DESIGN OF A LARGE SQUIRREL - CAGE INDUCTION MOT

DISSERTATION SUBMITTED

by

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INTRODUCTION

Even as the transformer assisted the single and multiphase system to victory in its competition with the d.c. system for the transmission of electrical energy to great distances, so has the competitio between the single phase system and the polyphase system been decided in favour of the latter by the polyphase induction motor. The determining factors were (1) low first cost (2) good efficiency (3) simple attendance and (4) great reliability in service. The immense extension of electrical transmission has led to a great yearly demand for polyphase induction motors. In view of these circumstances, it is readily understood that every improvement in construction or in the underlying characteristics of the motor mu be of considerable economic significance.

The motor with squirrel cage rotor is the cheapest and more robust out of the two kinds of pol phase induction motors, but its unfavourable attributes constituted a serious hindrence to its general use, specially for large outputs. Although with squ rrel cage motors any starting torque required in pra ctice can be readily and simply provided, but the corresponding current drawn from the supply circuit is several times greater than the current at normal load. In many cases these great starting currents would occasion fluctuations in supply circuits. By proportioning the rotor resistance at some reasonable value, such that the efficiency is not very low a reasonable amount of starting torque can be obtained by using starters and consuming starting currents which are two to three times normal f.l. current.

The field of application of the ideas, described above, remained very limited because the torques required during starting may be high. For this reason attention should be directed to a design, which makes use of the eddy current principle in the construction of the cage armature. Since the frequency in the rotor conductors is great at starting and small during running and since the losses through sk effect depend in a high degree on the frequency, the use of the eddy current principle is evidently particularly appropriate in the design of the cage armat

A further improvement the starting characteristics of the squirrel cage motors has been made by the use of double cage rotors in which the rotor is provided with two squirrel cage windings located one above the other. During the entire starting per iod each winding provides its own part of the torque which undergoes a steady alteration in dependence upon the increasing speed. The combined torque curv may be altered through wide limits by alterations of the resistance and of the reactance of the two cage windings so the characteristics similar to that of the d.c. series motor can be obtained in addition to its cheapness and ruggedness.

LIST OF SYMBOLS

b_s	=	slot width
b_o	=	slot opening
b_t	=	width of tooth
A	=	Ampere conductors / unit periphery
$\bar{B}$	=	Average flux density in the airgap
B	=	Flux density
C	=	Output Coefficient
D	=	Diameter of stator core
F	=	Conductor cross-section
h_s	=	height of slot
h_{cu}	=	height of copper
i	=	current density
I_n	=	Normal current at full load
I_o	=	n. . current ?
I_ϕ	=	Magnetizing current
l_s	=	length of slot
l_i	=	net non length ?
L	=	Gross length of stator
N_c	=	No. of conductors per slot
N_n	=	Output at full load
p	=	no. of poles
q	=	no. of slots per pole per phase
r	=	resistance

S	=	Total number of slots
s	=	slip
U_n	=	normal line voltage
U_p	=	phase voltage
W	=	Coil span
x	=	reactance
Z	=	total no. of conductors
Z_p	=	conductors per phase
m	=	no. of phases
δ	=	air gap length
$\cos \varphi_n$	=	Power factor
ϕ	=	flux
λ	=	permeance
τ_p	=	pole pitch
τ_s	=	slot pitch
ν	=	stator harmonic
μ	=	rotor harmonic

Suffix 1 and 2 refer to the stator and rotor respectively.

Suffix c, s, t, g refer to core, slot, tooth and gap, respectively.

1. DESIGN PRINCIPLES

1.1.1. Output Equation of the Induction Motor

The process of design is to obtain the dimensions and electrical particulars of a machine to satisfy the given operating characteristic, that determine the suitability of an induction motor. Though the continuous output is the main criterian, the purchaser, however, may place limits or guarantees on some or all of the following characteristics: starting torque, pull up torque, pull out torque, locked rotor,inrush current, efficiency and power factor at one half, 3/4 and full load, and the temperature rise at the required hp. output.

In large majority of cases it has been found that the operating characteristics, as regards torques, inrush current, efficiency and pf., may be obtained by suitably proportioning the design constts with in the motor. On the converse the temperature rise and the hp output, in most cases, provide the basic limitations on the physical size of the machine.

In bringing out the general relationsh between the power output and physical size of the induction motor the following specific procedure is adopted.

Power output of an induction motor is given by

$$N_n = 3\ U_p .\ I_n .\ \cos\varphi_n .\ \eta .\ 10^{-3}\ Kw \quad \text{--- } 1.1.1,$$

But $U_p = 4{,}44.f.\ \phi_1 .\ K_{dp1} .\ N .\ .\ 10^{-8}$ --- 1.1.2,

Where $\phi_1 = \frac{Z}{\pi} .\ B_1 .\ \tau_p .\ \ell = \bar{B} .\ \tau_p .\ \ell$

$$= \bar{B} .\ \frac{\pi D}{p} .\ \ell$$

and $6\ I_n .\ N = I_n . Z = A . \pi . D$

so that $N = \frac{A .\ \pi .\ D}{6 .\ I_n}$

Hence on substitution in (1.1.2)

$$U_p = \frac{4{,}44 . \pi^2}{6} . \frac{n_s}{120} . \frac{A}{I_n} . \frac{\bar{B}}{5000} . D^2 . 1.\ K_{dp1} . 10^{-}\ \text{Vol}$$

which on substitution in (1) gives

$$N_n = 4{,}55\ K_{dp1} .\ \cos\ \varphi_n .\ \eta .\ \frac{\bar{B}}{5000} . \frac{A}{500} . D^2 . \ell . n_s\ K_{w}$$

-----1.1.3

Where D and ℓ are in meters

Putting $C = 4{,}55.\ K_{dp1}\ \cos\varphi_n .\ \eta .\ \frac{\bar{B}}{5000} . \frac{A}{500}$

-----1.1.4

$N_n = C.\ D^2 .\ \ell .\ n_s$ ---- ---- -----1.1.5

The constant C is termed as the output coefficient and was first employed by Essen and by Kapp.[3] Although the above output equation is used almost in

..

every design office, however the following arrangements are worthy for consideration and future research.

The equation (1.1.5) is derived directly from the fundamental voltage equation and no consideration has been made of 1. the variation of losses with the motor size and speed and 2. the variation of ventilatic with the motor size and speed consequently there is n reason to suppose that the hp output for a permissibl temperature rise will vary directly with the D^2 1 n_s of the machine. Variation of losses with major dimensior An accurate calculation in a motor can be made only by considering all of the detail dimensions of the electr -cal parts. However, very useful relations are obtain by considering only the variation in the losses with changes in various dimensions. The machines are assum to be geometrically similar i.e. the minor dimensions are assumed to change in the same ratio as the major dimensions. The power loss in an induction motor may divided as follows:

1. Stator $I^2 R$ loss which may be further subdivi -ded into copper loss in the slot portion and copper l in the end turns
2. Rotor $I^2 R$ loss comprising of the copper loss in the slot portion and copper loss in the end rings
3. Load losses which consist of eddy current loss in the stator copper and high frequency iron and copp losses due to the flow of load current in the stator a

rotor rotor conductors.

4. No load iron loss which consists of fundamental iron losses in the stator and rotor due to slot ripple in the no load airgap flux

5. Friction and windage losses

The first three groups vary with the load on th motor while the last two are the constant losses which are substantially independent of load.

The basic construction of a squirrel cage motor may be represented as shown in fig. 1, and the major dimensions given the symbols D, l and δ.

To preserve geometric similarity between machi--nes, consider that the outside diameter of the stator punchings the inside diameter of the rotor punchings and the depth of stator and rotor slots all change in the same proportion as the stator bore diameter, D. Assuming also that the ratio between the number of rot and stator slots, ratio of the slot width to slot pitc and the line frequency all remain constant.

Under these assumptions the various losses i a motor will vary with the major design constants appr ximately in the proportions shown in Table I.[10]

The equation for the stator and the rotor sl I^2 R loss is derived on the assumption that the ratio cu. cross section to slot corss section is constant whi is very nearly true in the case of large induction mot The equation for end turn loss is derived on the basis that the copper X-section in the end turns bears a cons tant proportion to the copper X-section in the slots regardless of changes in speed or diameter.

The equation for higher frequency load loss i derived from the relation that the no load slot ripple is closely proportional to the expression (Kcs- 1). The expression varies very approximately as $\sqrt{bs/\delta}$ in large machines with open slots.

The manner in which the total motor losses will vary with the major dimensions will depend on proportions in which each component of loss is present. It is difficult to express this in general terms, however, from test results it is found that the total full load loss expressed as a percentage of the power output vari approximately as $1/D^{0.5}.n^{0.5}$ for large motors.

Variations of ventilations with major dimensions

Most of the heat in an open motor is dissipat by the circulation of cooling air over the coils and, iron core. Usually the large induction motors generall have radial ventilating ducts in addition to fans which allow additional cooling air to circulate over the end turns. Certain typical high speed large induction moto employ both radial and axial ventilating ducts.

The equation for temperature rise is of the form

$$\text{Temp. rise} \propto \frac{\text{total losses}}{\text{(Effective dissipating area)} \sqrt{\text{peripheral velocity}}}$$

or Temp. rise $\propto \dfrac{(\%\text{ losses based on output})(\text{hp output})}{(\text{effective dissipating area})\sqrt{D n_s}}$

since peripheral velocity $\propto D. n_s$

$\therefore$ Temp. rise $\propto \dfrac{(\%\text{ losses based on output})(\text{hp output})}{(\text{effective dissipating area})(\sqrt{D.n_s})}$

The effective dissipating area is a combination of the end turns vent duct, and end laminations.

It has been found that in large motors the heat dissipated from the end windings and the vent ducts i: more or less the similar while the end turns dissipati: area is approximately proportional to $D^2 n$ and the ven' duct area to $D^2 \ell$. Consequently the totoà effective di -sipating area will vary about as the expression $D^2 \ell^{0,5} n_s^{0,5}$

On substitution in the output equation

$$\text{HP out put} \propto D^2(\ell^{0,5} n_s^{0,5})(D^{0,5} n_s^{0,5}) - \frac{1}{D^{0,5} n_s^{0,5}}$$

$$\propto D^3 \ell^{0,5} n_s^{1,5}$$

In practical designs , however, equation (1.1.5 is most widely used and the value of the output coeffi cient C varies from 1---5; for larger machines the higher values of C. are chosen. Since the higher the value of C the smaller the value of the $D^2 l$ required. The art of design consists in obtaining the maximum ou put per pound of material. This maximum output is li by many factors cheif of which is the maximum permissible temperature rise in service, since the failure of the insulation is caused chiefly by its being subjected to too high a temperature.

1.1.2 Specific Loadings

The output coefficient C is given by

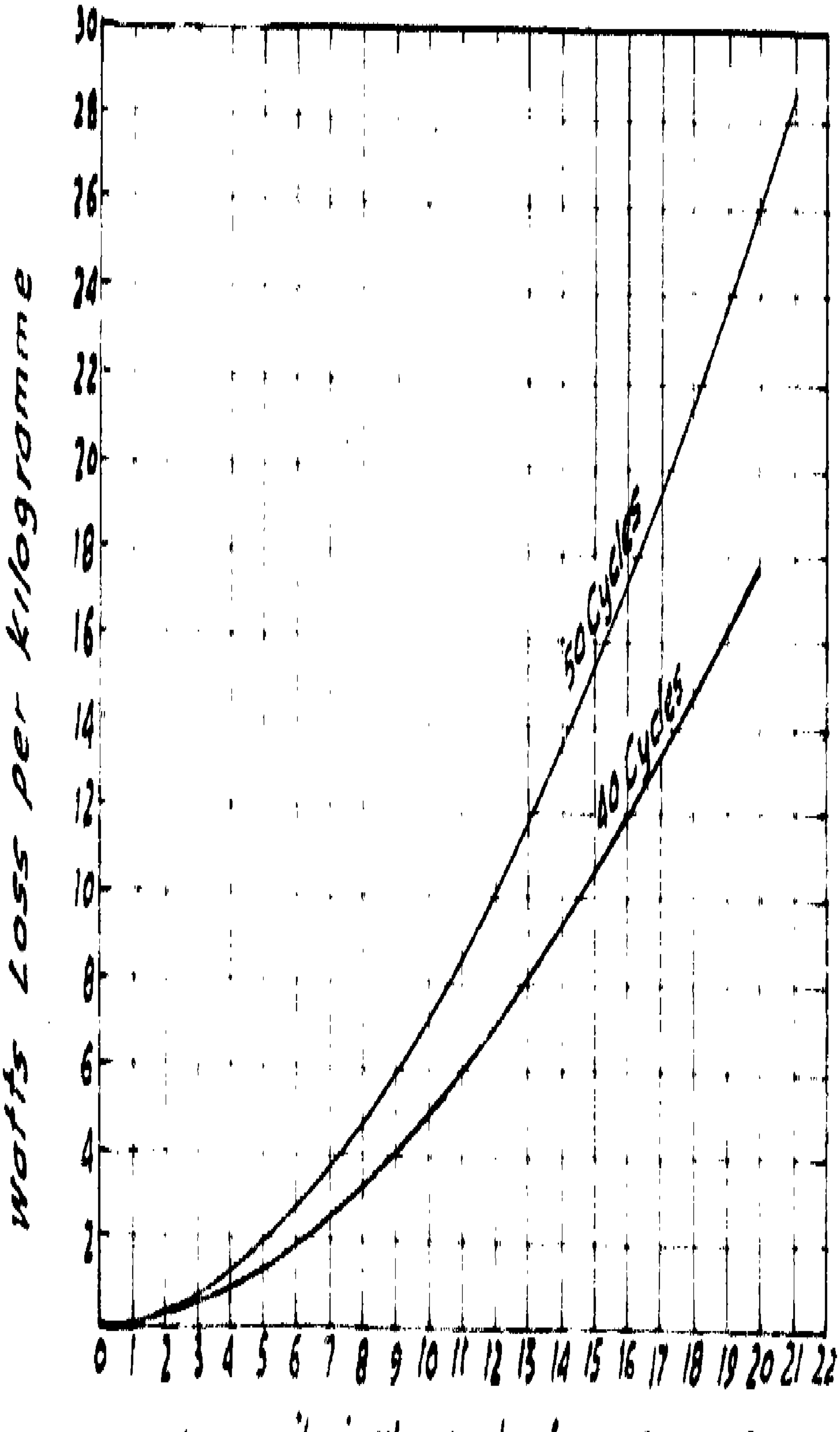
$$C = 4{,}55\ Kd_{p1} .\ \cos\varphi_n .\ \eta_n \quad \frac{\bar{B}}{5000} . \frac{\bar{A}}{500}$$

The output coefficient thus largely dep-nds on the values of $\bar{B}$ and A which are known as the specific magnetic and electric loadings.

Apart from the temperature considerations th value of B is determined by the condition that for hig power factor, there must not be saturation in any part of the magnetic circuit, for the value of B in the air gap is directly related to the value of B in the teeth and core. This condition B at 50 c/s more or less agrees to the heating limit also. Thus for no saturation the maximum flux density at the minimum too section should not exceed 16000 lines /cm^2 at 50 c/s. This corresponds to 10000 lines/em^2 average at minim section and the corresponding average appament flux de -sity in the air gap will be about 4000 - 5000 lines/e Of course in cases where power factor is not important but the over load capacity is the main characteristic required, saturation in the tooth and core are usual and higher densities are used then those given above. On high speed machines sufficient overlaod capacity can be obtained with lower values of flux density but as the number of poles increases it is difficult to get both high p.f. and high overload capacity. The two things are incompatible and one perforce has to sacrifice the one or the other. Higher values of the flux densities in the gap are generally resorted to when the number of poles are large.[2,6]

The values of flux densities in the teeth, gap given above are for 50 c/s machines for higher frequencies the flux densities has to be reduced. Also for totally enclosed machines of continuous rating lower flux densities in the magnetic circuits are used.

Again other considerations then power factor and overload capacity may be more important. The iron losses in teeth and core are determined by the value o the flux densities used, since the hysteresis loss var -es as $(B_t)^{1.7}$ and the eddy current loss ravies as B_t^2 where B_t is the flux density in the teeth, and the same applies for the core also. Thus with a highe flux density the iron losses are increased and thereby the efficiency is decreased occasionally machines are designed which are completely free from noise of any k This invariably means low flux densities and large phy



watts Loss per kilogramme
50 Cycles
40 Cycles
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
Flux Density in Thousands of Lines Per Sq. Cm.

Fig 1.1.1

-sical dimensions of machines. So in choosing the average flux density in the air gap $\bar{B}$ the following point must be kept in mind : (a) power factor, (b) overload capacity, (c) efficiency, (d) temperature rise and (e) noise.

It is now to investigate how the heating limit affects the electric loading of the machine.

Analysis of the curve in fig. 1.1.4 shows that the iron loss per kgm. for lohys[6]

$$= 0{,}000227\ B^{1{,}8} . f^{1{,}6} \text{ watts}$$

where B = Maxm. flux density in kilo lines per square cm.

and f = supply frequency

or iron loss in watts per cubic centimeter

$$= 0{,}00000\,179\ B^{1{,}8}\ f^{1{,}6}\ W/cm^3 \quad ...1.1.6$$

Therefore the iron loss in the state teeth assuming a maxm. flux density B = 16 kilo-lines/sq.cm and

f = 50 c/s

$$= 0{,}00000\,179 . 16^{1{,}8} . 50^{1{,}6} \text{ watts}/cm^3$$

$$= 0{,}135\ W/cm^3$$

If hs is the height of the slot and it is assumed that all the tooth loss is dissipated at the gap

$$= 0{,}135 . hs$$

If
Nc = number of conductors in series per slot
I = Current per conductor in amperes
hs = ht of slot

F = area of conductor in cm.

i = current density in Amperes/sq.cm.

= specific resistance of copper at the temp considered then considering unit length o slot axially

$$\text{Copper loss per cm.} = \frac{I^2 N_e \cdot \rho}{F}$$

$$= \frac{I}{F} . I. N_e . \rho$$

$$= i. \; I. \; N_e . \rho$$

But the specific electrical loading

$$A = \frac{I. N_c . \text{ number of slots}}{\pi D}$$

$$= \frac{I. N_e}{\tau_{sq}}$$

$$= \frac{I. N_e}{k. \; b_s} \qquad \ldots\ldots 1.1.7$$

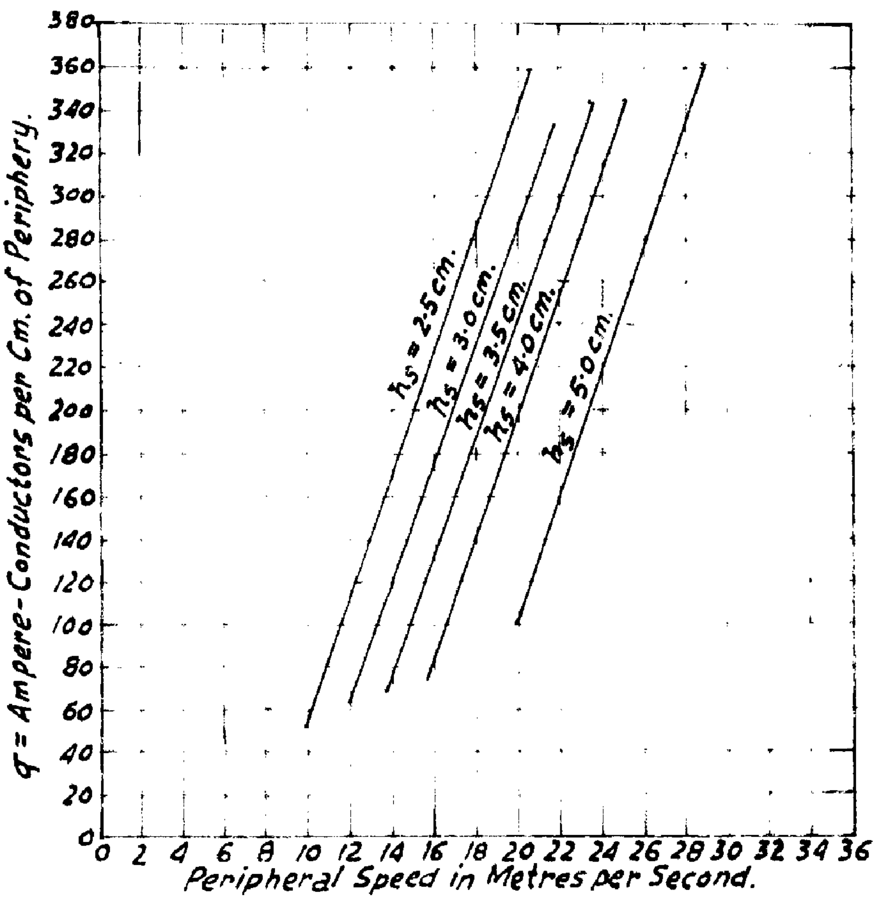
where K is some constant such that $K . b_s = \tau_{sq}$

$$\text{or} \qquad \frac{I. N_c}{b_s} = A. K$$

Thus the copper loss at the gap surface

$$= \frac{i. I. N_c . \rho}{b_s}$$

$$= A. K. \rho . i$$



q = Ampere-Conductors per Cm. of Periphery.
Peripheral Speed in Metres per Second.
hs = 2·5 cm.
hs = 3·0 cm.
hs = 3·5 cm.
hs = 4·0 cm.
hs = 5·0 cm.
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36

Fig 1.1.2

Hence the total losses dissipated per sq.cm. at the gap surface

$$= A. K. \quad . i + 0{,}135 \text{ hs}$$

But the permissible watts per sq. cm. of the stator barrel at the gap with a peripheral velocity of above 12 m/sec

$$= 0{,}0408 \, v_b$$

where

v_b = peripheral velocity in meters / second

Therefore, for a peripheral velocity above then 12m/sec.

$$A. K. \rho . i + 0{,}135 \text{ hs} = 0{,}0408 \, v_b \quad .....1.1$$

From this equation a series of curves are drawn for different values of hs, giving A as a function of Fig.1.1.2. It has been found that the product of current density and specific electric loading is sensibly constant for a given peripheral speed and depth of slot.

