph} \sin \psi$$

$$\cos \psi = \frac{I_q}{OB} = \frac{I_q}{I_{ph}} \; ; \; I_q = I_{ph} \cos \psi$$

The triangles $OI_q\, B$ and DEG are similar because EG is perpendicular to $I_q\, B$, GD is perpendicular to BO, and DE is perpendicular to OI_q. Thus angle O is equal to angle D. Also, triangles DEG and HFG are similar



ϕ_q
ϕ
ϕ_d
H
ψ
F
G
E
L
K
ψ
N
I_q
ϵ
D
J
M
O
A
C
θ
ψ
B
I_d
P

because DE is parallel to HF, EG is concentric with FG, and GD is concentric with GH, and therefore angle D and angle H are equal. From a similar triangle relationship the angle A of triangle AMC is also equal to ψ .

From triangle DHN

$$\sin \psi = \frac{DN}{DH} = \frac{I_d X_{ad}}{DH}$$

$$DH = \frac{I_d X_{ad}}{\sin \psi} = \frac{I_d X_{ad}}{I_d / I_{ph}} = I_{ph} X_{ad}$$

$$CH = I_{ph} X_{ad} + I_{ph} X_{\ell} = I_{ph} X_d$$

$$CJ = KF = CH \sin \psi = I_{ph} X_d \sin \psi$$

$$OL = OA \cos \epsilon = E_{ph} \cos \epsilon$$

$$AM = LK = I_{ph} r_e \cos \psi$$

Thus the nominal voltage e_d is derived as

$$e_d = OL + LK + KF$$

$$e_d = E_{ph} \cos \epsilon + I_{ph} (r_e \cos \psi + X_d \sin \psi)$$

In the per unit system of notation E_{ph} and I_{ph} are unity at rated load conditions and if resistance is neglected the nominal voltage equation becomes

$$e_d = \cos \epsilon + X_d \sin \psi$$

From triangle DEG

$$\cos \psi = \frac{DE}{DG} = \frac{I_q X_{aq}}{DG}$$

$$DG = \frac{I_q X_{aq}}{\cos \psi} = \frac{I_q X_{aq}}{I_q / I_{ph}} = I_{ph} X_{aq}$$

$$CG = CD + DG = I_{ph} X_\ell + I_{ph} X_{aq} = I_{ph} X_q$$

Therefore, if resistance is again neglected the angles ϵ and ψ can be determined by

$$\text{Tan } \psi = \frac{PG}{OP} = \frac{I_{ph} X_q + E_{ph} \sin \theta}{E_{ph} \cos \theta} = \frac{X_q + \sin \theta}{\cos \theta}$$

When load is applied to the generator the flux wave shape will be distorted and the wave form under load will be less effective in generating voltage than the no load wave form. The reason for this is that the fundamental of the wave form under load is relatively less than that of the no load form for an equal total flux per pole under each condition. Therefore the flux per pole under load conditions will be greater than that required at no load, and the flux per pole under load is

$$\phi_{PL} = \phi_p \left[e_d - .93 X_{ad} \sin \psi \right]$$

The leakage flux under load will also increase and

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

The total flux per pole in the rotor thus becomes

$$\phi_{pt\ell} = \phi_{PL} + \phi_{\ell\ell}$$

and the density of the pole under load is

$$B_{PL} = \frac{\phi_{pt}\ell}{a_p}$$

The total ampere turns per pole under load can thus be calculated as

$$F_L = e_d F_g + (1 + \cos\theta)\, F_T + F_C + F_{PL}$$

SINGLE PHASE CALCULATIONS

When two phases of a normal three phase generator are used for single phase operation the machine reactances are first calculated on the basis of a three phase machine and the single phase reactances then become:

$$X_{ad}(1\phi) = \frac{X_{ad}(3\phi)}{\sqrt{3}}$$

$$X_d(1\phi) = \frac{X_d(3\phi) + X_2(3\phi)}{\sqrt{3}}$$

$$X_q(1\phi) = \frac{X_q(3\phi) + X_2(3\phi)}{\sqrt{3}}$$

$$X_d'(1\phi) = \frac{X_d'(3\phi) + X_2(3\phi)}{\sqrt{3}}$$

$$X_d''(1\phi) = \frac{X_d''(3\phi) + X_2(3\phi)}{\sqrt{3}}$$

The negative sequence component of the single phase armature reaction wave will induce large currents in the damper winding and this will cause high

damper losses under load conditions. Until further experience is accumulated it is not felt advisable to exceed current densities of 10,000 amps/sq. in. in the damper bars under normal load conditions when the current is calculated in the following manner.

$$\text{Neg. Seq. A. T.} = \frac{\left[X_{ad}(\text{3 phase})\right] \; F_g}{\sqrt{3}}$$

$$I_{RMS} \text{ per bar} = \frac{(\pi)(\text{Neg. Seq. A. T.})}{(\sqrt{2})\,(n_b + 1)}$$

WOUND-POLE NON-SALIENT POLE GENERATOR

NON-SALIENT POLE SYNCHRONOUS DESIGN SHEET

STATOR

Bore Punchings _____
Core Length _____
DBS x 2 _____
Frame Bore _____
Slots _____
Size Slots _____

Type Winding _____
Throw _____
Skew-Dist.Fact. _____
Chord Factor _____
Cond. per Slot _____
Total Eff. Cond. _____
Cond. Size _____
Area of Cond. _____
Current Density _____

Winding Constant _____
Total Flux _____
Area of Gap _____
Air Gap Density _____
Pole Constant _____
Flux per Pole _____

Tooth Pitch _____
Tooth Density _____
Core Density _____
Grade of Iron _____

1/2 Mean Turn _____
Res. per PH at ___ _____
Eddy Factor Top _____
Eddy Factor Bottom _____

Demag. Factor _____
Demag. A.T. _____
Amp.Cond. per In. _____

Reactance Factor X _____
Cond.Perm. λ_i _____
End Perm. λ_E _____
Leakage React. _____
Air Gap Perm. λ_a _____
React. of Arm _____
Reaction

Wt. of Copper _____
Wt. of Iron _____

ROTOR

Total Air Gap _____
Rotor Diameter _____
Peripheral Speed _____
Slots Punched _____
Slots Wound _____ α _____
Size Slots _____
Tooth Pitch _____
Grade of Iron _____
Core Length _____

Cond. per Slot _____
Turns per Pole _____
Cond. Size _____
Area Cond. _____
Mean Turn _____
Res. at _____

Flux in Pole Center _____
Leakage Flux _____
Center Section Density _____
Core Density _____

% Load		
Amps		
Volts		
Amps/In^2		

Field Leakage React. X_F _____
Field Self Induct _____
Damper Leak. React. X_{DD} _____

Wt. of Copper _____
Wt. of Iron _____

REACT.-TIME CONSTANT

Synchronous _____
Unsat. Trans. _____
Sat. Trans. _____
Subtransient _____
Neg. Sequence _____
Zero Sequence _____
Potier _____
Open Circuit Time Con. _____
Arm. Time Const. _____
Trans. Time Const. _____

SLOTS

Carter Coeff. Sta. _____
Carter Coeff. Rot. _____
Effective Gap _____

SATURATION

Air Gap A.T. _____
Stator A.T. _____
Rotor A.T. _____
No Load A.T. _____
Rated Load A.T. _____
Overload A.T. _____
Short Circuit A.T. _____
Short Circuit Ratio _____

LOSSES - EFFICIENCY

% Load		
F & W		
Sta. Teeth		
Sta. Core		
Pole Face		
Damper		
Sta. I^2R		
Eddy		
Rot. I^2R		
Σ Losses		
Rating		
Rtg. & Loss		
% Loss		
% Eff.		

Stator Watt per In.^{2}
Rotor Watts per In.^{2}

EWO _____ MODEL NO. _____ TYPE COOLING _____

_____ KVA _____ % PF _____ VOLTS _____ AMPS _____ PHASE

_____ CYCLES _____ RPM DESIGN ENGINEER _____

Chord Factors K_p For Harmonics At Different Pitches — Table I.