The above derivation is imperfect, for it assumes that the whole of the copper and iron losses are dissipated at the gap surface. It is well known that a certain amount of heat is dissipated from the ducts and end plates. In order to account this the values of A from curve 1.1.2 may be increased by about 10 to 20 %. Such curves are approximate, only,

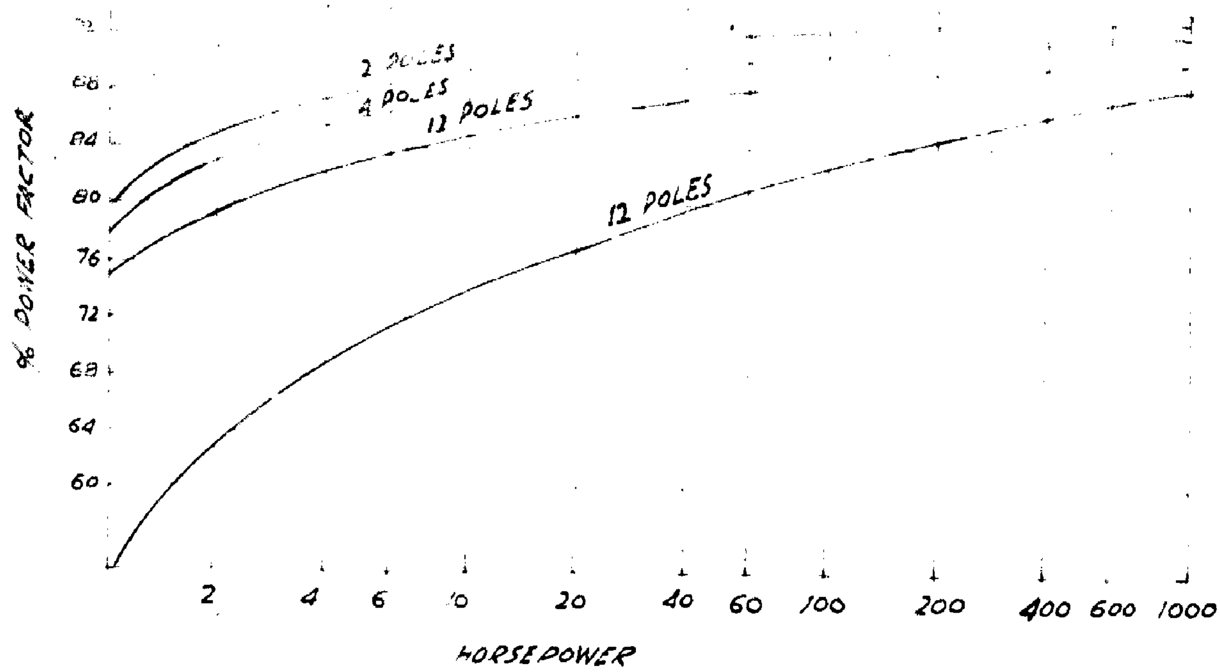


Fig 1.1.3

Ref. 3

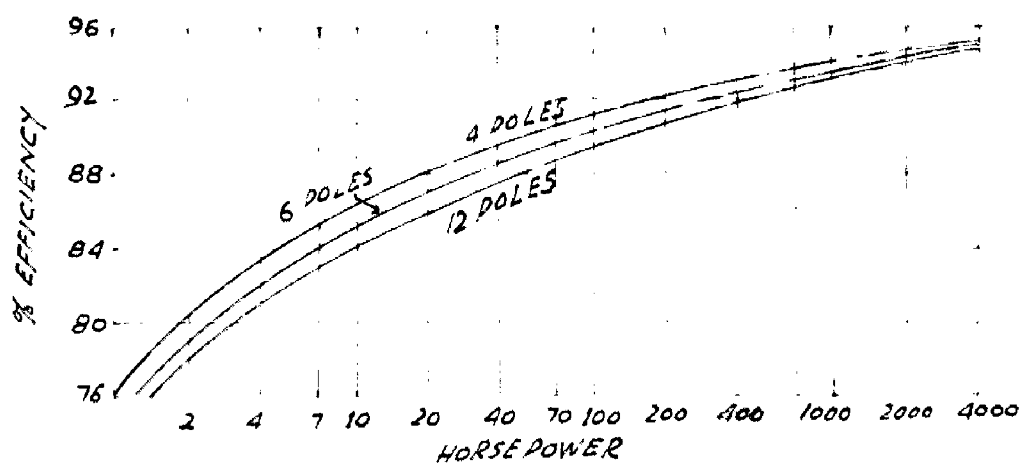
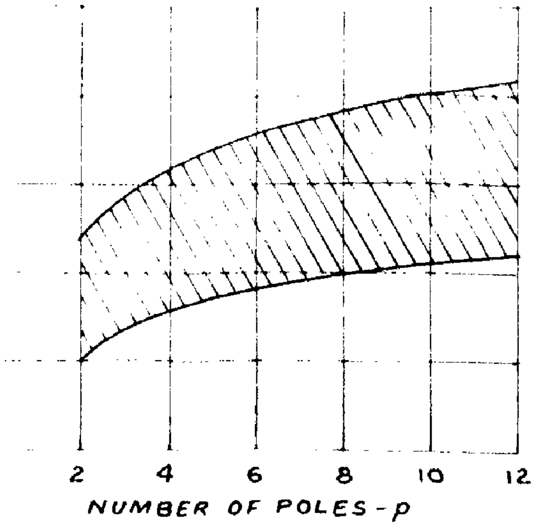
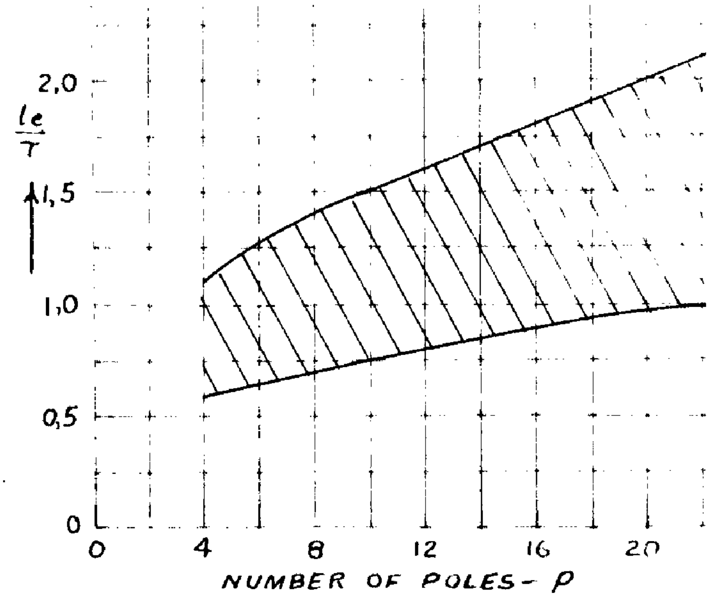


Fig. 1.1.4

Ref. 3





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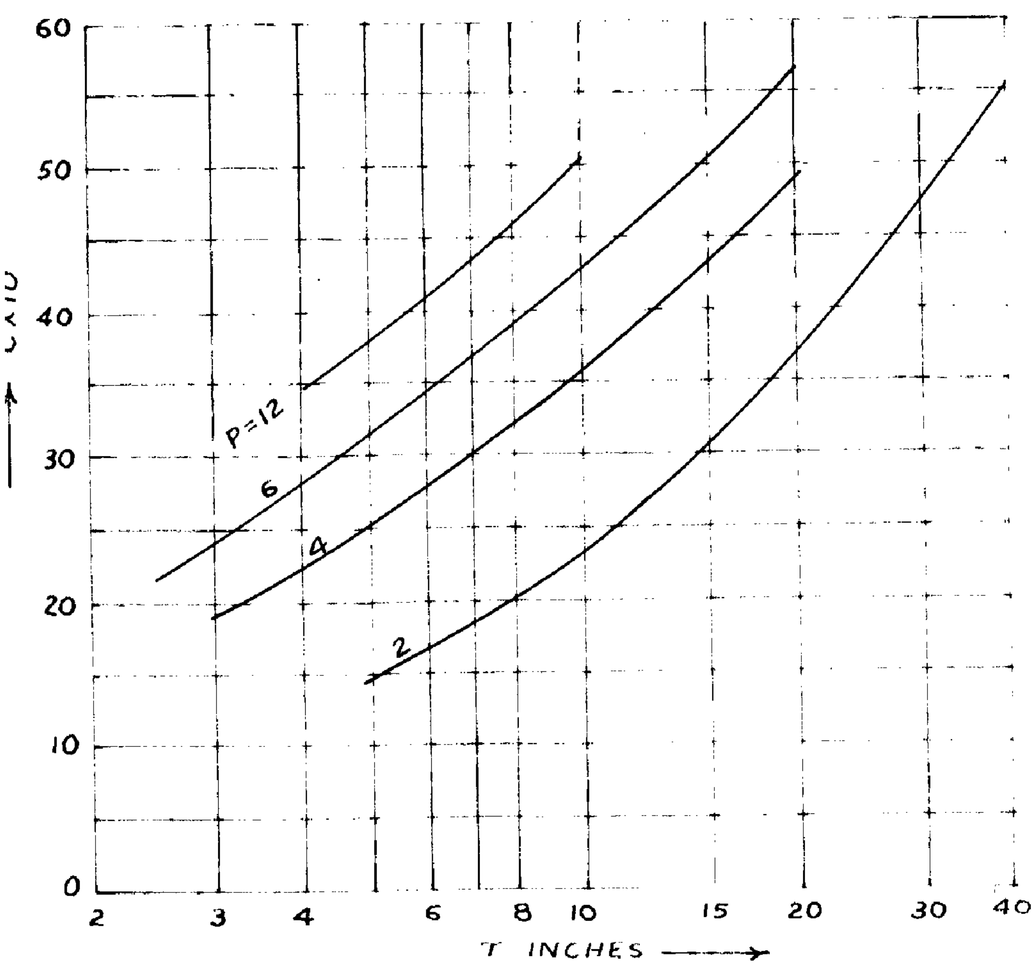


Fig 1.1.5

but they do give a suitable working basis for arriving at a suitable value of A.

1.1.3. Powerfactor and Efficiencies

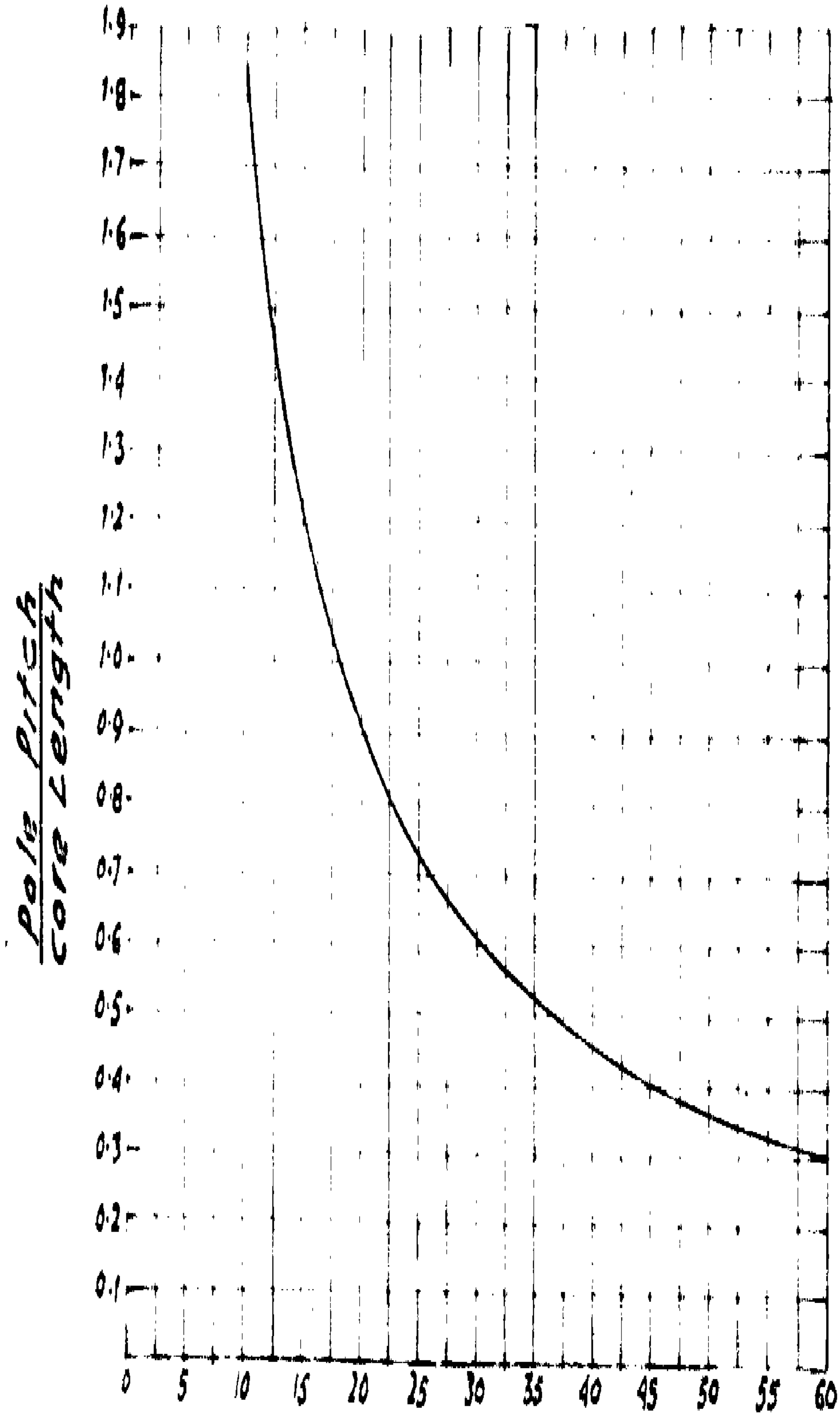
After determining the specific electric and magnetic loadings it now remains to determine the power factors and efficiencies of induction motors. These are generally specified by the customer, or else, are specified in the NEMA catalogues and can be found out from there. Figures 1.1.3 and 1.1.4 shows the power factors and efficienceis of a range of induction motors.

After having determined approximately th specific loadings, the power factor and the efficiency the output coefficient of the m/c can be calculated by eq.(1.1.4). However, in the design offices curves are available which are drawn from the actual design data. Fig. 1.1.5 shows such a curve.[3]

1.1.4. Determination of Stator Bore D and Length L

With larger values of D the cooling is increased and so a higher value of A i.e. the ampere conductors per unit periphery can be used with the resu -lt a higher value of C, the output coefficient. Thus

Fig 1.1.7



Pole Pitch in centimetres

Fig 1.1.7

it can be said that very approximately $C \propto D$.
As the diameter of stator bore is increased its length has to be increased proportionately hence roughly $D \propto l$
Thus (from eq. 1.1.5)

$$N_n \propto D^4$$

$$\text{or} \quad \log N_n \propto 4 \log D \quad \ldots\ldots \quad \ldots\ldots \quad 1.1.9,$$

If D is plotted against N_n on a double log paper then a st line is obtained whose slope is 1/4 (Fig. 1.1.6).

From the power factor consideration, however for best p.f. the following result given by Dr. Herbert Vickers[6] holds good

$$\frac{\tau_p}{L} = \frac{18}{\tau_p} \quad \ldots\ldots \quad \ldots\ldots \quad 1.1.10,$$

This relation is plotted in fig. 1.1.7. It does not follow that one must adhere to this ratio, since there are other factors, such as cooling consi--deration or an excessive length of the m/c etc., which may decide the τ_p/L ratio. On high speed large mach--ines this relation may lead to lengths of cores too long for cooling purposes and it is possible to alter this ratio on high speed machines quite a lot, but on large slow speed machines shall be the first griding factor. It is best to work out several designs and choose the one with best performance.

After determining the diameter of stator bore D the length l can be found out from the $D^2 L$ product. Radial ventilating ducts each of about 10 mm. wide are provided after every 50 mm. and no this way the no. of ventilating ducts is determined and the gross length of the Iu is also determined.

1.1.5. Air-gap of the Motor

It is better to have the length of the air gap as small as possible, since $\Phi = \frac{M.M.F}{reluctance} = \frac{1}{\delta}$ and thus an increase in δ means increase in the magnetizing current, also the harmonic reactance decreases s that for the same amount of real loading the power fact decreases. Also there is a reduction in the maximum power that the motor can supply. These effects of incr-easing the air gap are undesirable.

Thus the air gap is determined by the safe mechanical clearance. Several empirical relations are available among which the following are most suitable:

For large machines[5]

$$\delta = \frac{D}{1200}(1 + 9/p) \quad \text{for } 2 - 16 \text{ pole machines}$$

and $$\delta = \frac{D}{1600} + 0,6 \quad \text{for } 18 - 56 \text{ pole machines}$$

(Here D and δ both are in millimeters and p = no. of poles).

Certain curves fig. 1.1.8 are also available from which δ can be calculated for differ-ent diameters.

Contd

1.2 STATOR DESIGN

1.2.1. Windings

The following items specify a 3 phase winding:

a)	Type of coil:	concentric, lap, wave
b)	Overhang:	diamond, multiplane, mush involute
c)	Layers:	Single, double
d)	Slots:	Open, closed, semiclosed
e)	Connection:	star, mesh
f)	Phase spread:	60°, 120°
g)	Slotting:	integral, fractional
h)	Coil span:	full pitch, short pitch
j)	Circuits:	series, parallel
k)	Coils :	single turn, multi turn

The most usual winding has the features underlined.

The double layer windings are very comm-only used for large induction motors, the conductors may consist of rectangular copper straps, suitably lami-nated to reduce the eddy current losses. There are numerous advantages in the use of the double layer win-ing, tabulated as follows:

1. It is possible to adjust the span of the coi

i.e. the chorded windings can be used. By adjusting the chording, it is possible to obtain the equivalent of a fractional number of turns per coil, for example in a given case 3,6 turns are required for a requisite overload capacity then a coil with U turns and a coil span factor of 0,9 will give the desired effect.

2. With chorded windings it is possible to eliminate certain undesirable harmonics from the flux and torque; the coil span factor of ν th harmonic = $\sin \nu \frac{W}{\tau_p}$ W = coil span. When $\sin \frac{W . \nu}{\tau_p} . \frac{\pi}{2} = 0$ the amplitude of the ν th harmonic is zero.

3. A considerable saving in copper is effected by chording specially on two pole machines; since the amount of ineffective copper is reduced.

4. Slot leakage and end connection leakage is greatly reduced.

Thus the use of double layer winding is economical and provides greater flexibility.

With double layer windings the overhangs are generally of diamond shape and lie on a cylinderical surface. The lap connections are most usual.

When the voltage is high generally it is economical to use the star connection. However, in low voltage machines mesh connected winding are most popular since they can be started by star-mesh starter

Short Pitch Winding

The following investigation deals with the copper weight for all values of pole pitch and core lengths.

In making the calculation it is assumed that depth of the slots can not be increased in order to accommodate the increased numbers of conductors due to chording.

Let

z = total number of conductors with chorded coi

z' = total number of conductors with full pitch coils

$$\beta = \frac{W}{\tau_p} = \frac{\text{Coil span}}{\text{pole pitch}}$$

F = area of each conductor

ℓ = length of core

$\alpha \tau_p$ = length of overhang at each end of the full pitch coil.

In any case the value of α may easily be calculated, for the inclination of the coil end to the core with diamond shaped coils is given by

$$\sin^{-1}\theta = \frac{\text{width of slot copper + cleara}}{\text{width of slot + width of toot}}$$

The mean length per turn with full pitch coils

$$= 2(\ell + \alpha\tau_p)$$

$\therefore$ The volume of copper with full pitch coils and conductors

$$= \frac{z'}{2} \cdot 2\,(l + \alpha\tau_p) \times F$$

$$= (l + \alpha \cdot \tau_p) \cdot F$$

Similarly, length of mean turn with chorded coil

$$= 2\,(l + \beta \cdot \alpha \cdot \tau_p)$$

$\therefore$ Volume of copper

$$= z \cdot (l + \beta \cdot \alpha \cdot \tau_p) \cdot F$$

but, since $z = \dfrac{z'}{\sin \beta \cdot \frac{\pi}{2}}$

($\sin (\beta \frac{\pi}{2})$ being the pitch factor)

$$z \cdot (l + \beta \cdot \alpha \cdot \tau_p) \cdot F = \frac{z'}{\sin \beta \cdot \frac{\pi}{2}} \cdot (l + \beta \cdot \alpha \cdot \tau_p) \cdot F$$

$$\therefore \frac{\text{Volume of copper with full pitch coils}}{\text{Volume of copper with chorded coils}}$$

$$= \frac{z'(l + \alpha \cdot \tau_p) \cdot F}{\dfrac{z'}{\sin \beta \cdot \frac{\pi}{2}} \cdot (l + \beta \cdot \alpha \cdot \tau_p)\, F}$$

$$= \frac{(l + \alpha \cdot \tau_p) \sin \beta \cdot \frac{\pi}{2}}{l + \beta \cdot \alpha \cdot \tau_p} = A \text{ say}$$

The most economical span of the coil will be that which gives the above ratio a maximum value.

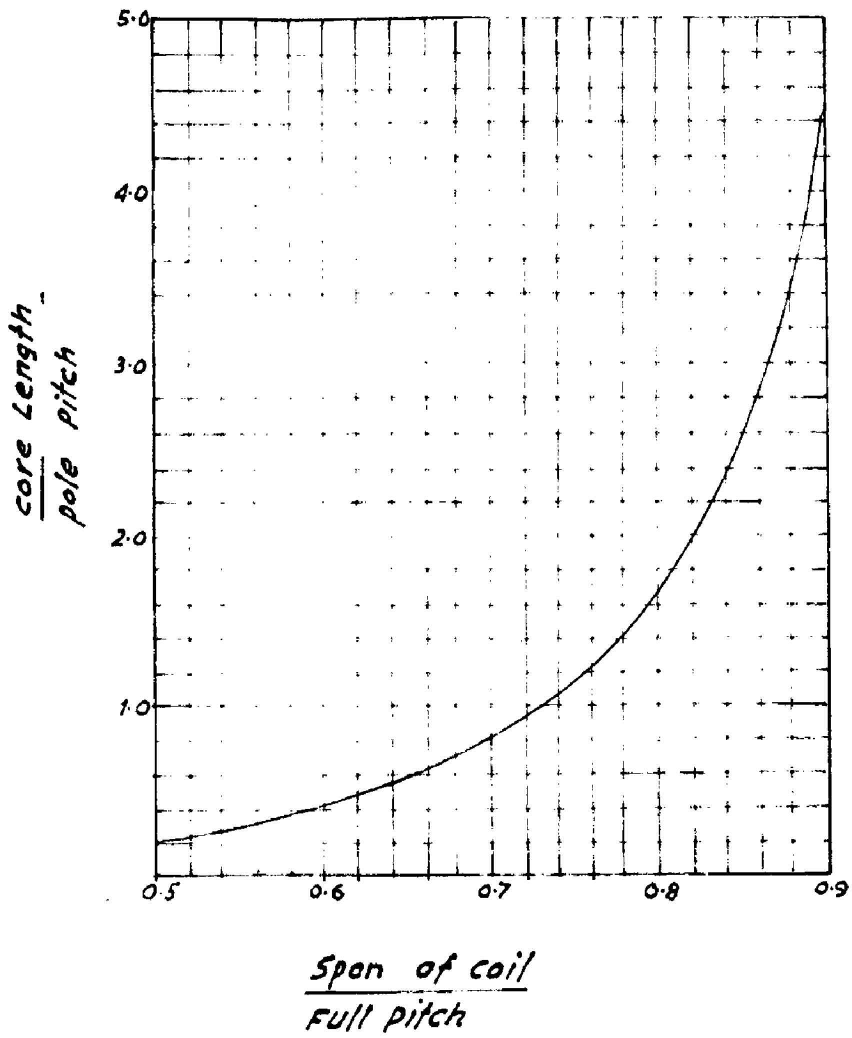

5.0
4.0
3.0
2.0
1.0
0.5
0.6
0.7
0.8
0.9
core Length / pole pitch
Span of coil / Full pitch

Fig 1, 2, 1

Therefore for a minimum

$$\frac{dA}{d\beta} = \frac{(\ell + \alpha \tau_p)\ (\frac{\pi}{2} \cos \beta \frac{\pi}{2})\ (\ell + \alpha.\beta.\tau_p) - \alpha\ _p(\sin\beta \frac{\pi}{2})(\ell +}{(\ell + \alpha.\beta.\tau_p)^2}$$

$$= 0$$

$$\therefore \frac{\pi}{2} \cdot \cos(\beta. \frac{\pi}{2})(\ell + \alpha.\beta.\tau_p) = \alpha . \tau_p . \sin \beta . \frac{\pi}{2}$$

$$\text{or} \quad \tan \beta . \frac{\pi}{2} = \frac{\pi}{2} \left(\frac{\ell + \alpha.\beta.\tau_p}{\alpha . _p}\right)$$

$$= \beta \cdot \frac{\pi}{2} + \frac{\pi}{2} \cdot \frac{\ell}{\tau_p} \cdot \frac{1}{\alpha}$$

Putting $\beta = \frac{W}{\tau_p}$

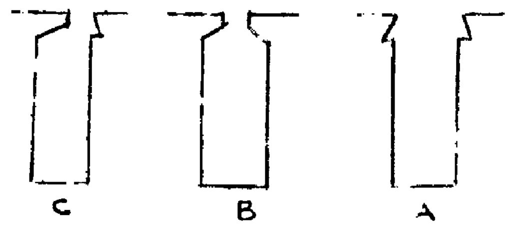
$$\tan \left(\frac{W}{\tau_p} \cdot \frac{\pi}{2}\right) = \left(\frac{W}{\tau_p} \cdot \frac{\pi}{2}\right) + \frac{\pi}{2.\alpha} \cdot \frac{\ell}{\tau_p} \quad \ldots 1.2.$$

This ratio gives the most economical span of the coil for different ratios of ℓ/τ_p curve 1.2.1, shows the solution of the above equation in which the value of α is taken as 1,2 .

1.2.2 Type of Slots

Figure 1.2.2, shows the types of slot that are in use for large induction motors[2,3,4,6]. These are all shown with parallel sides, which is the usual arrangement.

P T O



1.2.2

The considerations which determine the shape of the mouth of the slots are a) The average value of air gap permeance should be kept down and the limits of its variation from point to point should be narrow; b) the leakage inductance arising from magnetic lines crossing the mouth of the slot should be small; and c) the shape of the slots shall be such that the winding can be inserted as easily and as cheaply as possible, fixed firmly and insulated securely.

Consideration (a) involves the use of slots which has the smallest possible openings but (b) and(c) require that the space between the tips of the tooth shall be of moderate dimensions.

The wide open slots shown in fig. A, are the worst from the point of view of the reluctance of the a: gap. When these slots are used the reluctance is necessarily high even when the slots are narrow and numerou: moreover, the variations in magnetic density from point to point along air gap are large, and extra iron losses are caused through the rapid fluctuations in density in the tops of the opposite teeth, in addition to this noise and vibrations are increased. On the other hand the leakage across the mouth of the slot is relatively small, although this advantage is set off by the fact that the whole slot is deeper and narrower then the alternative half closed slot would be, and therefore, the leakage lower down may be greater. From the point of view of insertion and insulation of the winding, however, the wide open slot is by far the most advantageous because it allows fully formed and insulated coils to be inserted radially with out appreciable bending.

The partly open slot in fig. B, is the one which posses the best all round characteristics. Its aperture can be kept relatively small in comparison with slot pitch, say 1/5th of it or even less and need not be more than about 5 or 6 times the length of the air gap. Even under these conditions the density at the rotor surface opposite the center of the rotor slot may fall to one third of the density opposite the center of a tooth. If the overhanging tips of the teeth are too thin they will become saturated and will be the seat of unnecessary iron loss, and, further they will not spread the flux in the air gap as much as is desired. Moreover when it is desired to insert the windings through the slot openings the safety of the insulation is leopardised and the work of the winders becomes very difficult if the edges are too sharp. On the other hand, the thinner the tips can be made, lesser will be the slot leakage. Hence a compromise have to be made for determining the thickness of the slot lips. In machines where the no. of slots per pole per phase is high the leakage react- -ance is generally low and thicker lips can be used with out the danger of increasing the leakage reactance excessively.

The disadvantages of the open slots can be overcome (whilst retaining the case of winding which they present) by providing wedges, partly constructed of magnetic materials to be inserted after the winding and to have the effect of reducing the virtual slot opening, from the magnetic point of view. However, the design of such wedges present a difficult problem, for the permeance of the wedge between the side of the tooth and the airgap must approximate to that of solid iron, if it is to fulfill its purpose, whilst the magnetic mat -erial which it contains must be laminated in radial planes or very finely devided.

When the winding is designed so that the conductors can be inserted radially, one at a time, full advantage can be taken of the partially closed slots and formed coils and bars can be used. When a bar win -ding has three or five bars per layer in each slot the shape shown in fig. B, is very suitable and the middle bar in the top layer can be inserted last of all. When a slot contains two bars side by side the slot shown in Fig. C, can be used.

1.2.3. Number of Stator Slot

Harmonic leakage reactance depends on th value of the stator slots per pole per phase q_1 and a it is not desirable to have high values of short circui current in large machines generally a high value of q_1 (q = 4 ----- 8, 10----- 12) is taken.

A suitable slot pitch is assumed; usual value are $\tau_{sq} =$ 30 mm. for low voltage m/c and $\tau_{sq} =$ 40 m for high voltage machines

Now, number of stator slots $S_1 = \frac{\pi D}{\tau_{sq}}$ ....1.2.

but for a 3 phase machine the total number of slots = $3.p.q_1$

$$\text{Hence} \quad 3p.q_1 = \frac{\pi D}{\tau_{sq}} = S_1$$

$$q_1 = \frac{S_1}{3p} \quad \ldots\ldots \quad \ldots. \ 1.2.3,$$

Generally for induction motors integral slot windings are used so that q_1 above shall have to be an integer. Taking q_1 as the nearest integer the values of S_1 and τ_{sq} are adjusted.

1.2.4. Number of Series Conductors Required in the Stator Winding:

Roughly

$$Un = \sqrt{3}.\ 4{,}44\ f.\ N_1.Kd_{p1}.\ \Phi_1.10^{-8}$$

where $\Phi_1 = \bar{B}.\tau_p.\ell = \bar{B}.\ \frac{\pi.D_1}{p}.\ \ell$

and N_1 = number of turns / phase of the stator

$$= \frac{Z_1}{6} = \frac{\text{Total no. condr. in the stato}}{2.3}$$

$$f = \frac{n_s.p}{120}$$

$$Un = \sqrt{3}.\ 4{,}44.\ \frac{n_s.p}{120}.\ \frac{Z_1}{6}.\bar{B}.\ \frac{\pi D}{p}.\ell.$$

$$Kd_{p1}.10^{-8}$$

Taking $Kd_1 = 0{,}955$

$$Un = \frac{\sqrt{3}.4{,}44.\ \pi.0{,}955}{120.\ 6}.n_s.\ Z_1.\bar{B}.D.\ell.$$

$$K_{p1}.10^{-8} \quad \ldots\ldots\ 1.2.4.$$

Here every thing is known except Z_1 and thus Z_1 can be calculated. But the number of conductors per slot have to be a whole number

i.e. $nc = \frac{Z_1}{S_1}$ = an integer

Thus taking Nc the nearest possible integer the value of and $\bar{B}$ are adjusted.

1.2.5. Conductor Cross-Section

$$\text{Full load current } I_n = \frac{N_n \cdot 10^3}{\sqrt{3}\ U_n \cdot \cos\varphi \cdot \eta} \qquad \text{-------- } 1.2.5,$$

Where N_n = output in Kw.

U_n = normal line voltage

$\cos\varphi_n$ = normal power factor

η = normal efficiency

With larger machines generally the current density in the conductors is taken 3 - 8 Amp/mm^2.[2,6] For high speed machines the larger values are taken since the cooling conditions are better. Also in high voltage machines and where lower magnetic and electric loading are taken, a high value of current density is chosen .

The conductor cross section F is determined as follows:

$$F = \frac{I_n}{i} \qquad \text{------} \qquad \text{------} \qquad 1.2.6,$$

where i = current density in the conductor.

In large machines, specially when the voltage is low, the current per conductor is too high requiring large dimensions of conductors and so two or more para--llel circuits are provided. The maximum number of parallel circuits are equal to the number of poles. Generally, use is made of reactangular conductors in order to have a better slot space,space factor,however, where bar winding is used bars of special sizes are employed.

Stranding of conductors - Conductors of large cross-section normally are devided into strands for mechanical as well as for electrical reasons. The mechanical reason is to make the conductor flexible, i.e. easy forming. The electrical reason is to avoid parasitic currents in the conductors which increases the heating of the copper. When conductors are stran--ded for electrical reasons, the individual strands must be insulated. The additional copper losses due to eddy currents are proportional to the height of the conductor, to the height of each strand, and to the frequency of the line current. Hence the thickness of the strands is made as small as possible.

P T O

1.2.6. Insulation of Conductors slots and End Windings:

The different kinds of insulating materi used in electrical machines are devided into 4 classes specified by A.I.E.E., on the basis of N E M A stand-ards. These 4 classes are given in table 2. The same table contains the limiting temperatures which car not be exceeded with out impairing the life of the material.

In the following the conductor insulation, strand insulation, ground insulation end winding insulation and binder insulation is considered.

Conductor insulation. On straps or large rectangular or square conductors, which are usually used for large induction motors, the insulation is applied after the coil has been formed or during the process of forming the coil.

The thickness of the conductor insulation depends upon the voltage between turns. In general Scc, SFG or enamel is used for voltage upto 12 volts, and D.cc, DFG or SCE for voltage upto 25 volts. For turn voltages between 25 and 40 volts, either Tcc or TFG, can be used or a certain amount of insulation can be added to the normal Dcc or DFG resulting in a conductor insulation equivalent to Tcc or TFG .

This additional insulation can be either cotton or glass tape, paper or mica strips applied through out the coil. For values of turn voltages greater than 40 volts the trend is to use additional insulation in the form of mica tape. For values upto 70 volts one serving of mica tape half lapped is used and for val--ues upto 120 volts two servings of mica tape are used.

Strand insulation:

When conductors with larger cross sections are stranded, the strand insulation is cotton,asbestos or glass with a thickness of 0,2 mm. to 0,25 mm. for both sides.

Ground insulation:

This is the insulation applied to the slot portion of the coil. It serves to prevent the breakdown of the insulation to ground (core iron) and must, therefore, have sufficient dielectric stren--gth. The ground insulation will be considered sepa--rately for semi-closed and for open slots.

TABLE 2 STANDARD CLASSIFICATION OF INSULATING MATERIALS AND TEMP. LIMITS

Class	Material Classification	Limiting Temperatures, for Industrial apparat		
		Thermo -meter	Embedded Detector	Hot Spo
O - Untreated organics	Untreated fabrics of cotton, silk, linen. Untreated paper, fiber, wood etc.	75	85	90
A - Treated or impregnated organics	Cotton, silk, linen, and similar organic materials when impregnated in oil, varnish, wax or compounds. Oil, varnish, bakelite, and organic fillers. Enamel as applied to wires.	90	100	105
B - Treated or impregnated inorganics	Asbestos, fiberglas, mica tape, oxide films, inorganic fillers, asbestos boards. (A limited amount of organic materials may be used for binding or structural purposes.)	110	120	130
H - Treated or impregnated inorganics	Mica, asbestos, fiberglas and similar inorganic materials in built up form with binding substances composed of silicone compounds, or materials with equivalent properties; silicone compounds in rubbery and resinous form or material with equivalent properties in minute proportions. Class	-	-	180

A material may be had only where

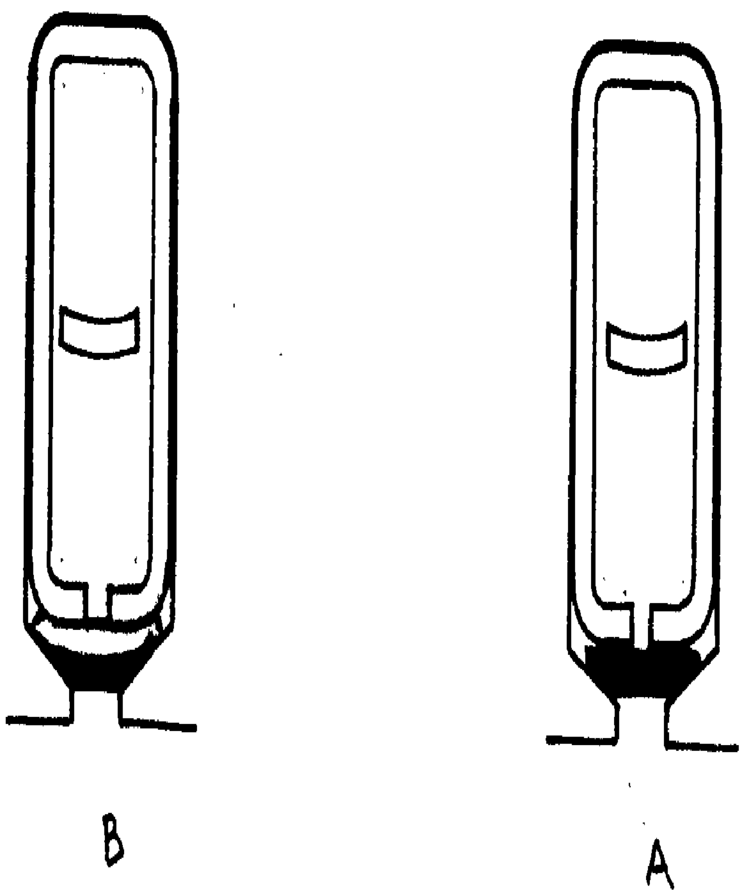


Fig. 1.2.3

Ground insulation for semi-closed slots:

Some arrangements of ground insulation i.e. of cell and seal of the slot openings for semi--closed slots are shown in figure . . . The thick--ness of cell is 0,5 mm. to 0,75 mm. Fish paper and varnished cloth is often used as cell material for class A insulation, the cloth being cemented to the fish paper and the latter laying outside against the iron. Combinations of mica and fish paper or mica and glass cloth are used for class B insulation; The mica usually being protected on both sides. Com--bination of mica and glass treated in silican varn--ishes are used for class H insulation.

In order to prevent tearing the edges of the cells, a selvage of thin Scotch tape or cotton tape is applied at each edge of the cell. For this purpose the cell material is cut into long strips as wide as the length of the cell, and the selvage is put on both edges of the strip, which is then cut into pie--ces of proper width.

In the arrangement A the wedge is made of wood giving a tighter seal. Fig.1.2.3 B is used for windings of higher voltages exposed to dirt. The strip in the middle of the slot is used to separate the upp--er coil side from the lower.

TABLE 3 NORMAL GROUND INSULATION FOR CLASS A,B AND H COIL

Voltage Range	Class A		Class B		Class C	
	Material	Turns of Wrapper or Mica Wall Thickness	Material	Turns of Wrapper or Mica Wall Thickness	Material	Turns of Wrapper or Mica Wall Thickness.
to 600	0,25 VC 0,25 FP M	1 1/4-2 1/4	0,25 FP M	1 1/4	0,25 SGC	1 1/4 - 2 1/4
600 to 1200	0,25 VC 0,25 FP M	3 1/4	0,25 FP M 0,15 MT	2 1/4-3 1/4 0,6	0,25 SGC 0,10 SGMT	2 1/4 - 3 1/4 0,6
1200 to 2500	0,30 VC 0,30 FP M	3 1/4	0,30 FP M 0,15 MT	3 1/4 0,9	0,25 SGC 0,10 SGMT	3 1/4 0,9
2500 to 3500	0,30 FP M 0,30 KP M	3 1/4	0,30 FP M 0,20 MT	3 1/4 1,2	---	---
3500 to 4500	0,30 KP M	4 1/4	0,30 KP M 0,20 MT	4 1/4 1,5	---	---
4500 to 6600	0,35 KP M	4 1/4	0,35 KP M 0,20 MT	4 1/4 2,5	---	---
6600 to 11,000	----	----	0,20 MT	3,5		

VC M = Varnished cloth
FP M = Fishpaper and mica
KP M = Kraft paper and mica

MT = Mica tape
SGC = Silicone glass cloth
SGMT = Silicone glass mica

(All dimensions in Millimeters)

Ground Insulation of Open Slots:

Contrary to the windings in semiclosed slots where the ground insulation is not a part of the coil, the ground insulation of windings in open slots is applied directly to the coils and is a part of the coil. It consists of a wrapper of which the material and number of turns depends on the voltage. Before spreading the coil, a temporary binder is applied. This binder has two functions it binds the conductors tightly to-gether to obtain a proper shape; and it protects mechanically, the strand or conductor insu-lation. This binder is usually 0,125 to 0,25 mm., thick and is applied without lap or with space betw-een turns. After spreading the coil is then impreg-nated with varnish for voltages below 3500 volts or with asphalt for higher voltages. The varnish impreg-nated coils are drained after dippling and then are baked in temperatures ranging from 165° to 250° C. One dip is applied below 1200 volts and two dips for voltages between 1200 - 3500 volts. The asphalt imp-regnation occurs under vaccum and pressure.