h																																									
														y/mq																											
1	3/3																																						2/3		
2	6/6																	5/6																				4/6		
3	9/9											8/9											7/9															6/9		
4	12/12								11/12									10/12								9/12												8/12		7/12
5	15/15						14/15							13/15							12/15							11/15									10/15			9/15	
6	18/18					17/18						16/18						15/18					14/18						13/18								12/18				
7	21/21				20/21					19/21					18/21				17/21					16/21					15/21							14/21				
8	24/24			23/24					22/24				21/24					20/24			19/24				18/24					17/24						16/24		15/24		14/24
9	27/27		26/27					25/27				24/27				23/27			22/27				21/27				20/27					19/27				18/27		17/27		16/27	
10	30/30	29/30					28/30				27/30			26/30				25/30			24/30			23/30				22/30					21/30		20/30	19/30				18/30		
y/mq	1.0	.967	.964	.959	.952	.945	.934	.926	.917	.905	.906	.889	.875	.867	.857	.852	.833	.815	.810	.800	.792	.779	.767	.762	.750	.741	.734	.722	.712	.709	.705	.700	.667	.634	.630	.625	.600	.592	.584
1	1.0	.999	.998	.998	.997	.996	.995	.993	.991	.989	.988	.985	.981	.978	.975	.973	.966	.958	.956	.951	.947	.940	.934	.931	.924	.918	.914	.906	.901	.897	.844	.891	.866	.839	.835	.831	.809	.800	.793
3	-1.0	-.988	-.985	-.981	-.975	-.966	-.951	-.940	-.924	-.901	-.891	-.865	-.831	-.809	-.782	-.766	-.707	-.643	-.623	-.588	-.556	-.500	-.454	-.434	-.383	-.342	-.309	-.259	-.222	-.195	-.174	-.156	0.0	.156	.174	.195	.309	.342	.383
5	1.0	.966	.958	.947	.931	.906	.866	.835	.793	.733	.707	.643	.556	.500	.434	.396	.259	.116	.075	0.0	.065	.174	.259	.295	.383	.447	.500	.574	.623	.660	.690	.707	.866	.966	.974	.982	1.0	.998	.993
7	-1.0	-.943	-.918	-.892	-.866	-.819	-.743	-.686	-.609	-.500	-.454	-.342	-.177	-.105	0.0	.058	.259	.449	.500	.588	.659	.766	.839	.866	.924	.958	.978	.996	1.0	.998	.993	.988	.866	.629	.588	.559	.309	.225	.139
9	1.0	.897	.866	.831	.782	.707	.588	.500	.383	.223	.156	0.0	.191	.304	.434	.500	.707	.866	.901	.951	.981	1.0	.998	.975	.924	.866	.804	.707	.623	.556	.500	.454	0.0	.358	.407	.462	.500	.755	.875
11	-1.0	-.834	-.802	-.750	-.680	-.574	-.407	-.287	-.131	.075	.156	.342	.556	.660	.782	.795	.966	.998	.989	.951	.897	.766	.629	.583	.383	.231	.105	.087	.222	.321	.396	.454	.866	.999	.994	.981	.809	.721	.618
13	1.0	.777	.727	.659	.563	.423	.208	.058	.131	.365	.454	.643	.831	.914	.975	.993	.966	.802	.733	.588	.442	.174	.052	.148	.383	.550	.669	.818	.901	.947	.973	.988	.866	.371	.294	.195	.309	.459	.598
15	-1.0	-.707	-.643	-.556	-.434	-.259	0.0	.174	.383	.624	.707	.866	.981	1.0	.975	.940	.707	.342	.223	0.0	.195	.500	.707	.782	.924	.981	1.0	.966	.907	.831	.766	.707	0.0	.696	.760	.831	1.0	.982	.930
17	1.0	.629	.550	.442	.295	.087	.208	.396	.609	.826	.891	.985	.981	.914	.782	.686	.259	.231	.365	.588	.752	.940	.999	.997	.924	.802	.669	.423	.222	.065	.058	.156	.866	.940	.948	.831	.309	.100	.113
19	-1.0	-.545	-.449	-.321	-.149	.087	.407	.597	.793	.956	.988	.985	.831	.669	.434	.284	.259	.727	.826	.951	.948	.940	.777	.680	.383	.116	.105	.423	.623	.752	.835	.891	.866	.072	.047	.194	.809	.952	.989
21	1.0	.454	.342	.195	0.0	.259	.588	.766	.924	1.0	.988	.866	.556	.309	0.0	.174	.707	.985	1.0	.951	.831	.500	.156	0.0	.383	.643	.804	.966	1.0	.981	.940	.891	0.0	.881	.935	.981	.809	.628	.402
23	-1.0	-.358	-.231	-.064	.149	.423	.743	.894	.991	.956	.891	.643	.195	.105	.434	.397	.966	.918	.826	.588	.321	.174	.545	.680	.924	.998	.978	.819	.623	.442	.287	.156	.866	.792	.696	.555	.309	.566	.778
25	1.0	.259	.116	-.064	-.295	.574	.866	.978	.991	.826	.707	.342	.195	.500	.782	.894	.966	.550	.365	0.0	.321	.766	.966	.997	.924	.727	.500	.087	.222	.442	.597	.707	.866	.061	.383	.555	1.0	.951	.809
27	-1.0	-.170	0.0	.195	.434	.707	.951	1.0	.924	.624	.454	0.0	.556	.809	.975	1.0	.707	0.0	.223	.558	.831	1.0	.897	.782	.383	0.0	.305	.707	.901	.981	1.0	.988	0.0	.983	1.0	.981	.309	.025	.356
29	1.0	.052	.116	.321	.563	.819	.995	.973	.793	.365	.156	.342	.831	.978	.975	.894	.259	.550	.733	.951	.948	.766	.358	.148	.383	.727	.914	.996	.901	.752	.597	.454	.866	.369	.412	.194	.809	.965	.995
31	-1.0	.052	.231	.442	.680	.906	.995	.894	.109	.075	.156	.643	.981	.978	.782	.597	.259	.918	.989	.951	.752	.174	.358	.383	.924	.998	.914	.574	.222	.065	.287	.454	.866	.317	.673	.831	.809	.525	.102
33	1.0	.156	.342	.556	.782	.966	.951	.766	.383	.223	.454	.866	.981	.809	.434	.174	.707	.985	.901	.588	.195	.500	.891	.975	.924	.643	.309	.259	.623	.831	.940	.988	0.0	.992	.944	.831	.309	.666	.910
35	-1.0	.259	.449	.659	.866	.996	.866	.597	.131	.500	.707	.985	.831	.500	0.0	.287	.966	.727	.500	0.0	.442	.940	.966	.866	.383	.116	.500	.906	1.0	.947	.835	.707	.866	.294	.079	.194	1.0	.905	.637
37	1.0	.358	.550	.750	.931	.996	.743	.396	.131	.793	.891	.985	.556	.105	.434	.686	.966	.231	.075	.588	.897	.940	.545	.295	.383	.802	.978	.906	.623	.321	.058	.156	.866	.855	.884	.981	.309	.150	.577
39	-1.0	.454	.643	.831	.975	.966	.588	.174	.383	.901	.988	.866	.195	.309	.782	.940	.707	.342	.623	.951	.981	.500	.156	.434	.924	.985	.809	.259	.222	.556	.766	.891	0.0	.909	.780	.555	.805	.990	.939
41	1.0	.545	.727	.894	.997	.906	.407	.058	.609	.989	.988	.643	.195	.669	.975	.933	.259	.802	.956	.951	.659	.174	.777	.931	.924	.550	.105	.574	.901	.998	.973	.891	.866	.010	.264	.555	.809	.414	.088
43	-1.0	.629	.802	.947	.997	.819	.208	.287	.793	.989	.891	.342	.556	.914	.975	.795	.259	.998	.956	.588	.065	.766	.999	.931	.383	.231	.669	.996	.901	.660	.346	.156	.866	.916	.990	.981	.309	.754	.984
45	1.0	.707	.866	.987	.925	.707	0.0	.500	.924	.901	.707	0.0	.831	1.0	.782	.500	.707	.866	.623	0.0	.556	1.0	.707	.434	.383	.866	1.0	.707	.222	.145	.500	.707	0.0	.739	.523	.194	1.0	.844	.262
47	-1.0	.777	.918	.998	.931	.574	.208	.686	.991	.733	.454	.342	.981	.914	.434	.058	.966	.944	.075	.588	.947	.766	.052	.295	.924	.958	.669	.087	.623	.897	.993	.988	.866	.312	.575	.831	.305	.273	.762
49	1.0	.839	.958	.998	.866	.423	.407	.895	.991	.500	.156	.643	.981	.669	0.0	.396	.966	.116	.500	.951	.947	.174	.629	.866	.224	.597	.105	.819	1.0	.897	.690	.454	.866	.944	.779	.831	.809	1.0	.823
51	-1.0	.891	.995	.981	.782	.254	.588	.940	.924	.223	.156	.866	.831	.309	.434	.766	.707	.643	.901	.951	.556	.500	.988	.975	.383	.342	.809	.966	.623	.195	.174	.454	0.0	.501	.208	.194	.805	.297	.333
53	1.0	.934	.998	.947	.680	.087	.743	.993	.793	.075	.454	.985	.556	.105	.782	.973	.259	.958	.989	.588	.065	.940	.819	.583	.383	.318	.978	.423	.222	.660	.894	.988	.866	.586	.818	.981	.309	.721	.997
55	-1.0	.966	.998	.897	.563	.087	.866	.993	.605	.365	.707	.985	.195	.500	.975	.973	.259	.958	.733	0.0	.659	.940	.259	.148	.924	.918	.500	.423	.901	.998	.844	.707	.866	.774	.993	.555	1.0	.771	.187
57	1.0	.988	.981	.831	.434	.255	.951	.940	.383	.624	.891	.866	.195	.809	.975	.766	.707	.643	.223	.588	.981	.500	.454	.782	.924	.342	.309	.966	.901	.556	.174	.156	0.0	.215	.741	.555	.309	.407	.899
59	-1.0	.997	.958	.756	.295	.423	.995	.835	.131	.826	.988	.643	.556	.978	.782	.396	.966	.116	.365	.951	.997	.174	.934	.997	.383	.597	.914	.819	.222	.321	.694	.891	.866	.897	.966	.981	.809	.994	.777
61	1.0	.994	.970	.694	.149	.574	.995	.686	.131	.956	.988	.342	.831	.978	.434	.058	.966	.449	.826	.951	.442	.766	.954	.680	.383	.958	.914	.087	.623	.942	.993	.891	.866	.772	.685	.194	.809	.175	.557
63	-1.0	.988	.866	.556	0.0	.707	.951	.500	.383	1.0	.891	0.0	.981	.809	0.0	.500	.707	.866	1.0	.588	.195	1.0	.454	0.0	.924	.866	.309	.707	1.0	.831	.500	.156	0.0	.091	.468	.831	.309	.894	.447