The material of wrapper its thickness and number of turns for different voltages are given in table 4.

TABLE 4 END WINDING INSULATION

(All dimensions in)

Voltage Range	Phase Coil			Plain Coil			Finish Tape		
	Class A	Class B	No. Layer or Mica Wall Thickness	Class A	Class B	No. Layer or Mica Wall Thickness	Class A	Class B	Varnis[h] Treatm[ent]
to 600	0,2 CT	0,2GT	1	.....	....	0.	0,2CT	0,2GT	2
600 to 1200	0,25BTC	0,15 MT	1	0,2 CT	0,15 GT	1	0,2 CT	0,2GT	2
1200 to 2500	0,25BTC	0,15MT	2	0,25BTC	0,15 MT	1	0,2 CT	0,2GT	2
2500 to 3500	0,25BTC	0,20	3	0,25BTC	0,20 MT	2	0,2 CT	0,2GT	2
3500 to 4500	0,25BTC	0,20MT	4	0,25BTC	0,20 MT	3	0,2 CT	0,2GT	3
4500 to 6600	0,25BTC	0,20MT	6	0,25BTC	0,20 MT	5	0,2 CT	0,2GT	3
6600 to 11000	...	0,20MT	0,35	...	0,20 MT	0,35	....	0,25GT	...

GT = Glass tape
CT = Cotton tape
MT = Mica tape

BTC = Bias cut varnis[hed] cotton tap[e]
SGT = Silocone glass [tape]
SGMT = Silicone glass [mica] tape.

TABLE 5 MECHANICAL CLEARANCES

(All Dimensions in Centimetres)

Voltage Range	Top Cell Extension	Bottom Cell Extension	Distance to Retaining Ring or clamp	Distance from Connection to End Brackets	Distar betwe End Wi
	A.	B.	C.	D.	E
Semi-Open Slots	1,2 to 1,6	0,9	0,8	0,75	0,15-(
Open Slots					
Up to 600	1,2 to 1,9	0,95 to 1,6	0,95	0,75	0,25
600 - 1200	1,6 to 2,2	1,5 to 1,9	1,2	0,95	0,25
1200 - 2500	2,2 to 2,9	1,9 to 2,5	1,6	1,2	0,30
2500 - 3500	2,9 to 3,5	2,5 to 2,9	1,9	1,6	0,4
3500 - 4500	3,5 to 4,5	2,9 to 3,9	2,5	2,9	0,5
4500 - 6600	4,5 to 6,5	3,9 to 4,5	3,2	3,2	0,5
6600 - 11000	6,5 to 7,5	4,5 to 8,5	3,8	4,5	6,5-8

End Winding Insulation:

The end windings of coils are taped in one or several layers. For class A insulator, cotton tape or bias-cut varnished cloth tape is used; for class B insulation mica tape is applied; and for clas H insulation, silicon glass mica tape is applied. The number of layers of the material and its thickness is given in table 4.

Lead Insulation:

When the leads are tied to the coils, strips of insulating material are between the leads and coil. Upto 600 volts, a piece of 0,25 mm. trea-ted material used under the starting lead. At volt-ages from 600 - 2500 V one strip of mica and fish paper 0,3 - 0,4 mm. thick, at voltage from 2500 - 6600 V, 2 strips are applied to each lead. For class H insulation silicon treated mica tape is used to protect the starting lead in the diamond point of the coil. The leads must be firmly tied to the coil and insulated with the same material and at the same time as the end winding. The number of layers is 2 for voltages upto 2500; 3 for voltages from 2500-4500 volts and 4 for voltages from 4500 - 6600 volts.

When the leads are loose, tubing or 0,175mm.

For voltages 600 to 3500 volts, 3 layers of 0,25 mm. bias-cut treated cloth tape, with one layer of half lapped 0,175 mm. cotton tape. For voltage 3500-4500 volts 4 layers and for voltages 4500 - 6600 V 6 lay--ers of the same material as before plus one layer of 0,25 mm. half lapped cotton tape. For class B insu--lation 0,3 mm. mica tape instead of treated cloth and 0,175 mm. glass tape instead of cotton, and for class H 0,1 mm. silicone glass mica tape and 0,175 mm. glass mica tape have to be used.

<u>Insulation of Stub Connections, Jumpers and Tie rings</u>

The tie rings must be insulated and the insulation applied is the same as far stub connections and jumpers. The thickness of the insulation depends upon the voltage. It is 1,0 mm. for voltages upto 600 volts; 1,5 mm. for voltages 600 - 2500 volts; 1,75 mm. for voltages 2500 - 3500 volts; 2 mm. for voltages 3500 - 4500 volts; 2,5 mm. for voltages 4500 - 6600 volts; 3,5 mm. for voltage 6600 - 11000 V and 4mm. for voltage 11000 - 13000 volts. The insu--lation for class A consists of one layer of 0,175 cotton tape half lapped, plus a number of layers (depending on the voltage) of black bias -cut varnished cloth tape 2,5 cm. wide, plus a finishing layer of 0,175 mm. cotton tape half lapped. For class B insu-

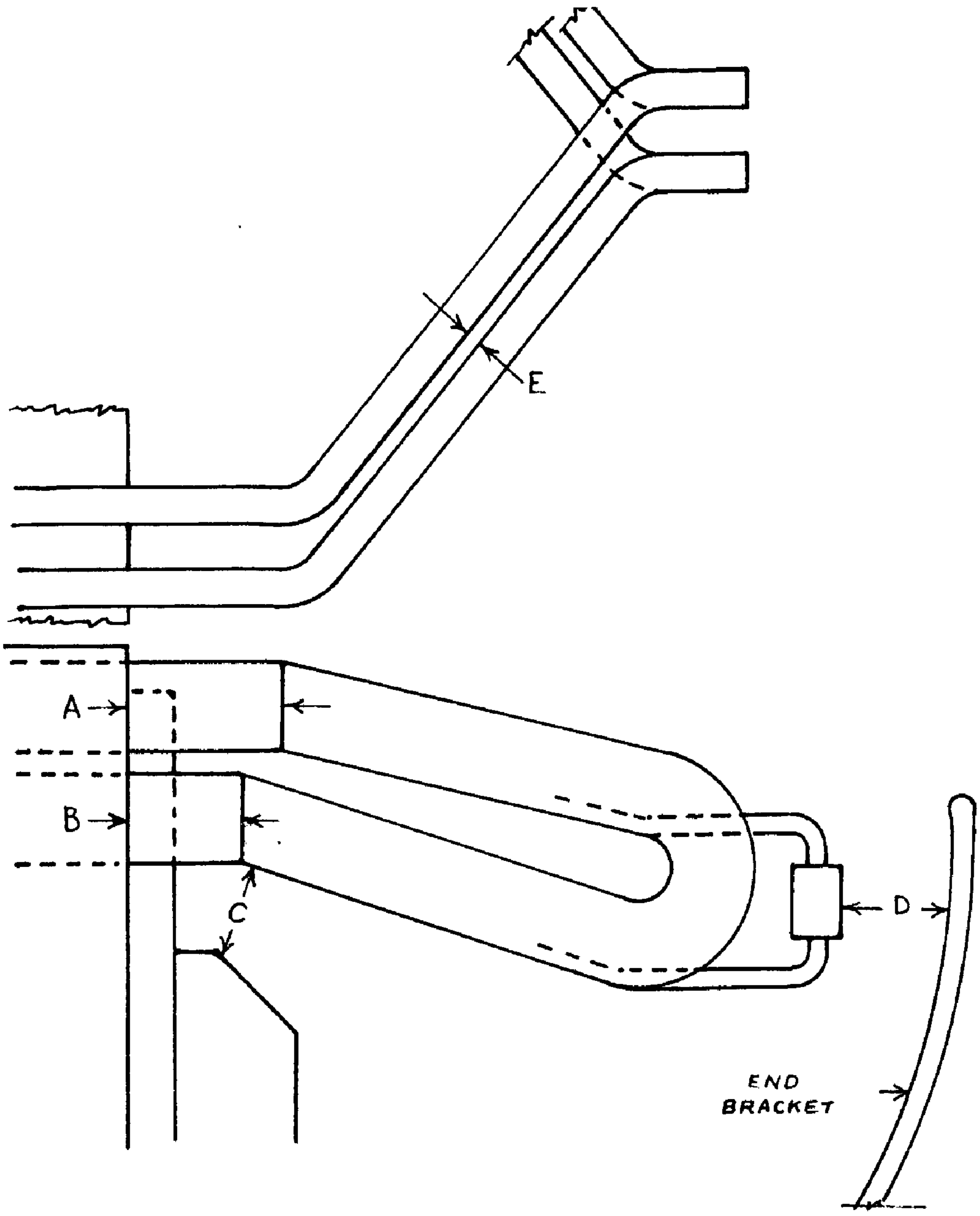


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Fig 1.2.4

by deterr
-mining the width of the tooth at its narrowest sectior from the flux and flux density considerations. As exp-

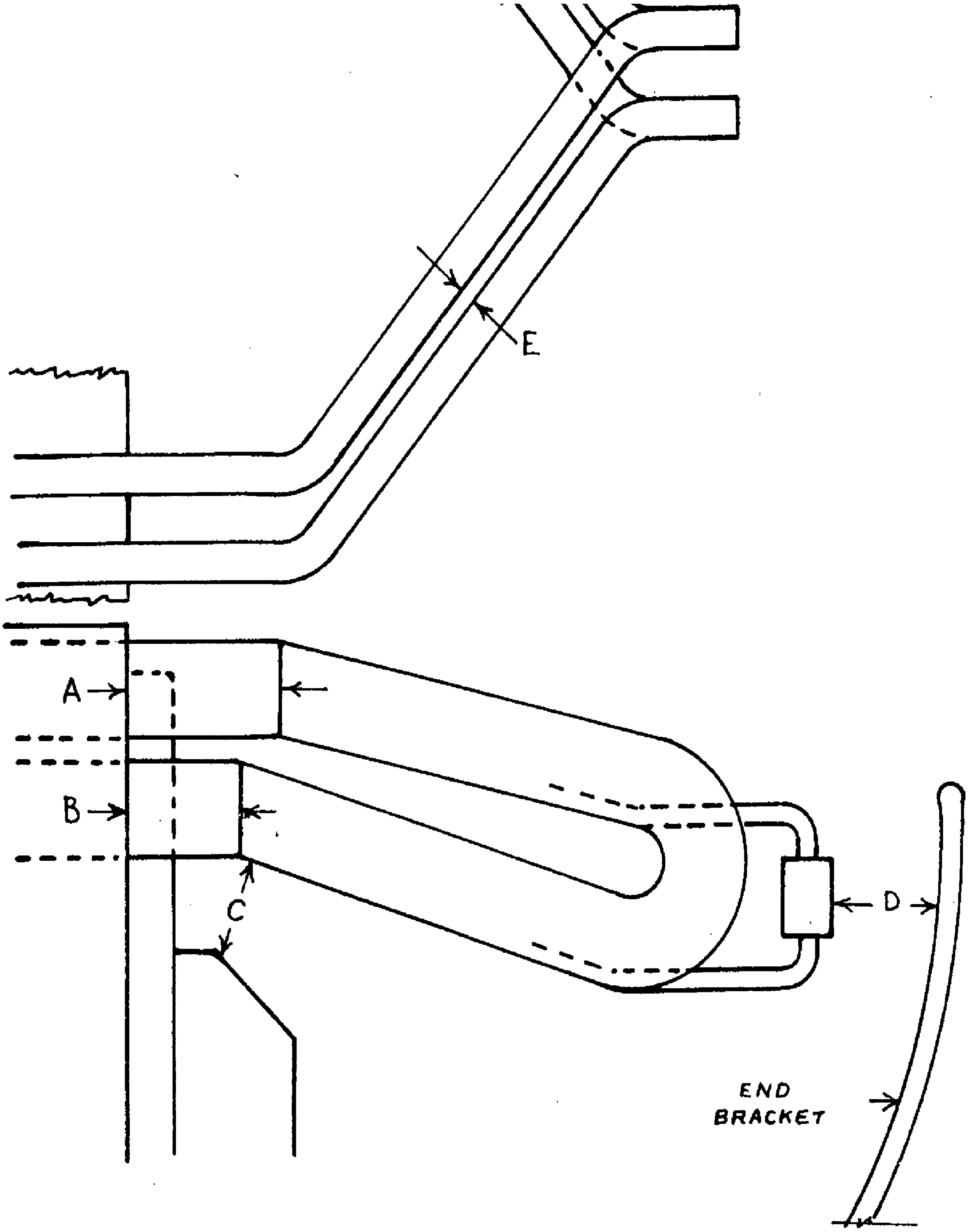


Fig 1.2.4

cloth tape 2,5 cm. wide, plus a finishing layer of 0,175 mm. cotton tape half lapped. For class B insu-lation, 0,15 mm. mica tape is to be used instead of varnished cloth and 0,175 mm. glass tape instead of cotton. For class H insulation, silicon glass mica tape and silicon glass tapes are to be used instead of mica and glass, tapes. Before applying insulation the ~~glass~~ metal must be first cleaned and brushed with a good baking varnish. The first layer of the insula-tion has to be applied when the varnish is wet.

Mechanical clearances:

An important factor for windings of electrical machines is the creepage distance, i.e., the distance which a current must creep across insu-lation or through the air, or through a space filled with dirt, no order to produce a fault to ground or to another phase. The clearance are given in table 5.

(Fig 1.2.4)

1.2.7. Slot Dimensions

The width of the slot is fixed by determ-mining the width of the tooth at its narrowest section from the flux and flux density considerations. As exp-

-lained earlier, it has been found that the maximum flux density shall not bemore than 16000 G in any part of the tooth.

If B_1 is the maximum flux density in the air gap than the flux that crosses one teeth is equal to the flux embraced by one slot pitch

$$\text{or} \qquad \phi_{sg} = \frac{2}{\pi} B_1 . \tau_{sg} . \ell \qquad ..... \text{-----} \; 1.2.7,$$

This flux is passing through one teeth if B is the maximum flux density at any point in tooth and its thickness at that point is b_t, then, flux cros-sing one tooth

$$\phi_t = \frac{2}{\pi} B_t . b_t . \ell \qquad ..... \text{-----} \; 1.2.8,$$

$$\text{As} \quad \phi_t = \phi_{sg}$$

$$B_t . b_t = B_1 . \tau_{sg} \qquad ..... \text{-----} \; 1.2.9,$$

Since at the narrowest E section of the tooth the flux density shall not increase by 16000 G the tooths width at that section is given by

$$b_t = \frac{B_1 . \tau_{sg}}{16000} \qquad \text{-----} \; 1.2.10,$$

No allowance has been made for the leakage flux in the above expression. If leakage flux is taken into account then

$$bt = \frac{B_1 . \tau_{sg}}{16,00} \left(1 - 2/3\,\epsilon_s\right) \quad \text{-----} \quad \text{---}(1.2.11)$$

$$\text{Where } \epsilon_s = \frac{\text{Leakage flux}}{\text{Total flux}} = \frac{I_\phi \cdot X_{al}}{E}$$

Thus the remaining space in slot pitch can be used as the width of the slot.

1.2.8. Mean Length Of The Conductor:

For diamond shaped coils the length of the con -ductor is calculated , as follows , in figure 1.2.5,

$$\cos \alpha = \frac{\sqrt{\tau_s^2 - a^2}}{\tau_s} \quad \text{----} \ 1.2.12$$

$$S = \frac{W . \tau_s}{2} \frac{1}{\cos \alpha} \quad \text{----} \ 1.2.13$$

where τ_s = slot pitch

and W = Coil span in no. of slots.

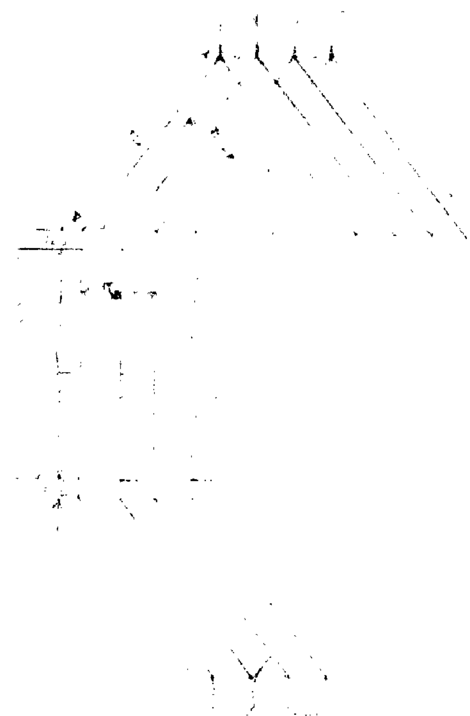


Fig. 1.2.5.

From equation 1.2.13 S can be calculated

The length in the top bend position is $\pi . h$

∴ Length of each conductor

$$L_Z = L + 2\, le_2 + 2S + \pi \frac{h_s}{4} + (50 \text{ m.m})$$

Total length of copper $= L_Z \cdot Z_1$

1.2.9. Stator Core:

Total flux above the teeth passes through the core in a manner shown in fig. 1.2.6. This flux Φ_s can be calculated from the fundamental voltage eqn.

$$U_s = \sqrt{3}.\ 4{,}44.f.N.\ K_{dp1}.\ \Phi_s . 10^{-8} \text{ Volts}$$

If Bc_1 is the stator core density and hc_1 is the depth of teeth then

$$hc_1 = \frac{\Phi_s}{2} \cdot \frac{1}{Bc_1} \cdot \frac{1}{l_i}$$

Fig. 1.2.6.

where l_i = net iron length

The value of Bc_1 is kept between 10000 - 12000

Out side diameter of the rotor

$$Do = D + 2h_{t1} + 2h_{c1}$$

1.3. ROTOR DESIGN

The induction motor with a cage rotor, in addition to its many advantages, has two serious faults, the worst being its great start- ing currents associated with small starting torque, and the other being its disagreeable characteristic of crawling. In some cases the starting only occurs to the accompniment of more or less loud noise or even hawling; in other cases, in certain ranges of speed, the rotors only accelerate exceedingly slowly, or indeed - this is the most disagreeable characteristic — they remain hanging at certain low speed; that is to say, the torque decreases to such a low value that it no longer suffices even for overcoming the frict- -ion losses.

1.3.1. Number of Rotor Slots:

The choice of the precise number of stator and rotor slots is of decisive influence on the starting behaviour of induction motors. If,for some particular number of rotor slots the torque curve has a deep saddle, it may in some cases be completely eliminated by increasing or decreasing the number of slots by one. 'Still' in his paper published a large collection of test results. Punga cited a large series of number of slots which in practice has been found to be either favourable or unfavourable. Punga, Kron and several others had given certain rules for the selection of the number of rotor slots.

The following is the summary of the results obtained by Punga and Moller.

The causes which render a cage motor can be of the three types

a). Strong noise production.- The main cause of strong noise production is magnetic vibrations, which set up resonance with mechanical vibrations. Dr. Moller advocates that with few exceptions, the odd number of rotor slots which tend to cause noise production shall be avoided.

b). Asynchronous torques.- The amplitude of the harmonic torques increases with increasing number of rotor slots and, for about doubled number of rotor slots, attains a value which exceeds the maximum torque of the fundamental. Therefore, there shall be avoided all number of rotor slots which exceed 1,7 times the number of stator slots, unless skewed slots are employed.

c). Synchronous torques.- This is the most important phenomenon and is eccasioned by the difference $S_2 - S_1$ being equal to $\pm$ p or $\pm$ 2p, p being the number of poles. The strongest synchronous actions appear when the number of rotor slot per pole is different by $\pm$ 1. from the no. of stator slots /pole.

If q_1 and q_2 are the number of stator and rotor slots per pole per phase of the stator respectively, then $q2 = q1 + 2/3$ is a common rule for determining the number of rotor slots S_2. However, check shall be made to ascertain that the synchronous crauvling is not present.

If the number of rotor slots is equal to the number stator slots, or to a multiple of that, then the motor will not start and so this also should be avoided.