TABLE 2 – VALUES OF K_{dn} FOR INTEGRAL SLOT 3φ WINDINGS

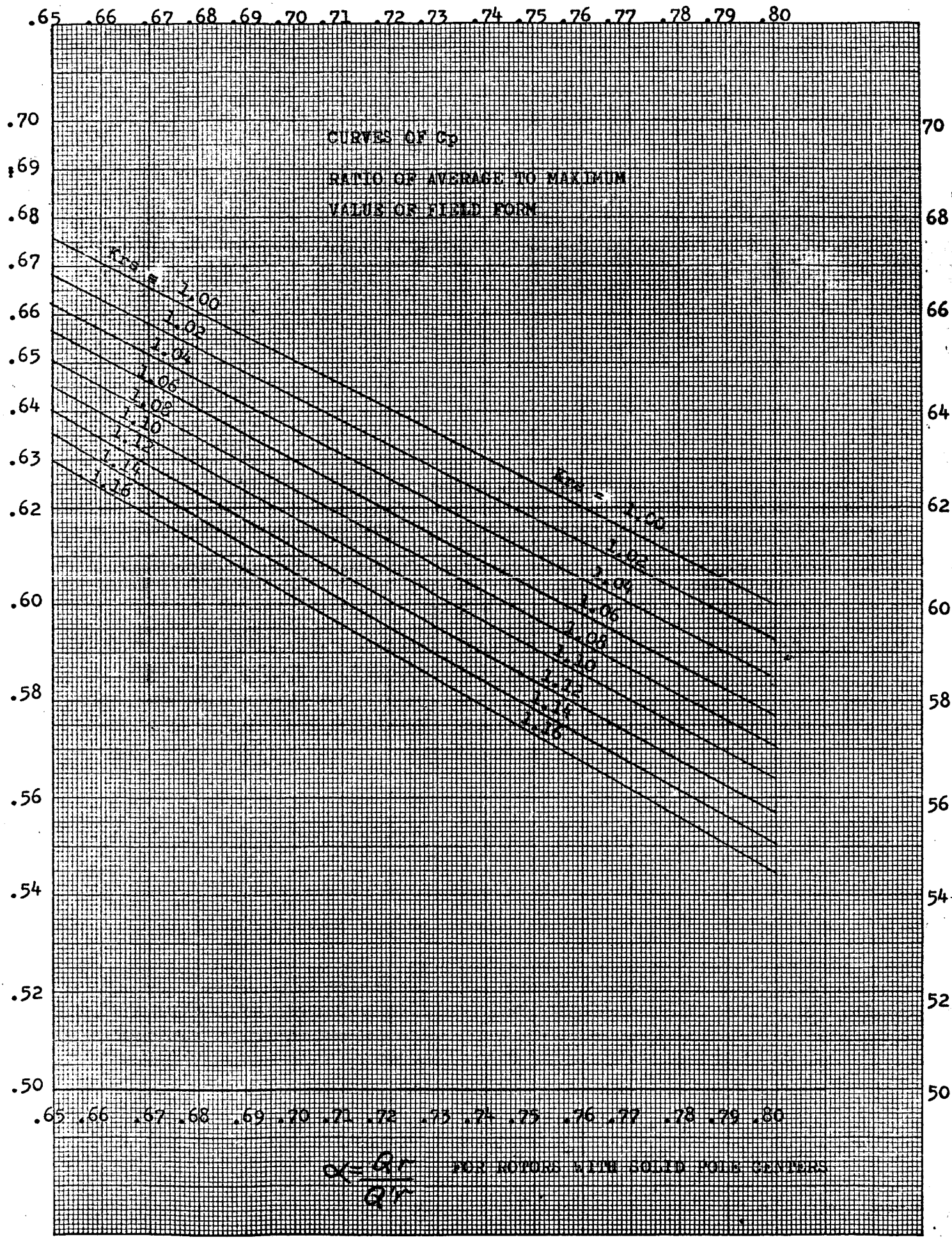
n	K_{dn} – HARMONIC DISTRIBUTION FACTORS									
q=	2	3	4	5	6	7	8	9	10	∞
1	.966	.960	.958	.957	.957	.957	.956	.955	.955	.955
3	.707	.667	.654	.646	.644	.642	.641	.640	.639	.636
5	.259	.217	.205	.200	.197	.195	.194	.194	.193	.191
7	-.259	-.177	-.158	-.149	-.145	-.143	-.141	-.140	-.140	-.136
9	-.707	-.333	-.270	-.247	-.236	-.229	-.225	-.222	-.220	-.212
11	-.966	-.177	-.126	-.110	-.102	-.097	-.095	-.093	-.092	-.087
13	-.966	.217	.126	.102	.092	.086	.083	.081	.079	.073
15	-.707	.667	.270	.200	.172	.158	.150	.145	.141	.127
17	-.259	.960	.158	.102	.084	.075	.070	.066	.064	.056
19	.259	.960	-.205	-.110	-.084	-.072	-.066	-.062	-.060	-.059
21	.707	.667	-.654	-.247	-.172	-.143	-.127	-.118	-.112	-.091
23	.966	.217	-.958	-.149	-.092	-.072	-.063	-.057	-.054	-.041
25	.966	-.177	-.958	.200	.102	.075	.063	.056	.052	.038
27	.707	-.333	-.654	.646	.236	.158	.127	.111	.101	.071
29	.259	-.177	-.205	.957	.145	.086	.066	.056	.050	.033
31	-.259	.217	.158	.957	-.197	-.097	-.070	-.057	-.050	-.031
33	-.707	.667	.270	.646	-.644	-.229	-.150	-.118	-.101	-.058
35	-.966	.960	.126	.200	-.957	-.143	-.083	-.062	-.052	-.027
37	-.966	.960	-.126	-.149	-.957	.195	.095	.066	.054	.026
39	-.707	.667	-.270	-.247	-.644	.642	.225	.145	.112	.049
41	-.259	.217	-.158	-.110	-.197	.957	.141	.081	-.060	.023
43	.259	-.177	.205	.102	.145	.957	-.194	-.093	-.064	-.022
45	.707	-.333	.654	.200	.236	.642	-.641	-.222	-.141	-.042
47	.966	-.177	.958	.102	.102	.195	-.956	-.140	-.079	-.020
49	.966	.217	.958	-.110	-.092	-.143	-.956	.194	.092	.019
51	.707	.667	.654	-.247	-.172	-.229	-.641	.640	.220	.038
53	.259	.960	.205	-.149	-.084	-.097	-.194	.955	.140	.018
55	-.259	.960	-.158	.200	.084	.086	.141	.955	-.193	-.017
57	-.707	.667	-.270	.646	.172	.158	.225	.640	-.639	-.033
59	-.966	.217	-.126	.957	.092	.075	.095	.194	-.955	-.016
61	-.966	-.177	.126	.957	-.102	-.072	-.083	-.140	-.955	.016
63	-.707	-.333	.270	.646	-.236	-.143	-.150	-.222	-.639	.030
65	-.259	-.177	.158	.200	-.145	-.072	-.070	-.093	-.193	.015

Round Copper Wire

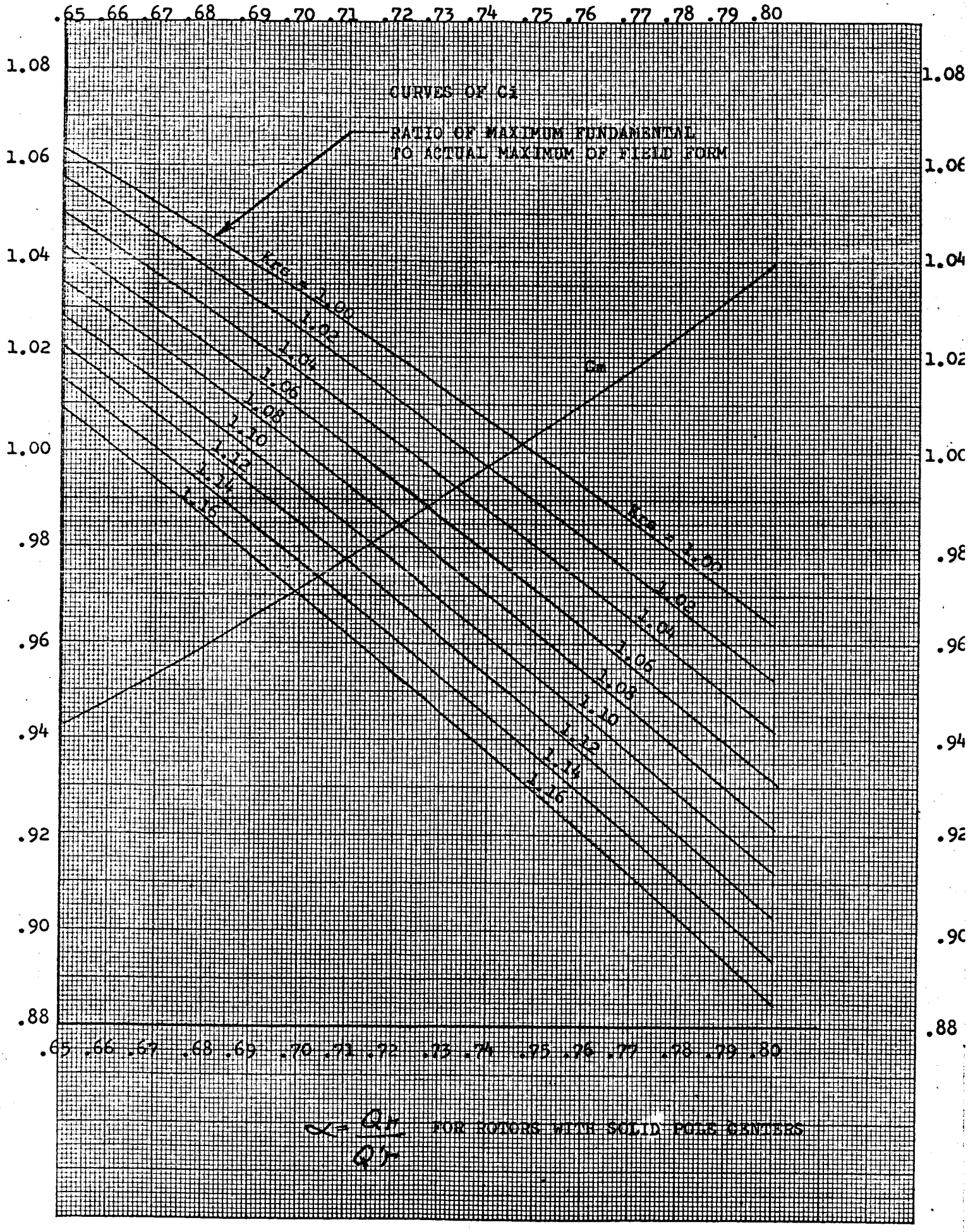
Size AWG	Bare Diameter	Area □"	Ω/1000' @25°C	Single Formvar	Heavy Formvar	Single Glass Formvar	Bare Wt. #/1000'	Single Glass Silicone	Double Glass Silicone
36	.0050	.0000196	424	.0056	.0060		.0757		
35	.0056	.0000246	338	.0062	.0066		.0949		
34	.0063	.0000312	266	.0070	.0074		.1201		
33	.0071	.0000396	210	.0079	.0084		.1526		
32	.0080	.0000503	165	.0088	.0094	.0121	.1937		
31	.0089	.0000622	134	.0097	.0104	.0130	.2398		
30	.0100	.0000785	106	.0108	.0116	.0142	.3025	.0132	.0152
29	.0113	.000100	83.1	.0122	.0130	.0156	.3866	.0145	.0165
28	.0126	.000125	66.4	.0135	.0144	.0169	.4806	.0158	.0178
27	.0142	.000158	52.6	.0152	.0161	.0186	.6101	.0174	.0194
26	.0159	.000199	41.7	.0169	.0179	.0203	.7650	.0191	.0211
25	.0179	.000252	33.0	.0190	.0200	.0224	.970	.0211	.0231
24	.0201	.000317	26.2	.0213	.0223	.0263	1.223	.0251	.0276
23	.0226	.000401	20.7	.0238	.0249	.0289	1.546	.0276	.0301
22	.0254	.000507	16.4	.0266	.0277	.0317	1.937	.0303	.0328
21	.0285	.000638	13.0	.0299	.0310	.0349	2.459	.0335	.0360
20	.0320	.000804	10.3	.0334	.0346	.0384	3.099	.0370	.0395
19	.0360	.00102	8.14	.0374	.0386	.0424	3.900	.0409	.0434
18	.0403	.00126	6.59	.0418	.0431	.0468	4.914	.0453	.0478
17	.0453	.00159	5.22	.0469	.0482	.0519	6.213	.0503	.0528
16	.0508	.00204	4.07	.0524	.0538	.0575	7.812	.0558	.0583
15	.0571	.00255	3.26	.0588	.0602	.0639	9.87	.0621	.0646
14	.0641	.00322	2.58	.0659	.0673	.0710	12.44	.0691	.0716
13	.072	.00407	2.04	.0738	.0753	.0789	15.69	.0770	.0795
12	.0808	.00515	1.61	.0827	.0842	.0877	19.76	.0858	.0883
11	.0907	.00650	1.28	.0927	.0942	.0977	24.90	.0957	.0982
10	.102	.00817	1.02	.1039	.1055	.1089	31.43	.1069	.1094
9	.114	.0102	.814	.1165	.1181	.1225	39.62	.1204	.1254
8	.129	.0131	.634	.1306	.1323	.1366	49.98	.1345	.1395
7	.144	.0163	.510	.1465	.1482	.1525	63.03	.1503	.1553
6	.162	.0206	.403	.1643	.1661	.1703	79.44	.1680	.1730
5	.182	.0260	.319	.1842	.1861	.1902	100.2	.1879	.1929
4	.204	.0327	.254				126.3	.2103	.2153
3	.229	.0412	.202				159.3		
2	.258	.0523	.159				200.9		
0	.325	.0830	.100						
2/0	.365	.105	.0791						
4/0	460	.166	.0500						

Half Size Round Copper Wire

Size AWG	Bare Diameter	Area □"	Bare Wt #/1000'	Ω/1000' @ 20°C
1/0½	.3071	.0741	285.5	.1100
1½	.2734	.0587	226.3	.1387
2½	.2435	.0466	179.5	.1749
3½	.2169	.0370	142.4	.2204
4½	.1931	.0293	112.9	.2781
5½	.1720	.0232	89.6	.3506
6½	.1532	.0184	71.0	.4419
7½	.1364	.0146	56.3	.5574
8½	.1215	.0116	44.7	.7025
9½	.1082	.0092	35.4	.8859
10½	.0963	.00728	28.1	1.118
11½	.0858	.00578	22.3	1.409
12½	.0764	.00458	17.7	1.778
13½	.0680	.00363	14.0	2.243
14½	.0606	.0288	11.1	2.824
15½	.0540	.00229	8.83	3.557
16½	.0481	.00182	7.00	4.482
17½	.0428	.00144	5.54	5.661
18½	.0381	.00114	4.39	7.143
19½	.0340	.000907	3.50	8.972
20½	.0302	.000716	2.76	11.37
21½	.0269	.000568	2.19	14.33
22½	.0240	.000452	1.74	18.01
23½	.0214	.000360	1.39	22.65
24½	.0190	.000284	1.09	28.73
25½	.0169	.000224	.864	36.31
26½	.0151	.000179	.690	45.49
27½	.0134	.000141	.544	57.75
28½	.0120	.000113	.436	72.02
29½	.0106	.000088	.340	92.27
30½	.0095	.000071	.273	114.85



K+E 10 X 10 TO THE CM. 359-14
KEUFFEL & ESSER CO. MADE IN U.S.A.



K+E 10 X 10 TO THE CM. 359-14
KEUFFEL & ESSER CO. MADE IN U.S.A.

GRAPH NO. 1

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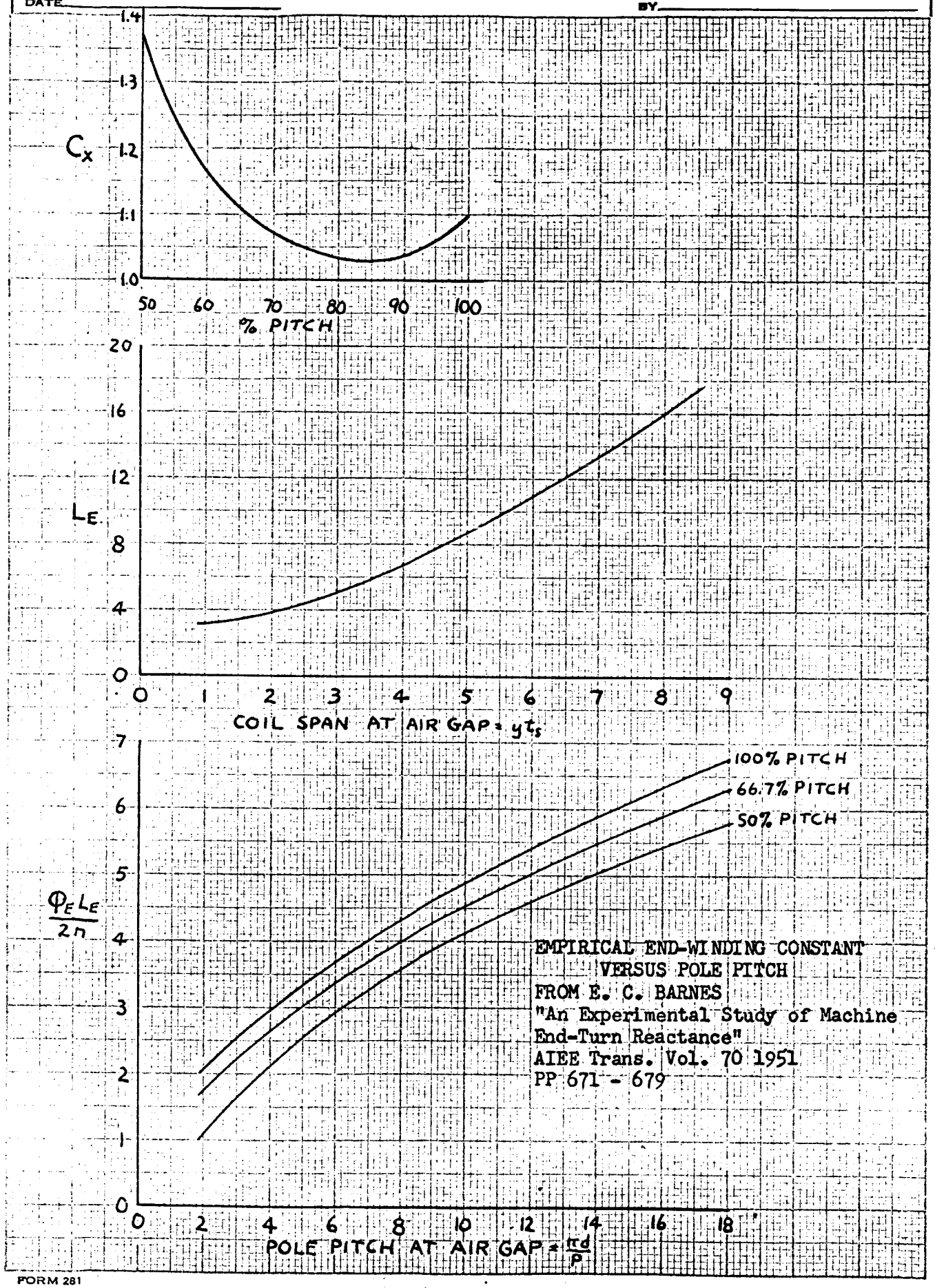
E. W. O. REP'T NO.