1.3.2. Squirrel cage Bar voltage:-

If E_1 is the voltage induced in the primary i.e. the stator winding, then

$$E_1 = 4{,}44.\ f.\ N_1.\ Kd_{p11}.\ \Phi_1.\ 10^{-8} \text{ volts}$$
phase

Similarly, if E_2 is the volt in the rotor, then at standstill

$$E_2 = 4{,}44 .\ f .\ N_2 .\ Kd_{p12} \cdot \Phi_1 . 10^{-8} \quad \text{volts}$$

where

f = supply frequency

N_1 and N_2 = Number turns / phase in the stator and rotor respectively

Kd_{p11} = Winding factor of the stator for fundamental wave

Kd_{p12} = Winding factor of the rotor for fund- -amental

Φ_1 = flux

so that

$$\frac{E_2}{E_1} = \frac{N_2 .\ Kd_{p12}}{N_1 .\ Kd_{p11}}$$

For an unskewed cage rotor $Kd_{p12} = 1$, and also for squirrel cage $N_2 = 1/2$ (Appendix A-2), thus

$$\frac{E_2}{E_1} = \frac{1}{2} \cdot \frac{1}{N_1 .\ Kd_{p11}}$$

But $E_1 = \dfrac{U_s(1-\epsilon_s)}{\sqrt{3}}$ (Appendix A-1)

and since the number of rotor slots per pole per phase is usually large (more than 4) the stator winding distribution factor may be taken as $K_{d_1} = 3/\pi$, hence

$$E_2 = \frac{Us(1 - \epsilon_s)}{\sqrt{3}} \cdot 1/2 \cdot \frac{\pi}{N_1 \cdot K_{p1} \cdot 3}$$

bar voltage

$$= \frac{\pi}{\sqrt{3}} \cdot \frac{Us(1 - \epsilon_s)}{Z_1 \cdot K_{p1}}$$

This bar voltage should be kept down below 40 volts.

1.3.3. <u>Bar and Ring currents</u>

If N_n = output in watts

s = slip

I_r = rotor phase current

r_r = rotor phase resistance

n = number of phases

Fig.1.3.1.

then, from the equivalent circuit

$$N_n = m \frac{1-s}{s} \cdot I_r^2 \cdot r_r$$

$$= m \frac{1-s}{s} \cdot \left[\frac{sE_2}{\sqrt{(r_r^2 + s^2 X_{r1}^2)}} \right]^2 \cdot r_r$$

$$= m \quad (1-s) \cdot \frac{sE_2^2}{\sqrt{(r_r^2 + s^2 X^2_{r1})}} \cdot \frac{r_r}{\sqrt{(r_r^2 + s^2 X^2_{r1})}}$$

$$= m \cdot \eta_r \cdot E_2 \cdot I_{rs} \cdot \text{Cos } \varphi_r$$

where

η_r = rotor efficiency

Cos φ_r = rotor power factor

I_{rs} = rotor current at standstill

thus

$$I_{rs} = \frac{Nn \text{ (watts)}}{m. \ \eta_r. \ E_2. \ \text{Cos } \varphi \ r}$$

Generally, η_r. Cos φ r = γ = 0,92 --------- 0,94.

In the squirrel cage rotor $m = \frac{2 \ S_2}{p} = \frac{2 \ Z_2}{p}$

Z_2 = no. of rotor bars

∴ rotor phase current at standstill

$$I_{rs} = \frac{p. \ N_n \text{ (watts)}}{2 \ Z_2. \ \gamma. \ E_2}$$

But p/2 bars are connected in parallel in one phase (Appendix A-2)

$$\therefore \quad I_{bar} = \frac{N_n}{Z_2 \cdot \gamma. \ E_2}$$

Also ring current S-

1.3.4. Cross-sectional Area of the Bars and Ring

The materials used for the rotor bars for normal machines are copper and aluminium, however, for motors having high starting torques materials of higher resistivity may be used.

Generally a current density of 4---8 A/mm^2 is kept in the rotor bars.

If i be the current density, then, the bar cross-section F_b is given by

$$F_b = \frac{I_b}{i}$$

and the ring cross-section F_r

$$F_r = \frac{I_r}{i}$$

1.3.5. Type of rotor slots:

Some slot shapes for squirrel cage rotor for large induction motors are shown in fig. 1.3.2

For general purpose induction motors - NEMA Class A- the slot shown in fig. 1.3.2 (a) are used. In the NEMA class B - normal torque, low starting current motor usually narrow and deep slots shown in fig. (b) are used. The class C- high starting torque and low starting current generally has a double cage rotor.

1.3.6. Squirrel Cage Winding:

For general purpose large induction motors either round, square or reactangular bars are emplo- -yed. These are made up of copper or aluminium and sometimes of brass. Generally the rotor bars are not insulated and they are connected on each side by a ring. The rings are made of either copper or brass or other material of higher resistivity.

Windings for securing High Starting Torque:

Deep bar rotors - In these types of winding use made of the eddy current effects in the conduc- -tor lying within the slot. If R_e is the effect- ive resistance, X_e is a reactance due to magnetic lines crossing the slot through the conductor, and additional to any reactance due to lines linking the conductor as a whole, the effects of which would be taken into account in estimating the common e.m.f. which applied to the conductor as a whole, then, if R_e is the time d.c resistance

$$\frac{R_e}{R_c} = \xi h \frac{\sinh 2\xi h + \sin 2\xi h}{\cosh 2\xi h - \cos 2\xi h}$$

and $$\frac{X_e}{R_e} = \xi h \frac{\sinh 2\xi h - \sin 2\xi h}{\cosh 2\xi h - \cos 2\xi h}$$

where $$\xi h = 2\pi h \sqrt{\frac{f.\ l_s.\ b_{cu}}{\rho\ .\ l_1\ b_s}}$$ Ref. 4,90

Here f is the frequency of the e.m.f.; l_s is the length of the slot; l_1 an assumed length between two sections of the conductor outside the slo[t] one at each end where the influence of the slot is no longer felt; ρ is the volume resistivity of the conductor; b_{cu} and b_s are the copper and slot widths respectively.

The end rings can be made up of some high resistivity material such as brass or german silver depending on how much starting torque is needed and the efficiency required.

Double cage rotor-

The behaviour of the double cage motor can be represented by the equivalent circuit shown in figure 1.3.3 in which X_1 and r_1 represent the reactance and resistance of the stator winding and Ym the excitation admittance. The impedance of this parallel connection may be ascertained to $Z = \frac{R2}{s} + j X_2$

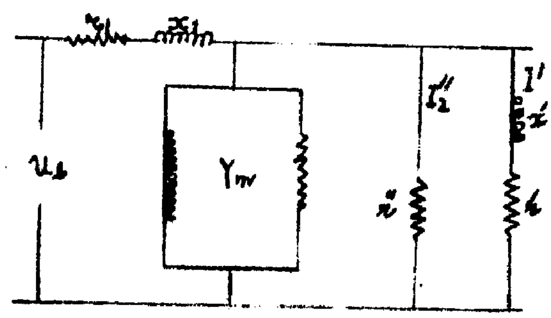


Fig 1.3.3

$$= \frac{1}{s} \frac{r''(r' + j s x')}{r' + r'' + j s x'}$$

$$\therefore R_2 = \frac{r''\left[r'(r'+r'')+(sx')^2\right]}{(r' + r'')^2 + (sx')^2}$$

$$\text{and} \quad X_2 = \frac{r''^2 . x'}{(r' + r'')^2 + (sx')^2}$$

$$\text{At} \quad s = 0; \; R_2 = \frac{r' r''}{r' + r''} \quad \text{and} \quad X_2 = \frac{r''^2 x}{(r' + r'')^2}$$

These values do not appreciably alter when the speed differs a few percent from synchronism and, so are applicable at full load also. Thus th

APPENDIX 1.

Flux condition in an induction motor: When a voltage U_s is applied to the stator winding, then on fullload the stator current is I_s, which produces leakage lines of flux. This leakage flux is in phase with the stator current. If there were no leakage flux the impressed voltage U_s must have developed a flux U_s, lagging 90^0 behind U_s, but due to the leakage lines of flux the flux is reduced to a value $\Phi_s = \Phi_s - \Phi_{al}$. which gives an induced electromotive force E_1. Φ is called the useful flux and is in phase with the magnetising current $I\phi$.

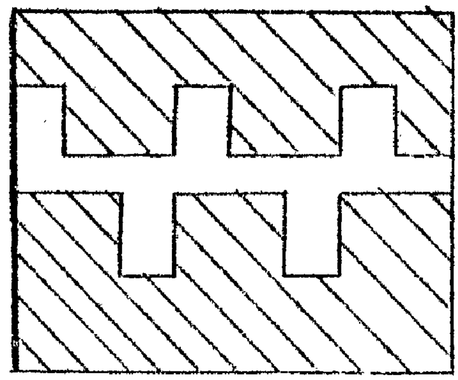


Fig.

This useful flux Φ crosses the air gap and enters the rotor body. There are leakages in the rotor also. The rotor leakage flux is caused by the rotor current. The flux that passes through the rotor core is thus $\Phi_r = \Phi - \Phi_{rl}$

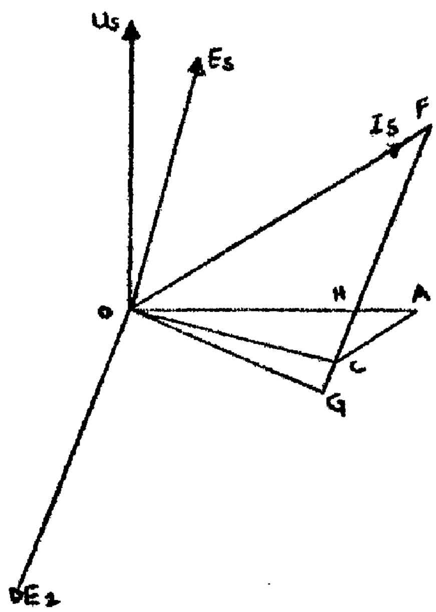


Fig.A-1.2.

In figure A-1.2,OA is the total flux which corresponds to U_s; Ac is the stator leakage flux corresp--onding to I_s. ...

starting characteristics depends on the value of the ratio r_2 / x_2.[16]

The most favourable starting characteristic is that which gives maximum starting torque per ampere of line current. The method for arriving at the value of $(= \frac{x_2}{r_2})$ to obtain this condition is given in the actual design later on the useful flux Φ GC is the rotor leakage flux Φ_{rl} and OG is the rotor useful flux corresponding to E_2

At no load

$$U_s = E_s + I\phi . X_{al}$$

or $$E_s = U_s - I\phi . X_{al} = U_s\left(1 - \frac{I\phi . X_{al}}{U_s}\right)$$

$$= U_s(1 - \epsilon_s)$$

Where $\epsilon_s = \dfrac{I\phi . X_{al}}{U_s}$, abd since the usual values of $I\phi = 40\%$ and $X_{al} = 15\%$, ϵ_s is about 6%. Curves are available in the books of design which gives the value of ϵ_s

In design calculations, it is usual to assume that the value of flux in the stator core and in the stator tooth bottom is Φ_s i.e. Φ_{ac} or $\Phi_{tv} = \Phi_s$. The flux at the middle of tooth is $\Phi_{tm} = \Phi_s(1 - 1/3\,\epsilon_s)$ and the flux at the tooth top $\Phi_{tt} = \Phi_s(1 - \frac{2}{3}\epsilon_s)$. The value of flux in airgap is taken as $\Phi = \Phi_s(1 - \epsilon_s)$.

Though there are flux leakages in the rotor also but it is usual practice to neglect these leakages and the rotor magnetic circuit is made up with assumption that flux in each part of the rotor is equal to the air gap flux.

APPENDIX 2.

A-2.1. The squirrel cage as a polyphase winding. Considering an induction motor running with normal slip, here the rotor leakage reactance (SX_{rl}) can be neglected, in comparison with the rotor resistance and the rotor current is in phase with the rotor emf.

? ?

The above figure shows the rotating field B and the bars for a 2-pole squirrel cage motor. Since emf and current are in phase, the current distribution curve is also sinusoidal and the bar which lies in the pole axis carrie the maximum current. To the sinusoidal ampere-conductor curve there corresponds a sinusoidal mmf curve. From this it foll--ows that the squirrel cage automatically produces the same number of poles as that of the stator.

While moving w.r.t. the rotating field B, the current in each bar changes sinusoidally. Considering the currents in two adjacent bars there vectors will not be in phase, but displaced by an angle

Thus the squirrel cage represents a polyphase windigg with as many phases as there are slots per pole pair, or m_2

$$m_2 = \frac{S_2}{p/2} \qquad \text{------} \qquad \text{----------} \qquad A\text{-}2.1.$$

A-2.2 Ring Current- Figure A-2.2 shows the currents in bars and rings of a two pole machine at a certain instant.

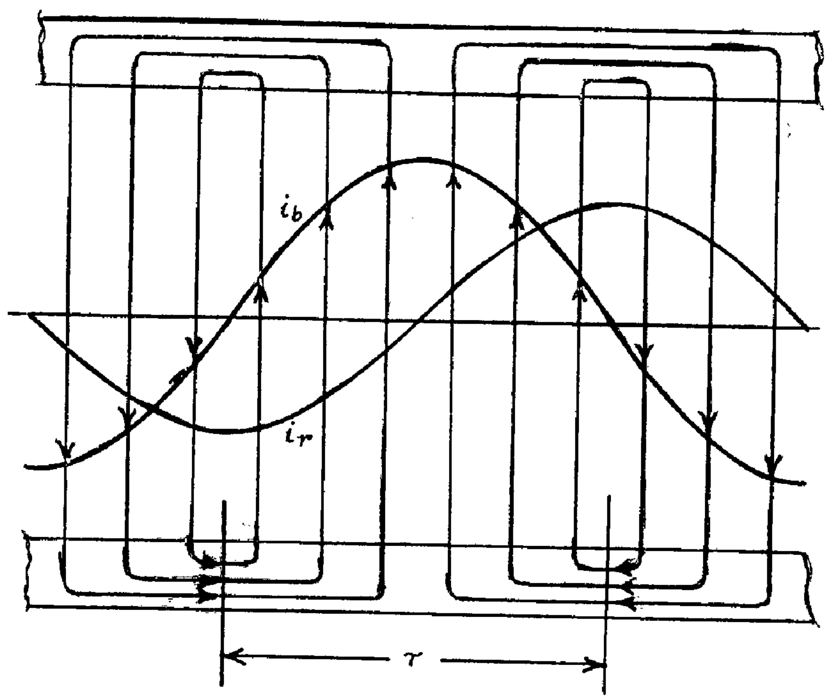


Fig. A-2.2

The maximum current in the ring apparently is equal to the average bar current $(\frac{2}{\pi})$ I_{bmax} multiplied by the number of bars in half pole pitch $S_2/2p$. Thus,

$$I_{rmax} = \frac{2}{\pi} I_{bmax} \frac{S_2}{2} = \frac{I_{bmax}}{\pi\, p/S_2}$$

and the effective value

$$I_r = \frac{I_b}{\pi\, p/S_2} \qquad \text{----------} A\text{-}2.2.$$

Copper losses in the cage are

$$P_{cu} = S_2 \left(I_b^{2} . r_b + 2 I_r^{2} r_r \right) \text{ ---------}$$

r_b and r_r are the resistanaces of a single bar and of a single ring segment respectively. The factor 2 takes into account the fact that there are two rings. Introducing the value of I_r from A-2.2.

$$P_{cu} = S_2 I_b^{2} \quad r_b + \frac{r_r}{2 \left\{\frac{\pi p}{2S_2}\right\}^2} \qquad = S_2 I_b^{2} . r_{be}$$

where $r_{be} = r_b + \dfrac{r_r}{2\left\{\dfrac{\pi p}{2S_2}\right\}^2}$

Similarly

$$X_{be} = X_b + \frac{X_r}{2.\left(\frac{\pi p}{2S_2}\right)^2}$$

The number of turns per phase (N_2) is equal to $\frac{1}{2}$. The distribution and pitch factors are equal to 1.

APPENDIX 3.

A3.1. STATOR M.M.F. AND FIELD HARMONICS

It has been shown in the books of Electrical Machine Theory that the ν th harmonic of a single stator phase is

$$f_\nu = F_\nu \sin wt \cdot \cos \frac{\nu x}{\tau_p} \cdot \pi \qquad \text{———3.1.}$$

The fundamental wave has a length $2\tau_p$ and the ν th harmonic has a length $2\tau_p/\nu$. Eqn. 2.1 refers to a definite phase which will be called as the zero phase. Considering the phase adjacent to the zero phase, the time angle between the two phases will be same for two harmonics, mainly $2\pi/m_1$. This is the time angle between the currents of two adjacent phases of an m_1 phase system. But the harmonics in consideration are space harmonics and in each phase all space harmonics are produced by the same current.

The space angle between two adjacent phases is equal to $2\pi/m_1$ for the fundamental wave and to for $\frac{\nu 2\pi}{m_1}$ for the ν th harmonic, due to the fact that the wave length of the th harmonic is $1/\nu$ th times that of fundamental. Thus the m.m.f. of the th harmonic of the neighbouring phase is

$$f_\nu = F_\nu \sin\left(wt - \frac{2\pi}{m_1}\right) \cdot \cos\left(\frac{\nu x_1}{\tau_p} \cdot \pi - \frac{\nu \cdot 2\pi}{m_1}\right) \qquad \text{———3.2.}$$

$$f_{\nu c} = F_\nu \sin\left(\omega t - c\,\frac{2\pi}{m_1}\right) \cdot \cos\left(\frac{\nu x_1}{\tau_p}\cdot\pi - c\cdot\nu\cdot\frac{2\pi}{m_1}\right) \qquad \text{------- 8.3}$$

Introducing the relation

$$\sin\alpha . \cos\beta = \tfrac{1}{2}\left[\sin(\alpha-\beta) \; .\sin(\alpha+\beta)\right]$$

$$f_{\nu c} = \tfrac{1}{2} F_\nu \left[\sin\left\{\left(\omega t - \frac{\nu x_1}{\tau_p}\cdot\pi\right) + (\nu-1).c\cdot\frac{2\pi}{m_1}\right\} \right.$$

$$\left. + \sin\left\{\left(\omega t + \frac{\nu x_1}{\tau_p}\cdot\pi\right) - (\nu+1)\cdot c\cdot\frac{2\pi}{m_1}\right\}\right] \qquad \text{------- 8.4}$$

In order to determine the resultant m.m.f. of the ν th harmonic of all m_1 phases, Equation 8.4 has to be summed up between $C = 0$ and $c = (m_1 - 1)$. The summation yields

$$f_{\nu t} = \tfrac{1}{2} F_\nu \left[\left\{ \sin\left(\omega t - \frac{\nu x_1}{\tau_p}\cdot\pi\right)\right\} \cdot \sum_{c=0}^{c=m-1} \cos(\nu-1)\cdot c\cdot\frac{2\pi}{m_1} \right.$$

$$+ \left\{\sin\left(\omega t + \frac{\nu x_1}{\tau_p}\cdot\pi\right)\right\}\cdot \sum_{c=0}^{c=m-1} \cos(\nu+1)\cdot c\cdot\frac{2\pi}{m_1}$$

$$+ \left\{\cos\left(\omega t - \frac{\nu x_1}{\tau_p}\cdot\pi\right)\right\}\cdot \sum_{c=0}^{c=m-1} \sin(\nu-1)\cdot c\cdot\frac{2\pi}{m_1}$$

$$- \left\{\cos\left(\omega t + \frac{\nu x_1}{\tau_p}\cdot\pi\right)\right\}\cdot \sum_{c=0}^{c=m-1} \sin(\nu+1)\cdot c\cdot\frac{2\pi}{m_1}$$

Denoting the four sums in turn by a, b, g & h

$$f_{\nu t} = \tfrac{1}{2} F_\nu \left[\sqrt{(a^2+b^2)} \cdot \sin\left(\omega t - \frac{\nu x_1}{\tau_p}\cdot\pi + \gamma_1\right) \right.$$

$$\left. + \sqrt{(g^2+h^2)} \cdot \sin\left(\omega t + \frac{\nu x_1}{\tau_p}\cdot\pi \cdot \gamma_2\right)\right]$$

The resultant m.m.f. of the ν th harmonic appears as two rotating m.m.f. waves, one travelling in the direction of the main wave the other travelling in the opposite direction.

But each harmonic produces only one travelling wave. Therefore, for all harmonics which travel in the direction of the main wave $\sqrt{g^2+h^2}$, i.e. g & h must be zero, while for those which travel in the opposite direction a & b must be zero.