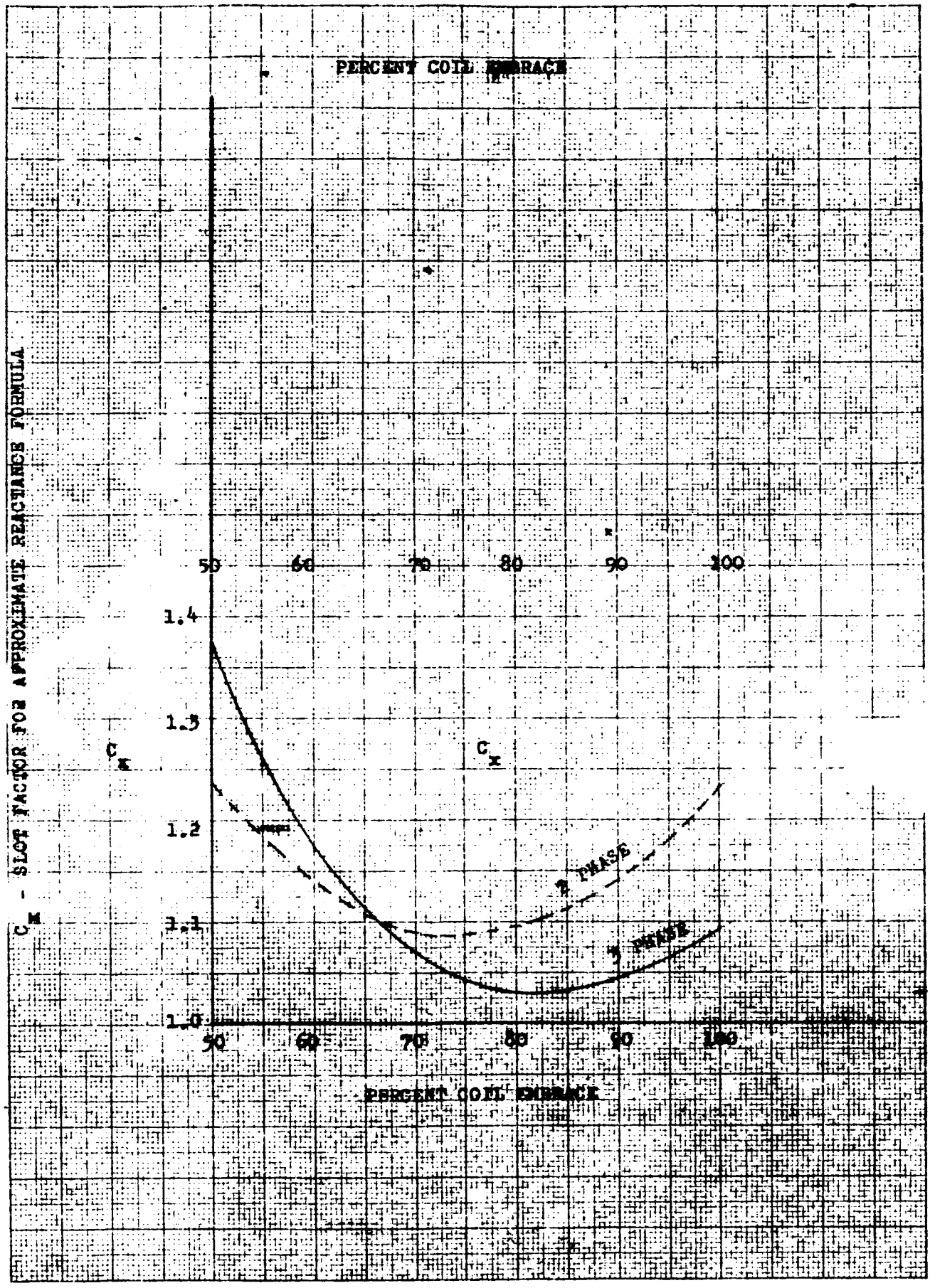
SHOWING

DATE_____ BY_____



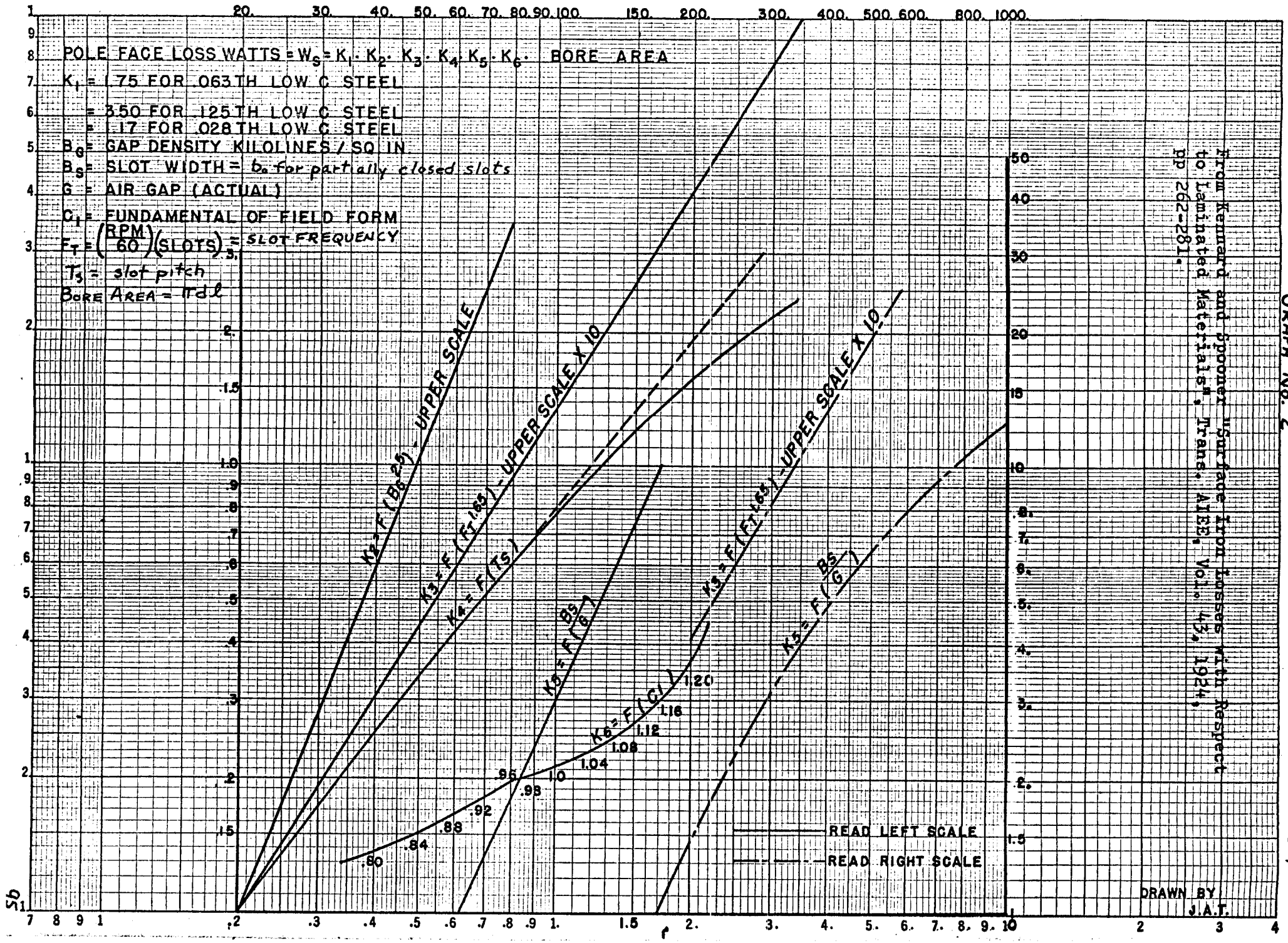
EMPIRICAL END-WINDING CONSTANT
VERSUS POLE PITCH
FROM E. C. BARNES
"An Experimental Study of Machine
End-Turn Reactance"
AIEE Trans. Vol. 70 1951
PP 671 - 679

FORM 281



K+E 10 X 10 TO THE CM. 18 X 25 CM. KEUFFEL & ESSER CO.

KEUFFEL & ESSER CO., N. Y. NO. 359-111
Logarithmic, 2¾ × 2 Cycles.
MADE IN U. S. A.



From Kennard and Spooner "Surface Iron Losses with Respect to Laminated Materials", Trans. AIEE, Vol. 43, 1924, pp 262-281.

GRAPH No. 2

1124

STATOR

PUNCHING I. D. --(d) The inside diameter of the stator punchings.

PUNCHING O. D. --(D) The outside diameter of the stator punchings.

CORE LENGTH--(ℓ) The overall length of the stator iron. Also record on this line the solid core length (ℓ_s). The solid length is the overall length times the stacking factor (K_i). The stacking factor allows for the coating on the punchings, the burrs due to slotting, and the deviations in flatness. Approximate values of K_i are given in the table below.

THICKNESS OF LAMINATIONS (INCHES)	GAGE	K_i
.014	29	0.92
.018	26	0.93
.025	24	0.95
.028	23	0.97
.063	--	0.98
.125	--	0.99

If ventilating ducts are used their length must be subtracted from the overall length also.

DEPTH BELOW SLOTS x 2--($2h_c$) The depth of the stator core below the slots times 2.

$$2h_c = D = (d+2h_s)$$

Due to mechanical strength reasons h_c should never be less than 70% of h_s.

SLOTS--(Q) The number of stator slots. Write Q as a product of poles (p) times phases (m) times slots per phase per pole (q). Thus pmq = Q. In general fractions of q close to 1/3 and 2/3 should be avoided, because these fractions are inclined toward producing force poles that cause excessive noise and vibration. In three phase machines fractions of q with thirds or any multiple of three in the denominator should be avoided because with these values a balanced winding cannot be obtained.

SIZE SLOTS--(b_s and h_s) The width of the stator slot (b_s) and the depth of the stator slot (h_s).

CARTER COEFFICIENT--(K_s) The Carter coefficient for the stator slots.

$$K_s = \frac{t_s(5g+b_s)}{t_s(5g+b_s)-b_s^2} \quad \text{(for open slots)}$$

$$K_s = \frac{t_s(4.44g+.75b_o)}{t_s(4.44g+.75b_o)-b_o^2} \quad \text{(for partially closed slots)}$$

TYPE WINDING-- Record whether star or delta (Y or Δ), and whether series or parallel.

THROW--(y) The coil span in slots. Record the percent span (y/mq) and designate the slots in which the coil is placed (1 + y).

SKEW AND DISTRIBUTION FACTORS--(K_{sk} and K_d) The skew factor (K_{sk}) is the ratio of the voltage induced in the coils to the voltage that sould be induced if there was no skew.

OR

$$K_{sk} = \frac{\sin \frac{t_{sk}\pi}{2t_p}}{\frac{t_{sk}\pi}{2t_p}}$$

The distribution factor (K_d) is the ratio of the voltage induced in the coils to the voltage that would be induced if the winding was concentrated in a single slot

$$K_d = \frac{\sin\left(q\alpha_{s/2}\right)}{q \sin\alpha_{s/2}} \quad \text{(for integral slot machines)}$$

$$K_d = \frac{\sin(N\alpha_{m/2})}{N \sin\alpha_{m/2}} \quad \text{(for fractional slot machines)}$$

See table 2 in the non-salient pole manual for a compilation of distribution factors for the various harmonics. See "Grouping of Fractional Slot Windings" and "Distribution Factor" sections of the non-salient pole manual for an explanation of K_d for fractional slot machines.

CHORD FACTOR--(K_p) The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil.

$$K_p = \sin\left(\frac{Y}{mq} \times 90^\circ\right)$$

See Table 1 in the non-salient pole manual for a compilation of the pitch factors for the various harmonics.

CONDUCTORS PER SLOT--(n_s) The actual number of conductors per slot. ~~For random wound slots use a space factor of 80% to 85%~~ when determining the permissable number.

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

$$n_e = \frac{Qn_s K_p K_{sk}}{C}$$

CONDUCTOR SIZE-- Record the number of strands making up each conductor and their bare and insulated sizes. Indicate also the type of strand insulation.

CONDUCTOR AREA--(a_c) 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.

$$a_c = (\text{width of cond.})x(\text{thickness of cond.}) - .858r_c^2$$

Corner Radii			
Thickness	Width		
	.751 & Up	.187 - .750	Up to .188
.689 & up	3/16	3/16	--
.688 - .439	1/8	3/32	--
.438 - .226	3/32	1/16	--
.225 - .166	1/16	3/64	3/64
.165 - .126	1/16	1/32	1/32
.125 - .073	Rounded edge	1/32	1/64
.072 - .051	Rounded edge	Rounded edge	1/64
.050 & under	Rounded edge	Rounded edge	Rounded edge

Corner	$.858r_c^2$
1/64	.00021
1/32	.00084
3/64	.00189
1/16	.00335
3/32	.00754
1/8	.0134
3/16	.0302

Square wire .072 and under has a radius of .012. A rounded edge is produced by rolling round wire to the specified size.

CURRENT DENSITY--(s) The amperes per square inch of conductor.

$$s = \frac{I_{ph}}{Ca_c}$$

WINDING CONSTANT--(C_w) 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.

$$C_w = \frac{EC_1K_d}{\sqrt{2}\,E_{ph}m}$$

Assuming $K_d = .955$, $C_w = .225\,C_1$ for three phase delta machines and $C_w = .390C_1$ for three phase star ones. C_1 is the ratio of the maximum fundamental of the field form to the actual maximum of the field form. For pole heads with more than one radius the field form is determined from a flux plot of the air gap flux at no load, neglecting saturation, and C_1 is then obtained by Fourier analysis. For pole heads with only one radius, C_1 is obtained from curve #4. The graphical flux plotting method of determining C_1 is explained in the section titled "Derivations."

TOTAL FLUX--(ϕ_T) The total flux that would exist in the gap if the density was uniform and equal to the maximum gap density.

$$\phi_T = \frac{6000E10^6}{C_w n_e RPM}$$

GAP AREA-- The area of the gap surface at the stator bore = $\pi d \ell$

GAP DENSITY--(B_g) The maximum flux density in the air gap.

$$B_g = \frac{\phi_T}{\pi d \ell}$$

POLE CONSTANT--(C_p) The ratio of the average to the maximum value of the field form. For pole heads with more than one radius C_p is calculated from the same field form that was used to determine C_1, and this method is described in the second part of the manual. For pole heads with only one radius C_p is obtained from curve #4. Note the correction factor at the top of the curve.