The condition that g & h are zero while $\sqrt{a^2+b^2}$ is not zero is satisfied when

$(\nu+1) = K$ — K is a + ve integer excl. 0

and $(\nu-1)\cdot\frac{2\pi}{m_1} = K_1\cdot 2\pi$ — K_1 is a + ve integer incl. 0

Here $\sqrt{a^2+b^2} = m_1$

The condition that a & b are zero while $\sqrt{g^2+h^2}$ is not equal to zero is satisfied when

$(\nu+1) = K$ — K - a + ve integer excl zero

& $(\nu-1)\frac{2\pi}{m_1} = k_1\cdot 2\pi$ — K_1 - a + ve integer incl .0

In this case $\sqrt{g^2+h^2} = m_1$

Thus the equations

$(\nu+1) = K$ — K is + ve integer excl. 0

and $\frac{1}{m_1}(\nu\pm 1) = k_1$ — K_1 is + ve integer incl. 0 —— 2.10

are the cirteria for the existence of the ν th harmonic in the m.m.f. curve. The first criteria, $\nu = k - 1$, which is independent of the number of phases and therefore relates to a single phase yields, for integral slot windings, all digits from zero to infinity, indicating that a single phase is able to produce an infinite number of harmonics. The limitations with respects to the possible values of ν in a polyphase winding are given by the second criteria

$$\nu = K_1 m_1 \pm 1 \quad K_1 \text{ is a + ve integer incl. 0}$$

The same results can be obtained from

$$\nu = k_1 m_1 + 1 \qquad \text{------} \qquad \text{------} \qquad 2.12$$

when k_1 is a + ve or - ve integer incl.o. Positive ν will yield the harmonics travelling with the main wave and -ve ν the harmonics travelling in the opposite direction.

Out of the all harmonics given by 2.12 the harmonics of the order

$$\nu_{sl} = \pm \frac{2S_1}{p} + 1$$

are most disturbing, these are called slot harmonics and have the same distribution and pitch factor phases the fundamental.

The amplitude of the ν th m.m.f. harmonic is

$$F_{\nu} = 0,9 \cdot m_1 \cdot \frac{N_1}{p} \cdot Kd_{p\nu} \cdot I_1$$

$$B_\nu = 0{,}4\pi \cdot F_\nu \cdot \frac{1}{\delta \cdot k_c \cdot k_s} = 0{,}9\, m_1 \frac{N_1}{p} \cdot \frac{k_{dp\nu}}{\nu} \cdot \frac{1}{\delta \cdot k_c \cdot k_s} \quad \text{---} 2.$$

and the equation of the ν th field harmonic is

$$b_\nu = B_\nu \sin\left(\omega t - \nu \cdot \frac{x_1}{\tau_p} \cdot \pi\right) \quad \text{---} 2.$$

In order to determine the speed of the νth harmonic field with respect to the stator, consider a fiexed point b'_ν of the field wave (Fig. A-3.1). Since the magnitude of b'_ν does not change while the harmonic moves, $(\omega t - \frac{\nu . x_1}{t_p} \cdot \pi)$ must be constant at any time. The differentiation of $\omega t - \frac{\nu x_1}{\tau_p} \pi$ w.r.t. time will yield the speed of the harmonic

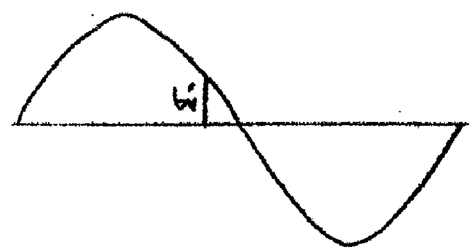


Fig. A - 3.1

$$\text{or.} \quad v_\nu = \frac{dx_1}{dt} = \frac{\tau_p}{\pi} \cdot \omega \cdot \frac{1}{\nu} = \frac{v_1}{\nu}$$

$$\text{where} \quad v_1 = \frac{\omega \cdot \tau_p}{\pi} = \frac{2\pi f}{\pi} \cdot \tau_p = 2\tau_p \cdot f$$

is the speed of the main wave w.r.t. the stator

A3-2. Rotor M.M.F. & Field Harmonics

In a way similar to that used for determining the order of the harmonics produced by a stator winding, it can be proved that a squirrel cage rotor produces due to the action of ν th stator harmonic, harmonics of the order

$$\mu = k_2 \frac{S}{p/2} + \nu$$

where μ is the order of the stator harmonic S_2 is number of rotor bars and K_2 is a + ve or - ve integer including zero.

The slot harmonics of the rotor are

$$\mu_{sl} = \pm \frac{2 S_2}{p} + 1$$

and the μth harmonic of the rotor field is

$$b_\mu = B_\mu . \sin \left(\omega t - \mu . \frac{x_2}{\tau_p} . \pi \right)$$

The distance X_2 is measured from same fixed point on the rotor. The distance X_1 is measured from some fixed point on the stator. Both distances are variable space coordinates. If at $t = 0$, $X_1 = X_2$, the difference between X_1 & X_2 at a certain instant t must be equal to the distance $v_r . t$ through which the rotor moves in this time.

If s is the slip w.r.t. the main wave then the velocity of the rotor is

$$v_r = (1-s) \, v_{(\nu=1)} = (1-s) \frac{\tau_p}{\pi} . \omega .$$

$$\text{Thus} \quad x_1 - x_2 = v_r . t = (1-s) \frac{\tau_p}{\pi} . \omega t$$

In order to determine the velocity of μ rotor harmonic w.r.t. the stator, the expression in the parenthesis has to be differentiated w.r.t. t.

$$\text{or } v_\mu = \left[1 + (\mu - \nu)(1 - s)\right]\frac{1}{\mu} \cdot \frac{\tau_p}{\omega} \cdot \pi$$

$$= \frac{1}{\mu}\left[1 + (\mu - \nu)(1 - s)\right] \cdot v$$

But $(\mu - \nu) = \frac{2 S_2}{p} \cdot K_2$ for squirrel cage rotor

$$\therefore \; v_\mu = \frac{1}{\mu}\left[1 + 2 \cdot \frac{K_2 S_2}{p}(1 - s)\right] v$$

A3-3. Parasitic Tangential Forces - Parasitic torques

The magnetic field in conjunction with current carrying conductors produces tangential forces and troques. Only the main wave produces the useful tangential force and torques while the harmonic will produce parasitic tangential forces and torques. These parasitic torques may cause considerable distortion of the speed torque curve produced by the main wave.

In induction motors the rotor is not connected to the line. The synchronous m.m.f. wave of the stator produces an m.m.f. wave in the rotor which is at standstill w.r.t. the stator wave at any speed of the rotor. This produces the useful torque of the motor and a troque of this kind is called an asynchronous torque.

a) Asynchronous torques .-

An asynchronous torque will occur when a stator harmonic produces a rotor harmonic of the same order, and which is at standstill with respect to the stator harmonic at all rotor speeds.

It can be seen from equation... that all those harmonics which correspond to $K_2 = 0$ have the same orders as the stator harmonics producing them. If these rotor harmonics are at standstill w.r.t. the stator harmonic producing them at any value of slip, then the torques produced by $K_2 = 0$ rotor harmonics are asynchronous torques. Considering the ν_ath stator harmonic and μ_ath stator harmonic produced by ν_ath such that $\nu_a = \mu_a$. The speed of ν_ath harmonic w.r.t. stator

$$v_{\nu a} = \frac{v_1}{\nu a}$$

The speed of μ_ath rotor harmonic w.r.t. stator

$$v_{\mu a} = \frac{1}{\mu a}\left[1 + (\mu a - \nu a)(1 - s)\right] v_1$$

In order that

$v_{\nu a} = v_{\mu a}$ the condition to be satisfied is

$$\frac{\mu a - \nu a}{p/2}(1 - s) = 0$$

and since $\mu a = \nu a$ this equation is satisfied for all values of s.

b) Synchronous Torques.-

In order that a synchronous torque may occur, there must be

$$\mu a = \pm \nu b \quad \text{and} \quad v_{\mu a} = v_{\nu b}$$

From equation 4

$$v_{\mu a} = \frac{1}{\mu a}\left[1 + (\mu a - \nu a)(1-s)\right] v$$

$$v_{\nu b} = \frac{v}{\nu b}$$

when $\mu a = +\nu b$ the condition $v_{\nu b} = v_{\mu a}$ is satisfied when

$$1 = 1 + (\mu a - \nu a)(1-s)$$

$$\text{or } (\mu a - \nu a)(1-s) = 0$$

But $\mu a = \nu a$ yields an asynchronous torque. Hence a synchronous torque will occur at $\mu a = \nu b$ when $s = 1$. Therefore if a stator harmonic produces a $\mu a \neq \nu a$ and there exists another stator harmonic $\nu_b = +\mu a$ the harmonic μa & νb will produce a synchronous torque at standstill

C) When $\mu = -\nu b$ the condition $v_{\mu a} = v_{\nu b}$ is satisfied when $-1 = 1 + (\mu a - \nu a)(1 - s)$

Since $\mu a \neq \nu a$ a synchronous torque will occur at $\mu a = -\nu b$ only when

Introducing the speed n

$$n = - \frac{120 f_1}{K_{2a}\, Q_2}$$

If the harmonic μ_a corresponds to a negative K_{2a} the synchronous cusp will occur at positive $n (S < 1)$ if μ_a corresponds to positive K_{2a} the synchronous cusp will occur at a negative $n (s > 1)$

2 DESIGN CALCULATIONS

Design of a 2900 kW, 5000 volts, 3000 r.p.m., 50 c/s squirrel cage Induction Motor.

The following quantities are sepcified:

Number of pole, p ---------------- 2

Rating, Nn ---------------- 2900 kW

Rating per pole ---------------- $\frac{2900}{2} = 1450$ kW

Synchronous speed ---------------- 3000 r.p.m.

Rated Voltage, Un ---------------- 5000 volts

Rated phase voltage U_p ---------- $\frac{5000}{\sqrt{3}} = 2890$ V.

2.1. Design of Major Dimensions

From curves 1.1.3 and 1.1.4

Approximate power factor = 0,915

and efficiency = 0,97

so that rated current $= \frac{N_n}{\sqrt{3}\ U_n . \cos\varphi_n . \eta}$

$= \frac{s\ 2900}{\sqrt{3} . 500 . 0,915 . 0,97}$

= 378 Amperes.

Average flux density B is taken as 6000 G at the first instance and the ampere conductors per unit periphery, A, as 600 amp. condrs./cm.

From equation 1.1.4.

$$C = 4,55.\ K_{d_{pl}} . \cos\gamma\ n.\eta\ \frac{B}{5000} . \frac{A}{500}$$

$$= 4,55.\ 0,955.\ 0,915.\ 0,97.\ \frac{6000}{5000} . \frac{600}{500}$$

$$= 5,5$$

Hence, C, the out coefficient is taken as 5,5

$C = 5,5$

From equation 1.1.5.

$$D^2 l = \frac{Nn}{C.\ n_s}$$

$$= \frac{2900}{5,5.\ 3000} = 0,176$$

(where D and l are in meters)

From curve 1 the value of D is 650 m.m.

If D is taken as 650 m.m. then the peripheral velocity, v, is given by

$$v = \frac{\pi.\ D.\ n_s.}{60} = \frac{\pi.0,65.3000}{60} = 102 \text{ m/sec}$$

This is safe, since from mechanical point of view peripheral speeds upto 140 m/sec. are safe.

Hence the stator bore diameter D is taken as 650 m.m

D = 650 m.m

With D = 0,65 meters

$$l = \frac{0,176}{} = 0,416 \text{ m.}$$

Ventilating ducts: 7, radial ventilating duct each 1 cm. wide, are provided after nearly every 50 m.m of the length of the stator core stampings.

Magnetic Circuit: 0,5 m.m. thick Lohys stampings are used and the magnetic circuit is made up as follows:

1 packet of stampings 60 m.m. wide	---60 m.m.
6 packets of stampings, each 50mm wide	---300 m.m.
1 packet of stampings 60 mm. wide	---60 m.m.
8 packets, totalling	----------------420 m.m.
7 ducts each 10 m.m. wide	------------ 70 m.m.
Gross core length, L	---------490 m.m.

Also taking a staking factor ki = 0,91

net iron length l_i = 0,91. 420 = 382 m.m.

L = 490, mm.

l =420 mm.

l_i = 382 mm.

Air gap : From article 1.15 the air gap of a 2 pole induction motor is given by

$$\delta = \frac{D}{1200} \cdot \left[1 + 9/p \right] \text{ m.m.}$$

$$= \frac{650}{1200} \left[1 + 9/2 \right]$$

For smoother starting the air gap is taken as 3,5 mm.

δ = 3,5 mm.

2.2. DESIGN OF THE STATOR

Number of stator slots: Assuming a slot pitch τ_{sg_1} = 30 mm.

Number of stator stolts $S_1 = \frac{\pi D}{\tau_{sg_1}} = \frac{\pi . 650}{30} = 68$

∴ No. of stator slots per pole per phase

$$q_1 = \frac{68}{6} = 11,3$$

Integral slot windings are used and so q_1 is taken as 11, so that total number of stator solts S_1 = 11.6 = 66; and the slot pitch $\tau_{sg_1} = \frac{\pi . 650}{66} = 30,9$

q_1 = 11

S_1 = 66

τ_{sg_1} = 30,9 mm

Type of winding; Double layer, lap wound, stator connected, chorded winding is to be used. From curve 1,2,1 , the ratio of coil pitch W to full pitch

τ_p, that gives minimum weight of copper, is 0,8. Hence a coil span W of 27 slots is used.

Hence,

distribution factor $K_{d_1} = 0{,}955$

pitch factor $K_{p_1} = \sin \frac{W}{\tau_p} \cdot \frac{\pi}{2} = \sin \frac{27}{33} \cdot \frac{\pi}{2}$

$= 0{,}965$

$\therefore$ Winding factor $Kd_{p_1} = Kd_1 \cdot K_{p_1}$

$= 0{,}955 \cdot 0{,}965 = 0{,}921$

A schematic diagram of the winding is shown in fig. 7

<u>Number of stator conductors:</u> Roughly the normal line voltage Un, applied to the stator winding, is given by [equation 1.2.4.]

$$Un = 3{,}2 \cdot n_s \cdot z_1 \cdot \bar{B} \cdot D \cdot l \cdot K_{p_1} \cdot 10^{-10} \text{ volts}$$

$$\text{or } z_1 = \frac{5000 \cdot 10^{10}}{3{,}2 \cdot 3000 \cdot 6000 \cdot 650 \cdot 42 \cdot 0{,}965} = 330$$

$$\text{No. of conductor per slot } N_c = \frac{330}{66} = 5$$

Let $Nc = 6$ so that $z_1 = 6 \cdot 66 = 396$

$$\text{and } \bar{B} = \frac{6000 \cdot 330}{396} = 4550 \text{ G.}$$

396

Ampere conductors /cm. $= \frac{I.\ N_e}{\tau_{sg_1}} = \frac{378.6}{3,09} =$

735 Amp. $\frac{\text{Condt}}{\text{Cm.}}$

$Z_1 = 396$

$N_c = 6$

$\bar{B} = 4550$ G

A = 735 Amp. Cond

Total flux per pole

$$\Phi_s = \bar{B}.\ \tau_p.\ \ell$$

$$= 4550.\ \frac{\pi.65}{2} \cdot 42 \text{ lines}$$

$$= 19,5.\ 10^6 \text{ lines.}$$

$\Phi_s = 19,5.10^6$ line

Cross-section of stator conductors : A current density of 4,5 Amp./mm^2 is taken

∴ Cross-section of each conductor $F_1 = \frac{378}{4,0}$

$= 94,5$ Sq. mm.

Since the cross-section of the conductor is too large, two parallel circuits are used so that the cross-section of each new conductor is halved.

Hence the cross-section of conductor $= \frac{96}{2} = 48$

Slot and tooth diamensions - Taking a flux density of 17000 G at the narrowest section of the tooth its minimum width is given by

$$b_{t_b} = \frac{B_1.(1 - 2/3\mathcal{E}_s).\ \tau_{sg_1}}{17000}$$

($\mathcal{E}_s$ is taken as 0,06)

Semiclosed parallel sided slots are used. The height of the lip is taken as 10 mm. so that the leakage reactance of the stator may not be very low; a tapering wedge of backelite and of depth 5 mm. is used to keep the condurctors in position. Thus the tooth will have a minimum width at a diameter of $650 + 2(10 + 5) = 680$ mm. The slot pitch at this diameter is $\frac{\pi.680}{66} = 32,4$ mm.

Tooth width at this point $b_{t_b} = \frac{7150.(1-2/3.0,06)}{17000}$

$$\frac{.32,4}{} = 12,4 \text{ mm}$$

$\therefore$ Slot width b_s ---= $\tau_{sg} - b_t = 32,4 - 12,4 = 20$mm.

The slot insulation will be 1 mm. thick mica cell. Allowing 3mm for clearance and slack, the net width available for the conductors is 20 - 3 - 2.1 = 15mm.

The conductors will be placed as shown in fig. i.e. there will be three conductors in the width The conductor insulation will be one serving of mica tape 0,5 mm. thick.

Space required for conductor insulation = 2.3.0,5 = 3 mm. space available for conductor copper = 15 - 3 = 12 mm.

Hence 4,0 mm. thick conductors are to be used and the slot width is made as follows:

Micanite cell 2 x 1	2 mm.
Conductor insulation 3x2x0,5	3 mm.
Conductor copper 3x4,0	12 mm.
Clearance and slack 3 mm	3 mm.
Total Width.	20 mm.

$b_{cu} = 3 \times 4$ mm.

$b_s = 20$ mm.

Depth of conductor $h_{cu} = \frac{F_1'}{b_{cu}} = \frac{48}{4} = 12$ mm.

In order to keep down the eddy current losses 6 strands each of 2 mm. thick are used. The slot depth is made up - as follows

Lip------------------------10mm.
Wedge -------------------- 5mm.
Micanite cell, 3 x 1----- 3mm.
Cordr. insulation4x2x0,5-- 4mm.
Strand insul, 6 x 0,2----1,2mm.
Separator,1mm. mica------- 1mm.
Conductor depth, 4x12----48mm.
Clearance and slack-----3,8mm.
Slot depth 76,0 mm.

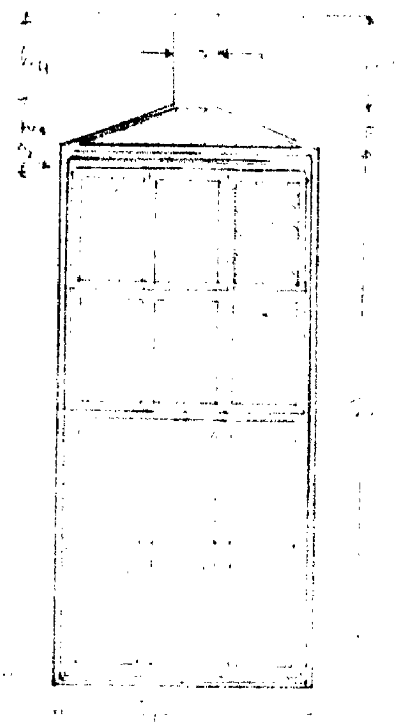


Fig 2.1

Lach finished conductor is of dimensions (4+1)X(12+0,2+1) i.e. 5X13,2, thus the slot opening b_o is taken as 5,5mm so that the conductors may be sliped in easily

$$h_s = 76 \text{ mm.}$$

$$b_o = 5,5 \text{ mm.}$$

Conductor area $F_1' = 12 \times 4 = 48$ Sq. mm.

Current density $i = \frac{378}{2.48} = 3,94$ amp./sq.mm.

Watts lost per sq.dm. of slot $= \frac{A. i. \tau_{sg}}{56(b_s + 2h_s)}$

$$= \frac{735 \cdot 3,94 \cdot 30,9}{56.(15,2 + 2)} = 9,3 \text{ w/dm}^2$$

This is within the safe limits.

62,404

Length of conductor:

The length of each conductor is given by

$$L_Z = L + 2le_2 + 2S + \frac{\pi . hs}{4} + 50 \text{ mm.}$$

where

$$S = \frac{W.\tau_s}{2} . \frac{\tau_s}{\sqrt{\tau_s^2 - a^2}} = \frac{2.7.3,09.3,09}{2.\sqrt{(3,09^2 - 2^2)}}$$

$$= 54,6$$

$$\therefore L_Z = 49 + 2.5 + 2.54,6 + \frac{\pi . 2}{4} + 5$$

$$= 174,8 \text{ cm. say } 175 \text{ cm.}$$

$$L_Z = 175 \text{ cm.}$$

Total length of Copper($4X12mm^2$)

$$= Z_1' . L_Z = 2.396 \times 175 = 1385 \text{ meters}$$

Resistance per conductor

$$R_Z = \frac{L_Z}{K.F} = \frac{1,75}{56.96} \text{ ohms.}$$

Resistance per phase

$$r_1 = Z_{1p} . R_Z = \frac{1,75 . 132}{56.96} = 0,043$$

Stator I^2R loss $= 3.I^2.r_1 = 3.378^2.0,043 = 18,4$Kw

Stator core

Taking a flux density of 15000 G in the stator core, radial depth he_1 behind the teeth is given by

$$he_1 = \frac{\Phi s}{2.\ li\ .15000} = \frac{19,5\ .\ 10^6}{2.38,2.15000} = 17\text{cm}.$$

External diameter of stator core

$Do = D + 2ht + 2\ hc_1 = 65 + 2.7,6 + 2.17 = 114,2$ cm.

say 114 cm.

Mean diameter of core = 65+15,2 + 17 = 97 cm.

Mean length of the magnetic path lc_1 in the stator core is given by

$$lc_1 = \frac{\pi\ .\ 97}{2} = 154 \text{ cm.}$$

stator losses (iron)

Weight of stator teeth

$= S_1.btmean,ht.li.7,5.10^{-3}$ Kg.

$= 66.2,18.7,6.38,2.7,5.10^{-3} = 313$ Kg.

Iron losses for stator tooth are 26W/Kg for a tooth density of 17000 G.

.·. Iron loss in tooth = 5 313.26.10^{-3} = 8,15 Kw.

Wt. of. stator core = $\frac{\pi}{4}(114^2 - 80,2^2).38,2.7,5.10^{-3}$ Kg

6500

2.3. ROTOR DESIGN

Number of Rotor Bars -

As has been explained in article 1.3.1. let $q_8 = q_1 + 2/3 = 11 + 2/3 = 35/3$ so that the rotor slots $S_1 = 35/3.6 = 70$. Since the strongest saddle appears when the number of stator slots is different from the number of rotor slots by $\pm$ p, hence, with S = 70, no strong saddles will appear in the torque slip curve.

The stator mmf produces harmonics of the order given by $\nu = K_1 m_1 + 1$ and these are given in the following tables with their winding factors

ν =	1	-5	7	-11	13	-1
Kd	0,955	0,193	0,139	0,091	0,079	0,063
K_p	0,959	0,141	0,414	1	0,841	0,141
Kd_p	0,915	0,027	0,057	0,091	0,066	0,009
ν =	-65	61	-59	55	-53	49

ν =	19	-23	25	-29	31	-35
Kd	0,058	0,051	0,0049	0,046	0,045	0,045
K_p	0,656	0,959	0,500	0,422	0,866	0,866
Kd_p	0,038	0,048	0,024	0,019	0,039	0,039
ν	-47	43	-41	37	-35	-

From the above tables it is clear that nearly all the harmonics are zero except the 65th and 67th The rotor harmonics are $K_2 m_2 + \nu$ i.e. with $K_2=0$ all those harmonic that are present in the stator and with $K_2 = \pm 1$ - 69th and 71th harmonics. Thus the 65th and 67th harmonics will produce asynchronous torques, but these torque will be 1/65th or 1/67th of the torque due to the fundamental. Hence they are insignificant (still the effect of these harmonics can be reduced by skewing, which will also reduce noise).

Thus the rotor with 70th slots is almost without any defect. Therefore the slot pitch

$$\tau_{sg_2} = \frac{\pi . 643}{70} = 29 \text{ mm.}$$

Bar and ring currents -

The bar voltage at standstill is

$$E_{2bar} = \frac{\pi}{\sqrt{3}} \cdot \frac{U_s(1-\epsilon_s)}{z_1 . K_{p1}} = \frac{\pi}{\sqrt{3}} \cdot \frac{5000.0,94}{396.0,959} = 22,5V.$$

∴ Bar current I_b at standstill is

$$I_b = \frac{N_n(\text{Watts})}{S_2 . \eta . E_2} = \frac{2900. 1000}{70.0,93.22,5} = 1950 \text{ Amp.}$$

and

$$I_r = \frac{S_2}{\pi p} . I_b = \frac{70}{\pi . 2} . 1950 = 21700 \text{ Amp.}$$

The following three designs are carried out

(A) Ordinary cage rotor

(B) Deep bar cage rotor

(C) Double cage rotor

<u>Design A</u>: A current density of about 6A/Sq.mm. is taken in the rotor bars so that the bar cross-section $F_b = I_b/i_b = 1950/6 = 325$ Sq.mm. A rectangular conductor of copper of 15 X 22 = 330 sq. mm. is used. The slot dimensions are 16 X 23 with a lip 1mm. wide 1 mm. deep and a trapezoidal wedge of 4mm. depth. The slot shape is as shown in figure 2.2 .

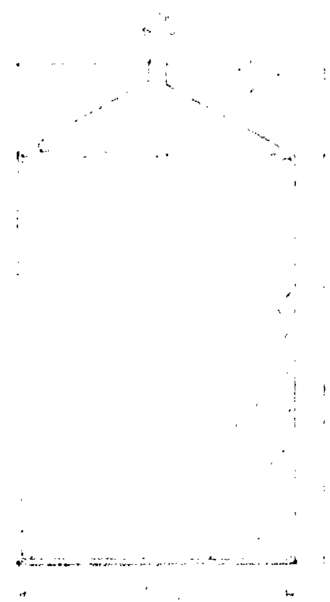


Fig. 2.2

Taking a current density of $5A/mm^2$ the ring cross-section $F_r = I_r/i_r = \frac{21700}{5} = 4340\ mm^2$ say 4400 sq. mm. A brass ring with = 0,06 of section 55 X 80 sq. mm. is used.

<u>Rotor resistance</u>: The length of each rotor bar is L + 20 mm. (taking 10 mm as the overhang on eac side) i.e. 50 + 2,0 = 52 cm.

$$r_b = \frac{0,52}{56.330} = 2,81.10^{-5} \quad \text{ohms.}$$

Length of each segment of the ring

$$= \frac{\pi\ (643 - 55\ )}{70} = 26,4 \text{ mm.}$$

resistance of each ring segment

$$r_r = \frac{0,6\ .\ 2,64}{4400} = 3,6.10^{-6}$$

∴ equivalent bar resistance is

$$r_{be} = r_b + \frac{r_r}{2.\left(\frac{\pi . p}{2\ S_2}\right)^2} = \left[2,81 + \frac{0,36}{2.\left(\frac{\pi . 2}{2.\ 70}\right)^2}\right].10^{-5}$$

$$= 12.10^{-5} \quad \text{ohms.}$$

The transformation ratio for the impedance is

$$\text{or} = \frac{2.p.(N.K_{dp11})^2 .\ m_1}{Z_2} = \frac{2.\ 2(66.0,92)^2 .3}{70}$$

= 635 <u>per phase</u>

∴ rotor resistance/ referred to stator is

$$r'_{2s} = 635.\ 12.10^{-5} = 0,076\ \Omega$$

Rotor tooth -

Slot pitch at 1/3rd of the slot depth

$$\tau_{s2(1/3)} = \frac{\pi . 643 - 2.1/3.\ 28}{70} = 28 \text{ mm.}$$

$\therefore$ Tooth width at 1/3rd slot depth = 28 - 16
= 12 mm.

Hence the flux density at 1/3rd of the slot depth

$$B_{t2(1/3)} = B_1 (1 - \epsilon_s).\ \frac{\tau_{s2}}{b_{t2(1/3)}} = 7150.0,94.\frac{29}{12}$$

$$= 16250 \text{ G.}$$

Rotor Core

The shaft diameter is roughly given by

$$d = 0,84.25,4 \sqrt[3]{\frac{\text{output (watts)}}{\text{rpm}}} \text{ mm.}$$

Hence approximately the shaft diameter

$$d = 0,84.25,4.\sqrt[3]{\frac{2900\ .\ 1000}{3000}}$$

$$= 210 \text{ mm}$$

Let the shaft diameter be taken as 200 mm.

The slot height is 28 mm. so that the depth of the core

$$hc_2 = 1/2\ (643 - 200 - 2 \times 28) = 193,5 \text{ mm.}$$

Say 190 mm. $hc_2 = 190$ mm

Also the flux density in the rotor core

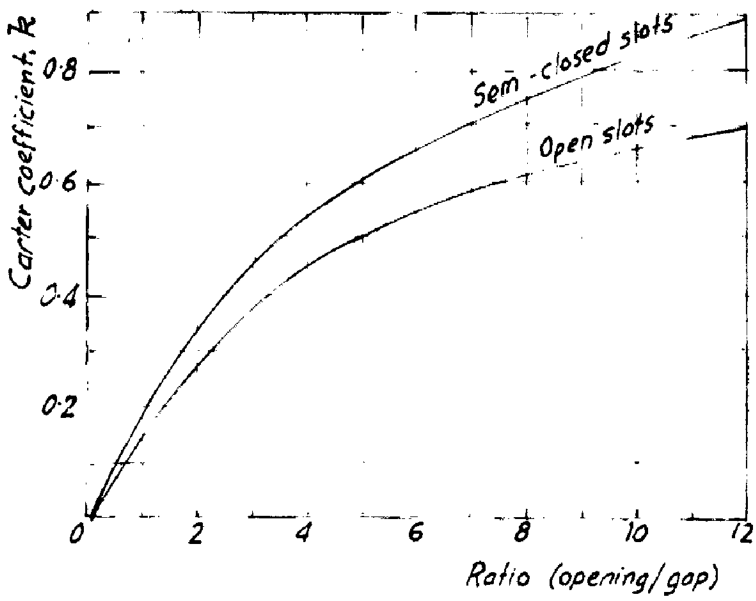

Carter coefficient, k
0·8
0·6
0·4
0·2
0
2
4
6
8
10
12
Semi-closed slots
Open slots
Ratio (opening/gap)

Fig. 2.3

$$Bc_2 = \frac{19,\ 5.(1-\ 0,06).\ 10^6}{2.\ 19.\ 38,\ 2} = 12600G.$$

$$Bc_2 = 12600G$$

Also the mean length of the magnetic path in the rotor core

$$\ell c_2 = \frac{\pi\ (643\ -\ 2.28\ -\ 190\ )}{2} = 625\ mm.$$

No load current

from curve $k_{o_1} = 0,28$ and $k_{o_2} = 0$

so that $$Kg_1 = \frac{30,9}{30,9\ -\ 0,28.5,5} = 1,09$$

and $Kg_2 = 1$

Equivalent gap length

$$\delta' = Kg_1 \cdot Kg_2 \cdot \delta = 1,09.1.\ 3,5 = 3,82$$

The calculation for the magnetizing current are based on the value

Magnetisation - The calculations for the magnetizin current are based on the value B_{30}, i.e. the flux density at 30° from the pole center (which is common to the actual flattend distribution and to the funda mental component ripon which the emf depends.

$$B_{30} = B_1 \cdot \cos 30 = B_1 \frac{\sqrt{3}}{2} = 0,866\ B_1$$

	B	B	at	l	AT = at.
Stator Core	15000	-	10	154	1540
Stator tooths (1/3)	15900	13800	5,4	2.7,6	82
Gap	7150	6190	4950	2.0, 382	3800
Rotor tooths (1/3)	16250	14100	6,1	2.2,8	34
Rotor Core	12600	-	3,5	62,5	219

Total AT_{30} = 5675 per pole pair

$$I\phi = \frac{\Sigma AT}{3.0{,}9 \cdot Nc. \; q1.Kd_{p1}}$$

$$= \frac{5675}{3.0{,}9.\ 6.\ 11.\ 0{,}921} = 34{,}6 \text{ Am}$$

$I\phi$ = 34,6 Am

$$Xm = \frac{Un}{\sqrt{3}.\ I\phi} = \frac{5000}{\sqrt{3}.\ 34{,}6} = 83{,}5$$

Losses. The no load losses are

Iron loss = 30,15 Kw

F and W loss 1% output = 29 Kw.

∴ No load losses = 59,15 Kw.

Active component of n.l. current $= \dfrac{59{,}15 \cdot 10^3}{\sqrt{3} \cdot 5000}$

= 6,85 Amp.

∴ No load current $I_o = \sqrt{34{,}6^2 + 6{,}85^2}$

No load power factor $\cos \varphi_0 = \frac{6,85}{35,3} = 0,194$

Magnetising reactance $X_m = \frac{5000}{\sqrt{3}.34,6} = 83$ ohms.

resistance equivalent to iron losses $r_m = \frac{5000}{\sqrt{3} . 6,85} = 420$ ohms

Short Circuit Current

Reactances -

Slot permeance.

$$\lambda_{sb} = \frac{24}{3.20} + \frac{40}{20} + \frac{10}{25,5} + \frac{10}{5,5} = 4,646$$

$$\lambda_{st} = \frac{24}{60} + \frac{4}{20} + \frac{10}{25,5} + \frac{10}{5,5} = 1,82$$

$$\lambda_{bt} = \frac{24}{40} + \frac{4}{20} + \frac{10}{25,5} + \frac{10}{5,5} = 3,012$$

$$\lambda_s = 1/4 \ (\lambda_{sb} + \lambda_{st} + 2K_r . \lambda_{bt})$$

$$K_r = \frac{1}{2q} \frac{\Sigma \cos \alpha}{2q} = \frac{1}{11} \left[2 + 9.0,5 \right] = 0,59$$

$$\therefore \lambda_s = 1/4 \ (4,646 + 1,82 + 3,012.2. \ 0,59)$$

$$= 2,6 \text{ /cm. length}$$

$$\lambda_s . l_s = 2,6.49 = 127,5$$

Zigzag permeance

$$\lambda_z = \frac{\varepsilon . \tau_p}{}$$

$$\epsilon = \frac{b_2 - a_1}{0,96\ \tau_{sg_2}} + \frac{b_1 - a_2}{\tau_{sg_1}} = \frac{28-5,5}{6,96.29} + \frac{25,4-1}{30,9} = 1,6$$

$$\therefore \lambda_{\angle} = \frac{1,6\ .\ 102\ .\ 6}{48\ .11.\ 70.\ 0,35} = 0,075/\text{cm length}$$

$$l_s.\ \lambda_{\angle} = 3,68$$

$$\therefore l_s\ (\lambda_{\angle} + \lambda_s) = 3,68 + 127,5 = 131,18$$

$$L_{(s + \angle)} = 1,6\ \pi\ \frac{N2}{pq}\ (\lambda(\angle + s).\ l_s)10^{-8}$$

$$= \frac{1,6\pi.\ 66.\ 66}{11.2}\ .\ 131,18.10^{-8}$$

$$= 1,3.10^{-3}\ \text{h.}$$

$$X_{s+\angle} = 100.\pi.\ 1,3.10^{-3} = 0,409\ \ \text{ohm.}$$

Overhang reactance

$$L_{ep} = 1,6\ \pi\ \frac{N2}{p}\ \Big|\ 1,2\ K_{d_1}{}^2.\ K_{p_1}{}^2.(\ l_{e_2} + \frac{l_{e_1}}{2}).1$$

$$l_{e_2} = 5\ \text{e,m.}$$

$$l_{e_1} = \frac{(\ \ .\tau_{sg})}{2}.\ \frac{a}{\sqrt{\tau_{sg}^2 - a^2}} = \frac{9.\ 30,9.\ 20}{2.\sqrt{(30,9^2 - 20^2)}}$$

$$= 118\ \text{mm} = 11,8\ \text{cm.}$$

$$L_{ep} = 1,6\pi\ \frac{66.66}{2}.\ \Big[1,2\ .0,921^2.(5+5,9)\Big].10^{-8}$$

$$= 12.2.10^{-y}\ \text{h}$$

$$X_{ep} = 12,2\ .10^{-4}.100.\pi = 0,382\ \text{ohm}$$

$$X_1 = 0,382 + 0y09 = 0,791$$

Rotor -

Slot permeance

$$\lambda_s = \frac{23}{48} + \frac{4}{17} + \frac{1}{1} = 1,72$$

$$L_b = 0,4\pi\ \ell_s.\ \lambda_s.\ 10^{-8} = 0,4\pi.49.1,72.10^{-8}$$
$$= 1,06.10^{-6}\ \text{h.}$$

$$L_r = 0,4\pi \frac{N2}{m_1 p} . \frac{2}{3} \left[(\ell_b - \ell_s) + K. \quad ' \right] . 10^{-8}\ \text{h.}$$

where $= \frac{643-80}{2} \pi = 88,5$ and $K = 0,18$

$$\therefore L_r = 0,4\pi . \frac{70}{6} . \frac{2}{3} \left[2 + 0,18 . 88,5 \right] . 10^{-8}\ \text{h}$$

$$= 1,55.10^{-6}$$

$$L_{be} = (1,06 + 1,55).\ 10^{-6} = 2,61\ .10^{-6}\ \text{h}$$

$$L_2' = 635.\ 2,61\ .10^{-6} = 1,66.10^{-3}\ \text{h}$$

$$X_2' = 100.\pi.\ 1,66.\ 10^{-3} = 0,52\ \text{ohm.}$$

$\therefore$ Reactance of the motor referred to primary

$$X = 0,52 + 0,791 = 1,311\ \text{ohm.}$$

$$R = 0,119$$

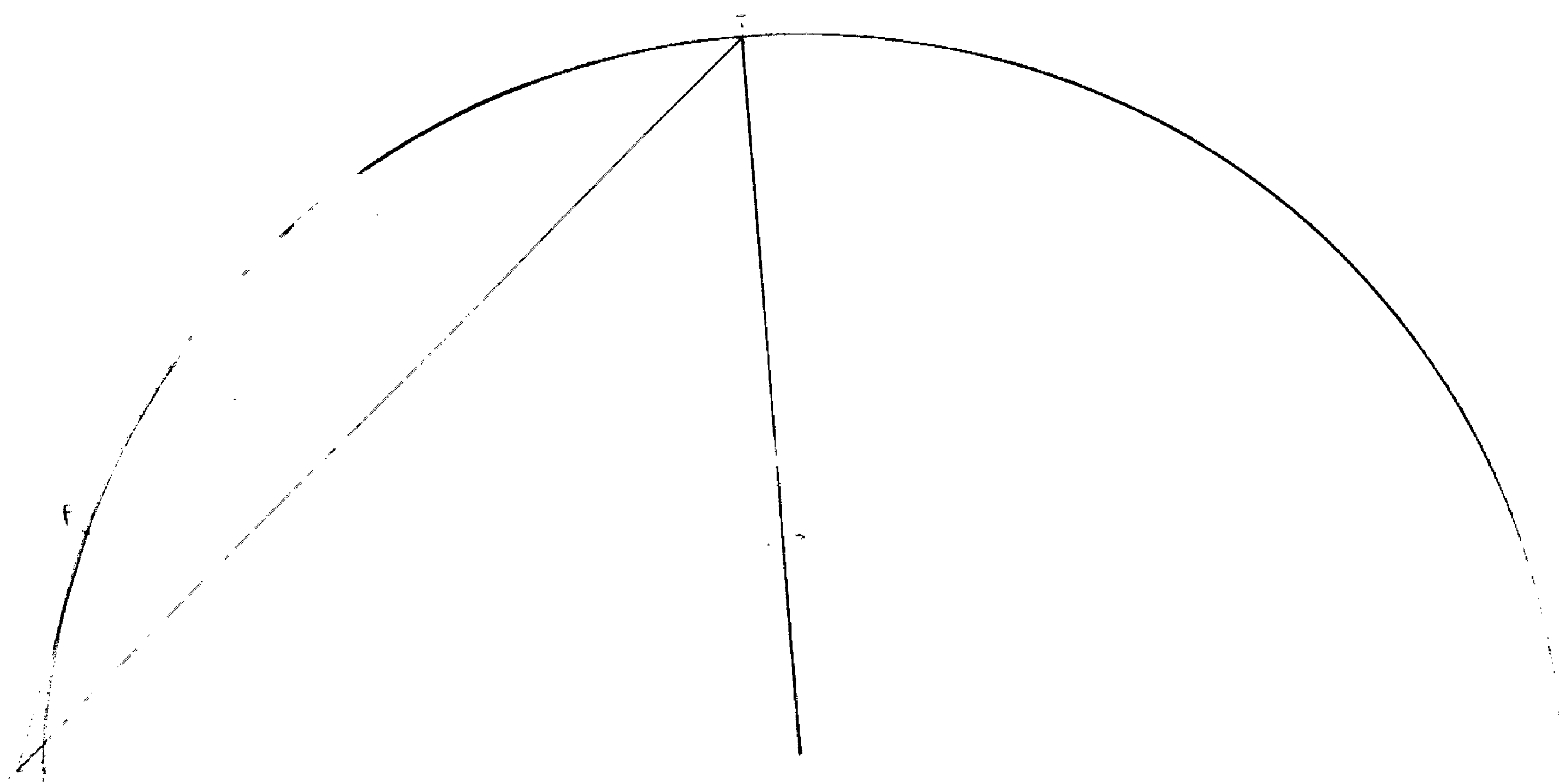
Equivalent Circuit

The following data is available

$X_1 = 0,791$; $X_2' = 0,52$

$r_1 = 00043$; $r_2' = 0,076$

Fig. 2,4



$r_m = 420$

$x_m = 83$

The short circuit current $I_{s.c.} = \frac{U_n}{\sqrt{3}.\ X}$

$= \frac{5000}{\sqrt{3}.1,311} = 2200$ Am

and the s.c. power factor $\cos \varphi_n = \frac{R}{Z} = \frac{0,119}{1,315} = 0,095$

Circle diagram

From the no load and the s.c. data the circl diagram as shown in fig. 2.4 is drawn.