FLUX PER POLE--(ϕ_p) The total flux per pole.

$$\phi_p = \frac{\phi_T C_p}{p}$$

TOOTH PITCH--(t_s and $t_{s\frac{1}{3}}$) The stator slot pitch on the inside stator bore, and the stator slot pitch at a distance a third of the way up the tooth.

$$t_s = \frac{\pi d}{Q} \qquad t_s 1/3 = \frac{\pi(d + \frac{2}{3} h_s)}{Q}$$

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

$$B_t = \frac{\phi_T}{Q \ell_s b_{t\,1/3}} \quad \text{where } b_{t\,1/3} = t_{s\,1/3} - b_s$$

CORE DENSITY--(B_c) The flux density in the stator core.

$$B_c = \frac{\phi_p}{2h_c \ell_s}$$

GRADE OF IRON-- Alloy identification and lamination thickness of stator iron.

1/2 MEAN TURN--(ℓ_t) The average length of one conductor.

$$\ell_t = \ell + L_E$$

where L_E = the end extension length

For random wound coils

$$L_E = .5 + \frac{K_t \pi y(d+h_s)}{Q}$$

where K_t = constant depending on the number of poles

K_t = 1.3 for 2 poles; 1.5 for 4 poles; and 1.7 for 6 poles and up

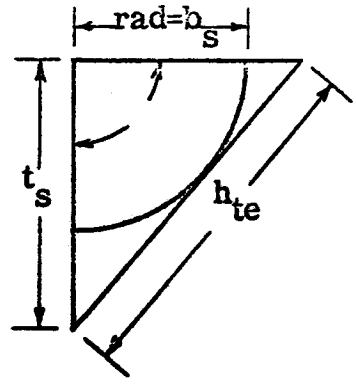
For formed coils

$$L_E = 2\ell_{e2} + \pi\left(\frac{h_1}{2} + d_b\right) + yh_{te}$$

where d_b = diameter of bender pin

h_{te} = is obtained from the diagram as shown

ℓ_{e2} = straight part of the coil extension beyond the core



RESISTANCE PER PHASE AT__ ^{o}--(R_{ph}) The resistance per phase calculated at the expected coil temperature.

$$R_{ph} = \frac{n_s Q \ell_t R_{1000}}{12000\, C^2 m} \times \frac{235 + X^{o}C}{260} = \rho \frac{n_s Q \ell_t}{m a_c C^2}$$

where ρ = resistivity at $X^{o}C$ = $.91 \times 10^{-6}$ $100^{o}C$

R_{1000} = resistance per 1000 ft. of conductor at $25^{o}C$

$X^{o}C$ = expected coil temperature in ^{o}C

EDDY FACTOR TOP-- The eddy factor of the top coil. Calculate this value at the expected operating temperature of the machine.

$$EF\,Top = 1 + \left[.584 + \left(\frac{N_{st}^2 - 1}{16}\right)\left(\frac{h'_{st}\ell}{h_{st}\ell_t}\right)^2\right]\frac{3.35}{1000}\left[\frac{h_{st} n_s f a_c}{b_s \rho'}\right]^2$$

where $\rho' = \rho \times 10^6$

N_{st} = number of strands per conductor in depth

h'_{st} = distance between centerline of strands in depth

h_{st} = height of uninsulated strand

EDDY FACTOR BOTTOM-- The eddy factor of the bottom coil at the expected operating temperature of the machine. Use same equation as E. F. top except use .0833 in place of .584.

DEMAGNETIZING FACTOR--(C_M and C_q) The ratio of the field ampere turns to the maximum sine wave stator ampere turns required to force

the same fundamental flux across the gap. The demagnetizing factor in the direct axis is

$$C_M = \frac{\alpha\pi + \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$$

and the cross magnetizing factor in the quadrature axis is

$$C_q = \frac{1/2\cos\frac{\alpha\pi}{2} + \alpha\pi - \sin\alpha\pi}{4\sin\frac{\alpha\pi}{2}}$$

The above factors can be read directly from curve #9 and calculation by the above formulas is thus unnecessary.

AMPERE CONDUCTORS PER INCH--(A) 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.

$$A = \frac{I_{ph} n_s K_p}{Ct_s}$$

REACTANCE FACTOR--(X) 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.

$$X = \frac{100AK_d}{\sqrt{2}\,C_1 B_g}$$

CONDUCTOR PERMEANCE--(λ_i) 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.

$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_2}{b_s} + \frac{h_1}{3b_s} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right] \qquad b_t = \text{tooth width at gap}$$

(b) For partially closed slots with constant slot width.

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

(c) For partially closed slots with constant tooth width.

$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_o}{b_o} + \frac{2h_t}{b_o + b_1} + \frac{2h_w}{b_1 + b_2} + \frac{h_1}{3b_2} + \frac{b_t^2}{16t_s g} + \frac{.35b_t}{t_s}\right]$$

(d) For round slots.

$$\lambda_i = C_X \frac{20}{mq}\left[.62 + \frac{h_o}{b_o}\right]$$

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

$$\left(C_X = \frac{1}{K_p^2 K_d^2}\right)$$

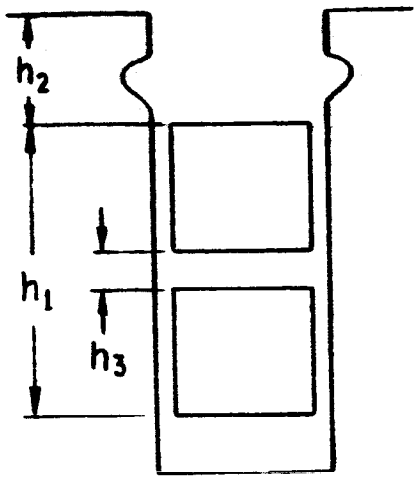
$$\lambda_i = C_X \frac{20}{mq}\left[\frac{h_2}{b_s} + \frac{h_1}{3b_s} + .6 + \frac{g}{2t_s} + \frac{t_s}{4g}\right] \qquad (K_X = 1)$$

In all of the above formulas C_X is a reduction factor that is dependent upon the pitch and distribution of the winding.

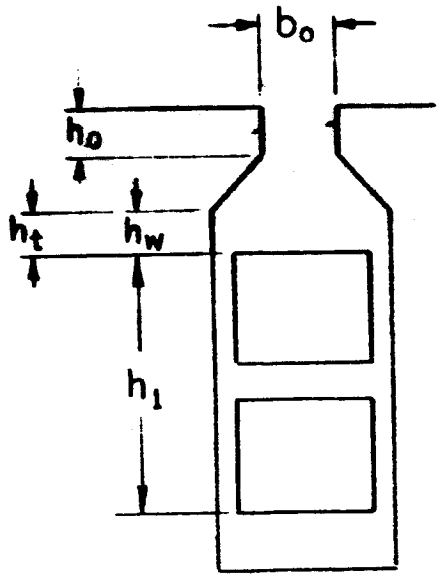
$$C_X = \frac{K_X}{K_p^2 K_d^2} \quad \text{where } K_X = \frac{1}{4}\left(\frac{3y}{mq} + 1\right) \text{ for 3 phase}$$

$$K_X = \frac{y}{mq} \text{ for 2 phase}$$

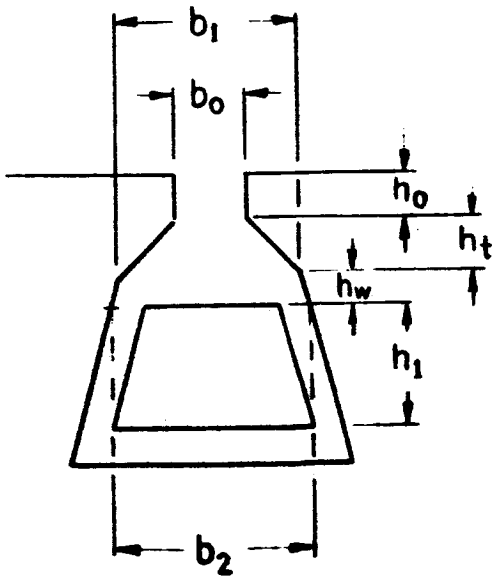
(a) Open Slots



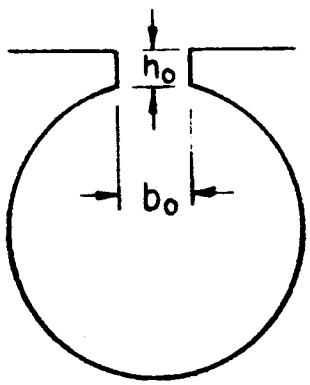
(b) Constant Slot Width



(c) Constant Tooth Width



(d) Round Slots



Values of C_X versus percent pitch for three phase windings are plotted on Graph #1. These values assume a distribution factor of .955. See Graph #1.

END WINDING PERMEANCE--(λ_E) The specific permeance for the end extension portion of the stator winding.

$$\lambda_E = \frac{6.28}{\ell K_d^2}\left[\frac{\phi_E L_E}{2n}\right] K_E$$

(Obtain the value of $\phi_E L_E$ from Graph #1

$$K_E = \frac{\text{Calculated valve of } L_E}{\text{Value of } L_E \text{ from Graph \#1}} \quad \text{(for machines of } d > 8'')$$

$$K_E = \sqrt{\frac{\text{Calculated value of } L_E}{\text{Value of } L_E \text{ from Graph \#1}}} \quad \text{(for machines of } d < 8'')$$

LEAKAGE REACTANCE--($X\ell$) The leakage reactance of the stator for steady state conditions

$$X_\ell = X(\lambda_i + \lambda_E)$$

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.

$$\lambda_B = \frac{.1d}{pg_e}\left[\frac{\sin \frac{3y}{mq} \times 90^\circ}{K_p}\right]$$

$$X_\ell = X(\lambda_i + \lambda_E + \lambda_B) \qquad \text{where } \lambda_b = 0 \text{ for 3 phase machines.}$$

AIR GAP PERMEANCE--(λ_a) The specific permeance of the air gap.

$$\lambda_a = \frac{6.38d}{pg_e}$$

REACTANCE OF ARMATURE REACTION--(X_{ad} and X_{aq}) The "fictitious reactance" due to armature reaction. In the direct axis

$$X_{ad} = X \lambda_a C_1 C_M$$

and in the quadrature axis

$$X_{aq} = X C_q \lambda_a$$

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

$$\# = .321\, n_s Q a_c \ell_t$$

WEIGHT OF IRON-- The weight in lbs. of the stator iron.

$$\# = .238 \left[b_{tm} Q \ell_s h_s + \pi (D-h_c) hc\, \ell_s \right]$$

WOUND-POLE NON-SALIENT-POLE GENERATOR

ROTOR

TOTAL AIR GAP--(2g) The dougle air gap

ROTOR DIAMETER--(d_r) The outside diameter of the rotor

$$d_r = d - 2g$$

PERIPHERAL SPEED--(V_r) The speed of the rotor surface in ft. per minute.

$$V_r = \frac{\pi d_r \text{ RPM}}{12}$$

SLOTS PUNCHED--(Q_r') The total number of slots punched in the rotor. If the rotor is built with a solid pole center section Q_r' is the number of slot pitches on the rotor circumference.

SLOTS WOUND--(Q_r) The total number of slots that are wound. Also record

$$\alpha = \frac{Q_r}{Q_r'}$$

SIZE SLOTS-- The width of the rotor slot (b_r) and the depth of the rotor slot (h_r).

TOOTH PITCH--(t_{rs}) The rotor slot pitch at the rotor diameter.

$$t_{rs} = \frac{\pi d_r}{Q_r'}$$

GRADE OF IRON-- Spec number and gage number of the rotor iron.

CORE LENGTH--(ℓ_r) The overall length of the rotor core. Record also on this line the solid core length (ℓ_{rs}). See stator core length for stacking factors.

$$\ell_{rs} = K_1 \ell_r$$

CONDUCTORS PER SLOT--(n_r) The number of rotor conductors per slot.

TURNS PER POLE--(N_f) The total number of field turns per pole.

$$N_f = \frac{n_r Q_r}{2p}$$

CONDUCTOR SIZES-- The bare and insulated sizes of the rotor conductors. Also indicate the type of strand insulation.

AREA OF CONDUCTOR--(a_{cr}) The actual area of the conductor taking into account the corner radius. See stator area of conductor for typical corner radii.

$$a_{cr} = (\text{cond. width x cond. thickness} - .858r_c^2)$$

MEAN TURN--(ℓ_{tr}) The mean length of rotor turn. This value must be estimated from a layout of the rotor winding or from data on a previous machine.

RESISTANCE AT X^o--(R_f) The resistance of the field winding at the expected operating temperature.

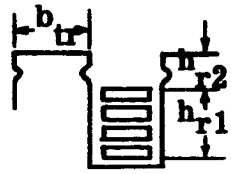
$$R_f = p \frac{Nf_p \ell tr}{a_{cr}}$$

FLUX IN POLE CENTER--(ϕ_{gp}) The portion of the total flux in each pole center.

$$\phi_{gp} = \left[\frac{Q_r' - Q_r + p}{Q_r'}\right]\frac{\phi_T}{p}$$

LEAKAGE FLUX--($\phi\ell_s$) The rotor slot leakage flux in each pole center.

$$\phi\ell_s = (F_g + F_s)\ell_r \lambda_{rs}$$



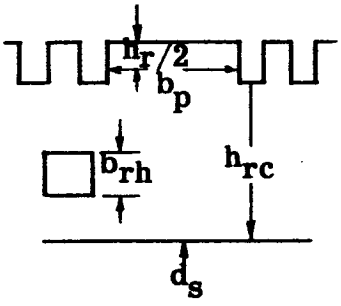
where λ_{rs} is the rotor slot leakage permeance

$$\lambda_{rs} = \frac{12.76p}{Q_r}\left[\frac{h_{r2}}{br} + \frac{h_{r1}}{2br} + \frac{.35b_{tr}}{t_{rs}} + \frac{g}{2t_{rs}}\right]$$

Record also on this line the total flux in the pole center.

$$\phi_{rc} = \phi_{gp} + \phi\ell_s$$

CENTER SECTION DENSITY--(Bpc) The flux density of the center section of the rotor at a section half way down the rotor tooth.



$$Bpc = \frac{\phi_{rc}}{b_p \ell_{rs}}$$

$$\text{where } bp = \left[\frac{\pi(d_r - h_r)}{p}\right]\left[\frac{Q_r' - Q_r + p}{Q_r}\right] \quad \text{(solid centers)}$$

$$bp = \left[\frac{\pi(d_r - h_r)}{p}\right]\left[\frac{Q_r' - Q_r + p}{Q_r'}\right] - (n_{rc} + 1)b_r \quad \text{(slotted centers)}$$

n_{rc} = no of slots in center section per pole.

CORE DENSITY--(B_{rc}) The flux density in the rotor core.

$$B_{rc} = \frac{\phi_{rc}}{2\, h_{rc}\, \ell_{rs}} \quad \text{where } 2h_{rc} = d_r - 2h_r - d_s - 2b_{rh}$$

% LOAD-- Space is provided for field voltage and current values at three load conditions. These loads will preferably be taken as no load, rated load, and guaranteed overload (usually 5 minutes).

FIELD AMPS. --(I_f) The field current at the various load conditions.

FIELD VOLTS--(E_f) The field voltage drop across the collector rings at the various load and temperature conditions.

CURRENT DENSITY--(s) The amps./sq. in. of the field conductors.

FIELD LEAKAGE REACTANCE--(X_F) The leakage reactance of the field winding.

$$X_F = X\frac{4}{\pi}\, C_M^{\,2}\, \lambda F, \text{ where } \lambda F = \lambda_{rs} + \lambda_{FE}$$

$$\lambda_{FE} = \frac{6.28}{\ell_r}\left[\frac{\phi_E L_E}{2n}\right] K_E$$

and

$\left[\frac{\phi_E L_E}{2n}\right]$ is taken from the 50% pitch curve of Graph #1

$$K_E = \frac{\text{calculated } L_E}{L_E \text{ from Graph 1}} \quad \text{(for } d_r \text{ above 8" diameter)}$$

$$K_E = \sqrt{\frac{\text{calculated } L_E}{L_E \text{ from Graph 1}}} \quad \text{(for } d_r \text{ below 8" diameter)}$$

Use the average pitch of the field winding

FIELD SELF INDUCTANCE--(L_F) The total self inductance of the field winding.

$$L_F = \frac{N_f^2 p \ell r}{10^8}\left[C_F\left(3.19\frac{t_p}{g_e}\right) + \lambda_F\right] \quad \text{(Henries)}$$

For rotors with solid pole centers the effective gap is taken as $K_s g$

and $C_F = 1 - \alpha + \frac{\alpha}{3K_r}$

For rotors with slotted pole centers the effective gap is taken as $K_s K_r g$

and $C_F = 1 - \frac{2\alpha}{3}$

DAMPER LEAKAGE REACTANCE--(X_{Dd}) The leakage reactance of the damper winding and eddy current circuits.

$$X_{Dd} = X\lambda_{Dd}$$

$$\lambda_{Dd} = \frac{3.19p}{d}(g + \delta_d + h_{r2})$$

where δ_d = depth of penetration factor and varies as $\sqrt{\frac{1}{f}}$

δ_d = 1.2 at 60 cycles and 0.47 at 400 cycles

WEIGHT OF COPPER-- The weight in lbs. of the field winding.

$$\# = .321\, N_f\, p\, \ell_{tr}\, a_{cr}$$

WEIGHT OF IRON-- The weight in lbs. of the rotor iron.

$$\# = .283\left[\pi(d_r - h_r) - Q_r b_r\right]\ell_{rs} h_r + .283\pi(d_s + h'_{rc})h'_{rc}\ell_{rs}$$

For slotted pole centers $Q_r = Q'_r$

$$h'_{rc} = \frac{d_r - 2h_r - d_s}{2}$$

REACTANCES AND TIME CONSTANTS

SYNCHRONOUS REACTANCE--(X_d) The steady state short circuit reactance.

$$X_d = X_{ad} + X_\ell$$

UNSATURATED TRANSIENT REACTANCE--(X'_{du}) The transient reactance due to the field winding assuming unsaturated conditions.

$$X'_{du} = X_\ell + X_F\left(\frac{X_{ad}}{X_F + X_{ad}}\right)$$

SATURATED TRANSIENT REACTANCE--(X'_d) The transient reactance due to the field winding assuming normally saturated conditions.

$$X'_d \approx 0.88\, X'_{du}$$

SUBTRANSIENT REACTANCE--(X''_d) The subtransient reactance due to the damper winding and eddy current circuits.

$$X''_d = X_\ell + X_{Dd}$$

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

$$X_2 = X''_d$$

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

$$X_o = X\left[\frac{K_{xo}}{K_x}(\lambda i + \lambda_{Dd}) + \frac{20(h_1 + 2h_3)}{12mqK_p^2K_d^2b_s} + 0.2\,\lambda_E\right]$$

$$K_{xo} = \frac{3y}{mq} - 2 \quad \left\{\begin{array}{l}\text{For a one conduction per slot}\\ \text{winding } K_{xo} = K_x = 1\end{array}\right\}$$

$$K_x = \left(\frac{3y}{4mq} + \frac{1}{4}\right) \text{ for pitches of 66 2/3\% to 100\%}$$

$$K_x = \left(\frac{3y}{mq2} - \frac{1}{4}\right) \text{ for pitches of 33 1/3\% to 66 2/3\%}$$

POTIER REACTANCE--(X_p) The reactance determined by the Potier triange.

$$X_p = X_\ell + \left(\frac{F_R}{F_s + F_R}\right)X_{Fs}$$

$$X_{Fs} = \left[\frac{\lambda rs}{\frac{2d}{pg_e} + \lambda rs}\right] X_d$$

OPEN CIRCUIT TIME CONSTANT--(T'_{do}) The time constant of the field winding with the stator open circuited and with negligible external resistance and inductance in the field circuit.

$$T'_{do} = \frac{L_F}{R_F} \text{ second}$$

ARMATURE TIME CONSTANT--(T_a) The time constant of the DC component.

$$T_a = \frac{X}{2\pi f r_a 100} \text{ seconds}$$

$$r_a = \frac{\text{Stator } I^2R(KW)}{\text{Rated KVA of generator}}$$

TRANSIENT TIME CONSTANT--(T_d') The time constant that determines the rate of decay of the transient component of symmetrical short circuit current.

$$T_d' = \frac{X_d'}{X_d} T_{do}'$$

SLOTS-- The blank space provided is to be used for sketches of the stator and rotor slots.

CARTER'S COEFFICIENT STATOR--(K_s) The Carter coefficient for the stator slots.

$$K_s = \frac{t_s (5g + b_s)}{t_s(5g + b_s) - b_s^2} \quad \text{for open slots}$$

$$K_s = \frac{t_s (4.44g + 0.75\, b_o)}{t_s(4.44g + 0.75\, b_o) - b_o^2} \quad \text{for partially closed slots}$$

CARTER'S COEFFICIENT ROTOR--(K_r) The Carter coefficient for the rotor slots.

$$K_r = \frac{t_{rs}(5g + b_r)}{t_{rs}(5g + b_r) - b_r^2} \quad \text{for open slots}$$

$$K_r = \frac{t_{rs}(4.44g + 0.75\, b_{ro})}{t_{rs}(4.44g + 0.75\, b_{ro}) - b_{ro}^2} \quad \text{for partially closed slots}$$

EFFECTIVE GAP--(g_e) The effective single air gap.

$g_e = K_s K_r g$ (for rotors with slotted pole centers)

$g_e = K_s g$ (for rotors with solid pole centers)

SATURATION

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

$$F_g = \frac{B_g g_e}{3.19}$$

STATOR AMPERE TURNS--(F_s) The ampere turns per pole required to force the flux through the stator iron.

$$F_s = F_T + F_C$$

F_T is the ampere turns per pole for the teeth.

It is calculated as the product of h_s and the NI per inch at a density of B_t.

F_C is the ampere turns per pole for the core. It is calculated as the product of $\left[\frac{\pi(D - h_c)}{4p}\right]$ and the NI per inch at a density B_C.

Use saturation curves from USS Electrical Sheets Manual.

ROTOR AMPERE TURNS--(F_R) The ampere turns per pole required for the rotor iron.

$$F_R = F_{TR} + F_{CR}$$

F_{TR} is the ampere turns per pole for the core. It is calculated as the product of h_r and the NI per inch at a density B_{pc}.

F_{CR} is the ampere turns per pole for the core. It is calculated as the product of $\left[\frac{\pi(d_s + h_{rc})}{4p}\right]$ and the NI per ~~inch at~~ a density B_{rc}.

Use saturation curves from USS Electrical Steel Sheets Manual.

An alternate method of calculating the rotor ampere turns is to determine the NI required at the maximum and minimum rotor pole center sections. From these values the NI can be determined approximately as

1/3 (Max. NI + 2xMin. NI)

NO LOAD AMPERE TURNS--(F_{NL}) The total ampere turns per pole required to produce rated voltage at no load.

$$F_{NL} = F_g + F_s + F_R$$

RATED LOAD AMPERE TURNS--(F_{FL}) The total ampere turns per pole required to produce rated voltage at rated load.

There are many proposed methods of determining generator field currents under load conditions but only one will be described here. Any of the proposed methods will give reasonably accurate results, but where possible previous test results should be referred to in order to determine the saturation component.

AMERICAN STANDARDS ASSOCIATION METHOD

Referring to Figure A, OB is the rated phase terminal voltage drawn at the power factor angle θ, with the base line of the figure taken as the direction of the current vector. BF is the % phase effective resistance drop and FD is the % phase Potier reactance drop drawn in the proper phase

$$(\% \, r_e = R_{ph} \times \frac{I_{ph}}{E_{ph}} \times EF_{AVG} \times 100)$$

$$EF_{AVG} = \text{Average Eddy Factor}$$

relation with respect to the current reference line. OD = E_g is then the air gap voltage at which the generator is operating. This voltage is considered a measure of the degree of saturation of the magnetic circuit. OB = E_{ph} is the terminal voltage.

Now refer to Figure B. The line F_g is the field ampere turns from the air gap line corresponding to the terminal voltage E_{ph}. Add vectorially to F_g the field ampere turns F_{sc} corresponding to the rated armature current from the short circuit characteristic. The ampere turns F_{sc} is added at an angle θ the load power factor angle, with a perpendicular drawn to F_g. The effect of the armature resistance is neglected on this diagram. Its effect would be to increase the angle θ by a very small angle but this angle is too small to be of importance. Neglecting saturation F'_{FL} is the field ampere turns for the given load and power factor. To take saturation into account, F_{SAT} is added directly to the ampere turns F'_{FL} to give the actual field ampere turns F_{FL}. The component F_{SAT} should not be added exactly in phase with F'_{FL} as shown but little error is introduced by doing this. Actually, all of

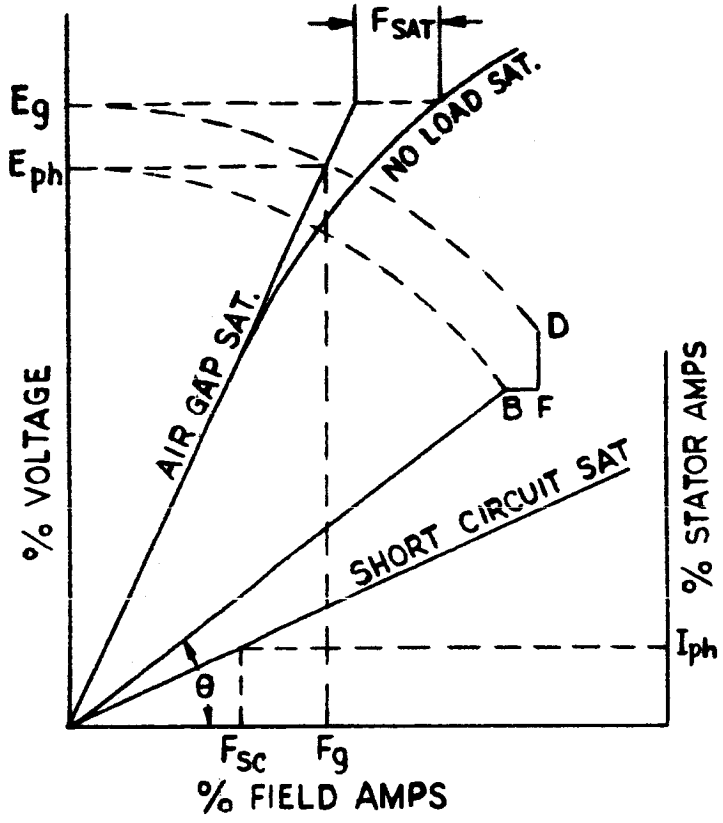


FIGURE A

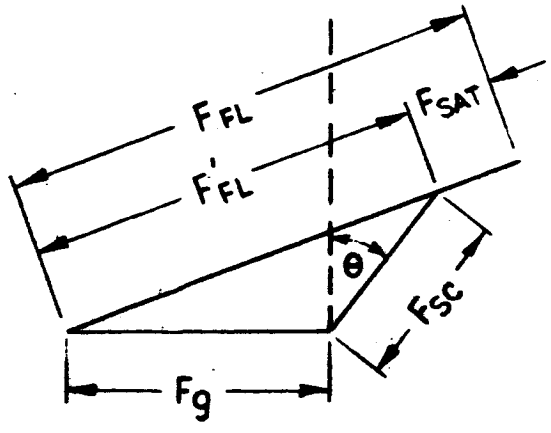


FIGURE B

the ampere turns F_g are affected by the saturation of the magnetic circuit, but only that part of F_{sc} which takes care of the leakage reactance drop is similarly affected. The rest of F_{sc} balances the ampere turns of armature reaction and neglecting the change in field pole leakage with change in saturation, is uninfluenced by the saturation of the magnetic circuit.

OVERLOAD AMPERE TURNS--(F_{oL}) The total ampere turns per pole required to produce rated voltage at the overload condition. This is determined by the ASA method as described in F_{FL}, by using the proper percentage values for r_e, X_p, I_{ph}, F_{sc}, and F_{SAT}.

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

$$F_{sc} = X_d F_g$$

SHORT CIRCUIT RATIO--(SCR) The ratio of the field current required 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 directly related to the SCR.

$$SCR = \frac{F_{NL}}{F_{sc}}$$

LOSSES AND EFFICIENCY

PERCENT LOAD-- Space is provided for three conditions of loading and these are preferably taken as no load, rated load, and overload.

FRICTION AND WINDAGE--(F & W) There is no known calculation method that will give even reasonable accuracy for this loss and so data from previous machines will have to be used. 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.

STATOR TEETH--(W_{TNL}, W_{TFL}, W_{TOL}) The no load tooth 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.

$$W_{TNL} = .453\,(t_{s\,1/3} - b_s)\,Q\,\ell_s\,h_s\,K_Q$$

K_Q = Watts per pound loss from USS Electrical Steel Sheets Manual at a density B_t.

The stator tooth loss under load (W_{TFL} & W_{TOL}) is increased because of the parasitic fluxes caused by the ripple due to the rotor teeth.

$$W_{TFL} = \left[2(.27X_d)^{18} + 1\right] W_{TNL} \quad (X_d \text{ in per unit})$$

For W_{TOL} use X_d corresponding to the overload condition.

STATOR CORE--(W_c) 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.

$$W_c = 1.42\,(D - h_c)\,h_c\,\ell_s\,K_q$$

K_Q = Watts per pound loss from USS Electrical Steel Sheets Manual at a density of B_c.

POLE FACE--(W_{PNL}, W_{PFL}, W_{POL}) The pole surface losses are due to the 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}) is calculated from Graph #2. The pole face loss under load (W_{PFL} & W_{POL}) is calculated as:

$$W_{PFL} = \left[\left(\frac{K_{sc} I_{ph} n_s}{c F_g}\right)^2 + 1\right] W_{PNL}$$

Graph #2 is plotted for open slots, thus $B_s = b_o$ for partially closed slots

K_{sc} is obtained from Graph #3.

For W_{POL} use I_{ph} corresponding to the overload phase current.

DAMPER--(W_{DNL}, W_{DFL}, W_{DOL}) The loss produced by the slot ripple in the rotor wedges. This loss is calculated as a damper loss and at no load W_{DNL} is taken from curves #7 and #8. The damper loss under load (W_{DFL} & W_{DOL}) for <u>polyphase</u> machines is calculated as:

$$W_{DFL} = \left[\left(\frac{K_{sc} I_{ph} n_s}{c F_g}\right)^2 + 1\right] W_{DNL}$$

K_{sc} is obtained from Graph #3

For W_{DOL} use I_{ph} corresponding to the overload phase current.

STATOR I^2R-- The copper loss based on the DC resistance of the winding. Calculate for the maximum expected operating temperature.

$$I^2R = m\, I_{ph}^2\, R_{ph}$$

EDDY-- The stator I^2R loss due to skin effect.

$$\text{Eddy Loss} \left[\left(\frac{\text{Eddy Factor Top} + \text{Eddy Factor Bottom}}{2}\right) - 1\right] \text{Sta } I^2R$$

ROTOR I^2R-- The copper loss in the field winding.

$$I^2R = I_f^2 R_f$$

SUM OF THE LOSSES-- The total losses at the various loads.

RATING-- The kilowatt rating of the generator x 1000.

RATING + LOSS-- The sum of the total losses and the KW rating x 1000.

PERCENT LOSS-- The total loss divided by the rating + total loss.

PERCENT EFFICIENCY-- 100% - % loss.

STATOR WATTS/SQ. IN. -- The stator watts per square inch of stator periphery.

$$\frac{W}{1N^2} = \frac{\text{Stator Tooth Loss} + \text{Stator Core Loss} + I^2R + \text{Eddy Loss}}{\pi D \ell}$$

ROTOR WATTS/SQ. IN. -- The rotor watts per sq. in. of rotor periphery.

$$\frac{W}{1N^2} = \frac{\text{Pole face loss} + \text{Damper loss} + \text{Rotor } I^2R}{\pi d_r \ell_r}$$