From the circle diagram -

F. L. Current	......	359 amps.
p.f.	......	0,97
η	......	97 %
slip	......	0,945 %

TORQUE-SLIP CURVE OF A PLAIN CAGE MOTOR

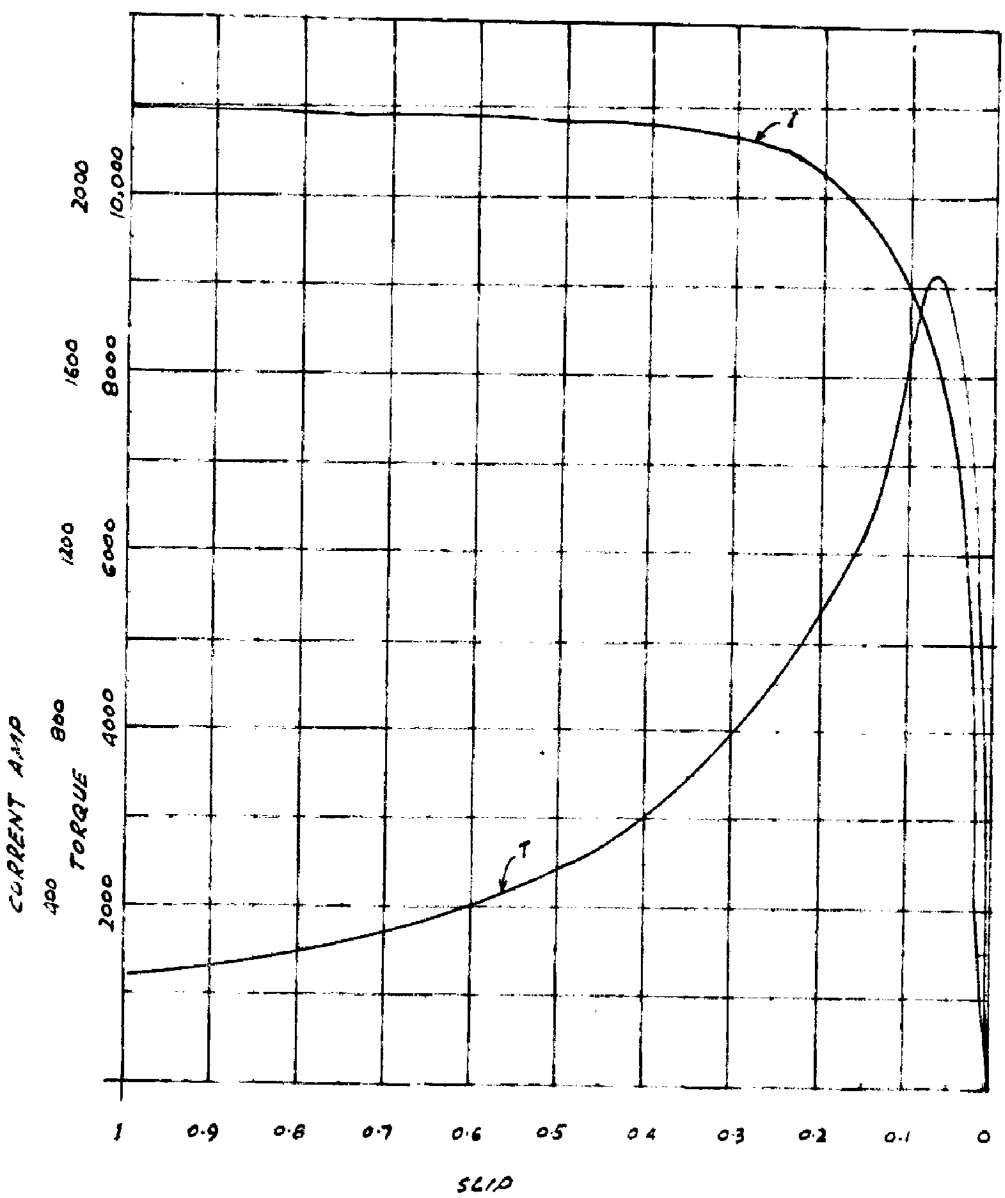
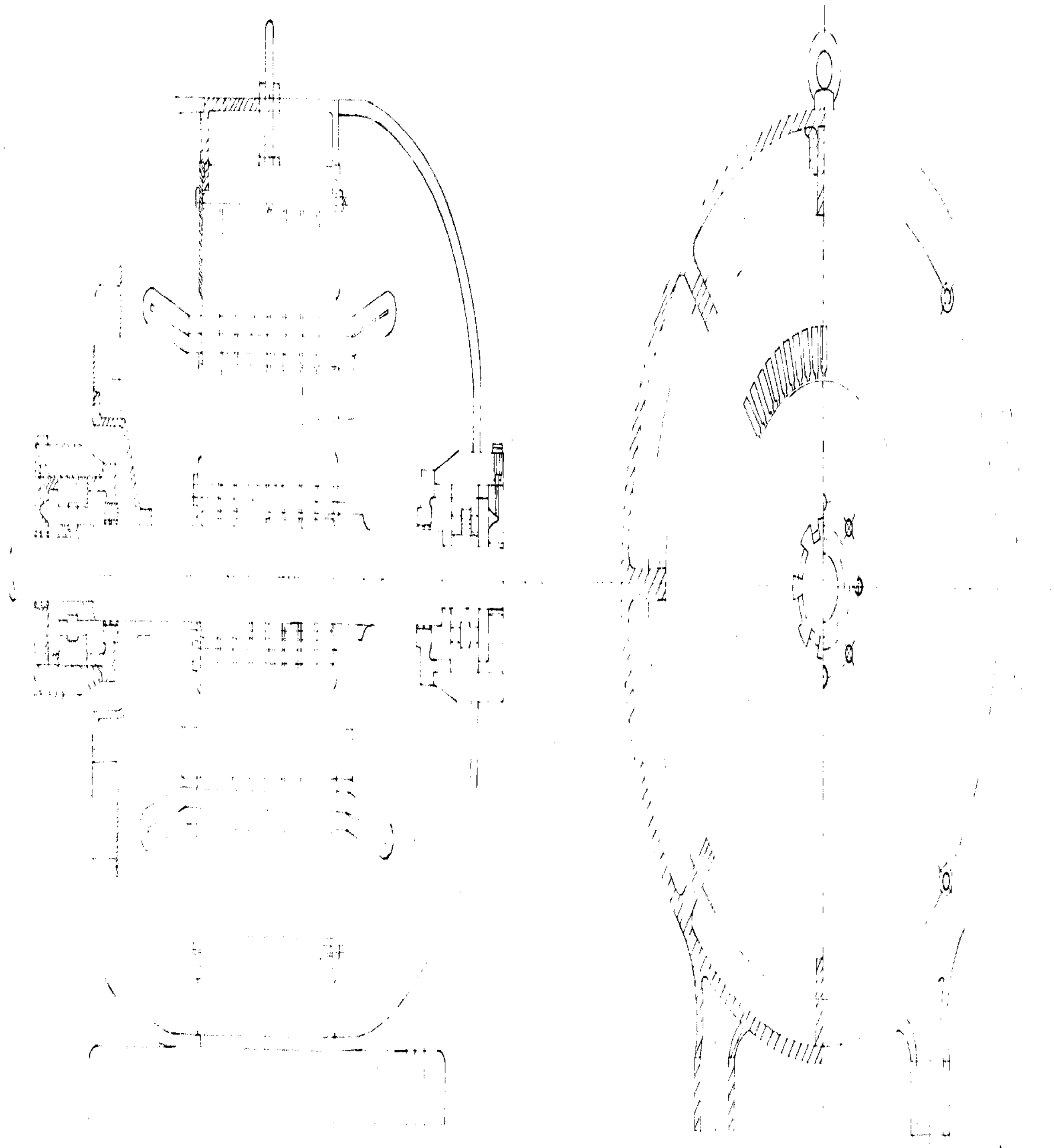


Fig. 2.5



2900 K.W. INDUCTION MOTOR WITH CAGE ARMATORE

Design B - The deep bar rotor

The conductor cross-section is taken as 5 X 65 sq.mm. so that the slot size is 5,5 X 65,5 sq.mm. with a lip 1 mm. wide and 1 mm. deep and a wedge space of 3 mm. as shown in fig. 2.7 . The ring is kept of the same dimensions as in design A.

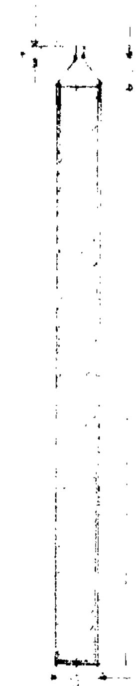


Fig. 2.7

Rotor tooth -

The pitch at the bottom of rotor tooth

$$\tau_{s\,2_b} = \frac{\pi}{70}(643-69,5.\,2)=22,6\text{mm}$$

Therefore tooth width at its bottom 22,6-5,5 = 17,1

$$\therefore\ B_{t2_b} = \frac{7150\ .\ 29(1-0,06)}{17,1} = 11260\ \text{G}$$

Also flux density at 1/3rd slot depth

$$\tau_{s_2}(1/3) = \frac{\pi}{70}\ (643\ -\ 69,5.\ 2/3) = 26,7\ \text{mm.}$$

$$b_{t_2}(1/3) = 26,7 - 5,5 = 21,2\ \text{mm.}$$

$$\therefore\ B_{t_2}\ (1/3) = \frac{11260\ .\ 17,1}{21,2} = 9400\ \text{G}$$

Ampere turns/unit periphery at+_ = 1,5 / cm

Rotor Core

Taking the shaft diameter as 200 mm.

The depth of rotor core $h_{c2} = 152$ mm.

$$\therefore \quad B_{c2} = \frac{19,5 \cdot 10^6 \cdot 0,94}{15,2 \cdot 38,2 \cdot 2} = 16000 \text{ G}$$

$$l_{c2} = \frac{\pi \cdot (200 + 152)}{2} = 552 \text{ mm}$$

$$at_{c2} = 12/\text{cm.}$$

$$AT_{c2} = 12 \cdot 55,2 = 662$$

No load current

$$\Sigma AT = 3800 + 82 + 1540 + 21 + 662 = 6105$$

$$\therefore \quad I_\phi = \frac{6105}{3 \cdot 0,9 \cdot 11 \cdot 0,921} = 37,2 \text{ amp.}$$

Since the iron losses at no load remain the same, as no change is made in the stator the active component of the N.L. current is 6,85 amp.

$$\therefore \quad I_0 = \sqrt{37,2^2 + 6,85^2} = 39,2 \text{ Amp.}$$

X_m = 77 ohms and r_m = 420 ohms

Rotor Impedance

(at stand still)

$$h' = h \sqrt{\frac{f}{\ } \cdot \frac{b_{cn}}{\ }}$$

$\therefore$ At . $s = 1$ the multiplication factor K from curve is 6,5.

The resistance of each bar

$$r_b = \frac{1,8 \cdot 10^{-6} \cdot 52}{325} = 2,86 \cdot 10^{-5}$$

Since only 50 cm is inside the iron core, the amount of resistance subjected to increase is 50/52. 2,86 . 10^{-5} = 2,75. 10^{-5} ohms.

Hence at $s = 1$

$$r_{be} = (9,19 + 0,11 + 2,75 \cdot 6,5) \cdot 10^{-5}$$
$$= 27,2 \cdot 10^{-5}$$

$$\therefore r_2' = 27,2 \cdot 635 \cdot 10^{-5} = 0,173 \text{ ohms.}$$

Reactance

$$\lambda_b = \frac{65,5}{3,5,5} + \frac{3.2}{6} + \frac{1}{1} = 6,36$$

$$L_b = 0,4\pi \cdot 52 \cdot 6,36 \cdot 10^{-8} = 4,21 \cdot 10^{-6} \text{ h}$$

$$L_r = 1,55 \cdot 10^{-6} \text{ h}$$

Performance -

From the torque slip curve and the performance chart the following values are obtained

Performances of the Deep Bar Induction Motor

1	slip	s = 1; f = 50	s = 0,8; f = 40	s = 0,4; f = 20	s = 0,1 f = 5	s = 0,05 f = 2,5	s = 0,04 f = 2	s = 0,01, f = 0,5
2	$h' = 0,875\sqrt{f}$	6,25	5,6	3,95	1,98	1,4	1,25	-
3	λ	6,5	5,6	4,0	2,0	1,2	1	1
4	r_b	$17,9.10^{-6}$	$15,4.10^{-6}$	11.10^{-6}	$5,5.10^{-6}$	$3,3.10^{-8}$	$2,75.10^{-6}$	$2,75.10^{-6}$
5	r_2'	0,173	0,157	0,129	0,0945	0,08	0,0765	0,0765
6	φ(h')	0,231	0,268	0,38	0,795	0,9	0,99	1,0
7	x_2'	0,526	0,55	0,646	0,98	1,059	1,14	1,15
8	r_2'/s	0,173	0,196	0,322	0,945	1,6	1,916	7,65
9	Z'_{2s}	0,173 + j0,526 = 0,55 ∠72	0,196 + j0,55 0,585 ∠70	0,322 + j0,646 0,724 ∠64	0,945 + j0,98 1,36 ∠46	1,6 + j1,059 1,92 ∠33,9	1,915 + j1,14 2,225	7,65 + j1,15 7,71
10	$c.Z'_{2s}$	0,1755 + j0,535	0,199 + j0,559	0,327 + j 0,656	0,96 + j0,995	1,622 + j1,072	1,94 + j1,155	7,75 + j 1,65
11	Z_1	0,043 + j0,791	0,043 + j0,791	0,043 + j0,791	0,043+ j0,791	0,043 + j0,791	0,043+ j0,791	0,043+ j0,791
12	$Z_1 + c.Z'_{2s}$	0,219 + j1,226 1,341 ∠82	0,242 + j1,35 1,37 ∠80	0,37 + j1,447 1,51 ∠76	1,003+ j1,786 2,045 ∠61	1,665 + j1,863 2,5 ∠48	1,983+ j1,946 2,78 ∠44,2	7,793+ j1,956 8,04 ∠14
13	$Z'_{2s}/Z_1 + c.Z'_{2s}$	0,41 ∠-10	0,42 ∠-10	0,49 ∠-12	0,665 ∠-15	0,769 ∠-14,5	0,8	0,96
14	U_1 = (13).V_1	1183 ∠-10	1212 ∠-10	1415 ∠-12	1920 ∠-15	2210 ∠-14,5	2310	2780
15	I'_2 = (14)/(9)	2150 ∠-82	2076 ∠-80	1940 ∠-76	1410 ∠-61	1155 ∠-48	1040 ∠44,2	360 ∠-14
16	$I'^2_2.r_2'.3/s$	2370	2560	3620	5640	6400	6200	2970
17	$I'^2_2.r_2'.3$ F and W Total	2370 - 2370	2050 29 2079	1450 29 1479	564 29 593	320 29 349	248 29 277	29,7 29 58,7
18	Output	-	481	2141	5047	6051	5923	2911,3
19	Torque	2370	2560	3620	5640	6400	6200	2970
20	$Y_m.Z'_{2s}$	0,0069-j0,00022	0,0072-j0,00257	0,00846-j0,00421	0,0129-j0,0124	0,0139-j0,021	0,015-j0,025	0,015-j0,1002
21	$1+Y_m.Z'_{2s}$	1,0069 1,0069-j0,00022	1,0072 1,0072-j0,00257	1,00846 1,00846-j0,00421	1,0129 1,0129-j0,0124	1,0139 ∠-1,19 1,0139-j0,021	1,0596 ∠-1,47 1,015-j0,025	1,02 ∠-5,7 1,015-j0,1002
22	$I_1 = I'_2.(21)$	2164 ∠-82	2091 ∠-80	1954 ∠-76	1397 ∠-61	1171 ∠-49,2	1058 ∠-45,7	367 ∠-1907
23	Cos φ_1	0,149	0,174	0,242	0,485	0,67	0,695	0,945

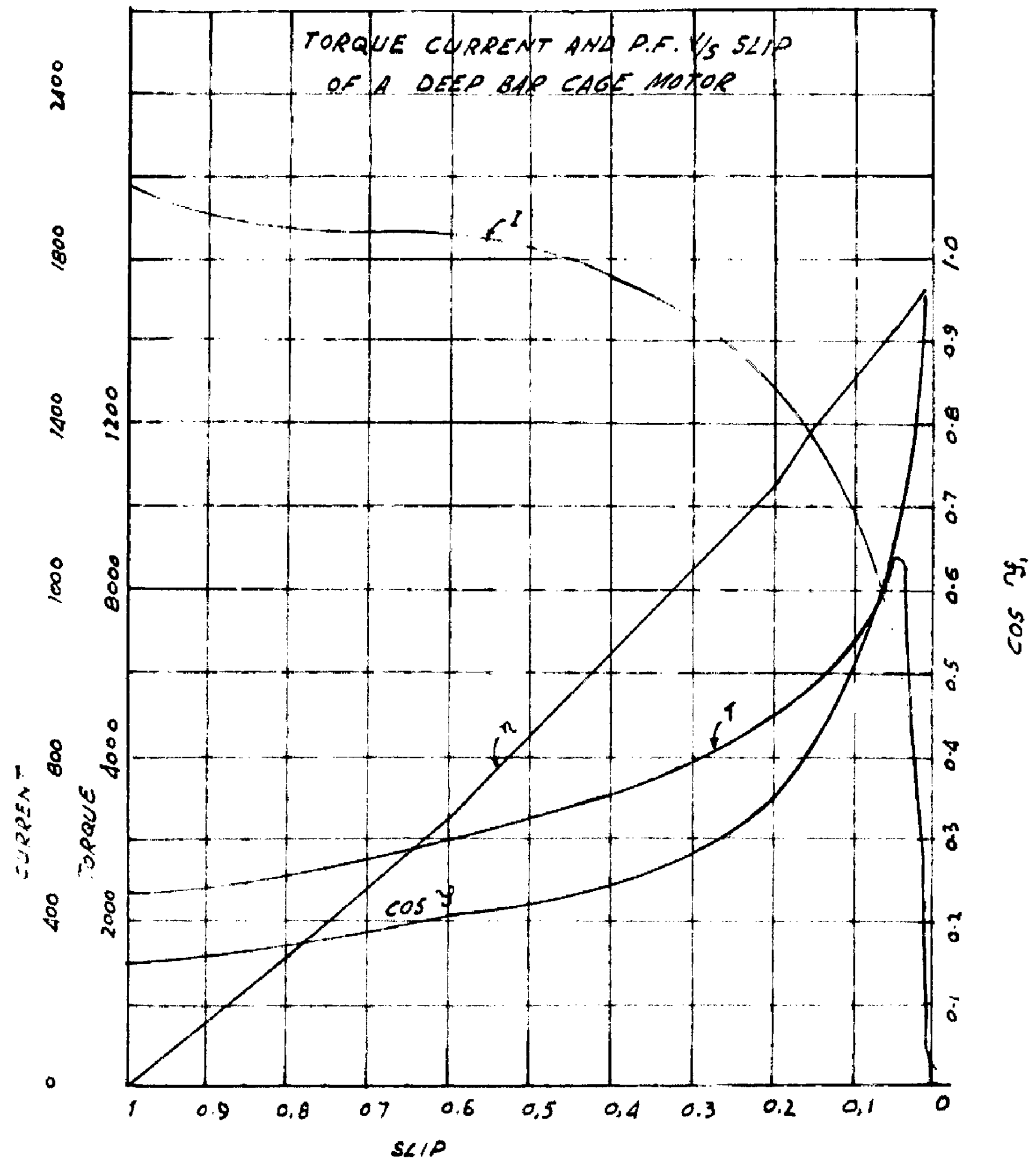

TORQUE CURRENT AND P.F. V/S SLIP
OF A DEEP BAR CAGE MOTOR
I
n
T
COS φ
CURRENT
TORQUE
SLIP
COS φ,
2400
1800
1400
1000
800
400
0
1200
8000
4000
2000
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Fig.2.8

Full load	slip	1 .%.
	torque	2907 syn Kw.
	current	367 Amp
	P.f.	0,945
	efficiency ..	95,8 %

At stand still	current	= 2164 Amp.
	P.f.	= 0,149
	Torque	= 2370 syn Kw.

Design C - Double Cage Rotor

The stator is kept the same as in design A so that x_1 and r_1 are fixed. Now the ideal short circuit currents for the circke K". (Fig. 2.9)

$$I'' \text{s.c.} = \frac{U_p}{x_1} = \frac{2890}{0,791} = 3650 \text{ Amp.}$$

The size of the inner circle K' can be dealt with freely. The smaller the diameter of the circle the worse will be the power factor of the machine at full load. Let the diameter of the inner circle represent 1000 Amp. so that in fig. $P_oD' = 1000 - 35 = 965A$ and $P_oD'' = 3650 - 35 = 3615$ A. From these values the positions of the circle K' and K" are determined and by the use of r_1 and r'_2 the positions of the points P_u' and P_k' are determined, such that the ordinates of P_u' and P_k' must be proportional to the copper losses in one phase of stator winding and copper losses in one phase of the stator and rotor winding respectively.

If we invert the circles K' and K" with reference to P_o then the inversion of K' is a vertical (g') passing through D" and correspondingly the inversion of K" is a vertical (g") through D'.

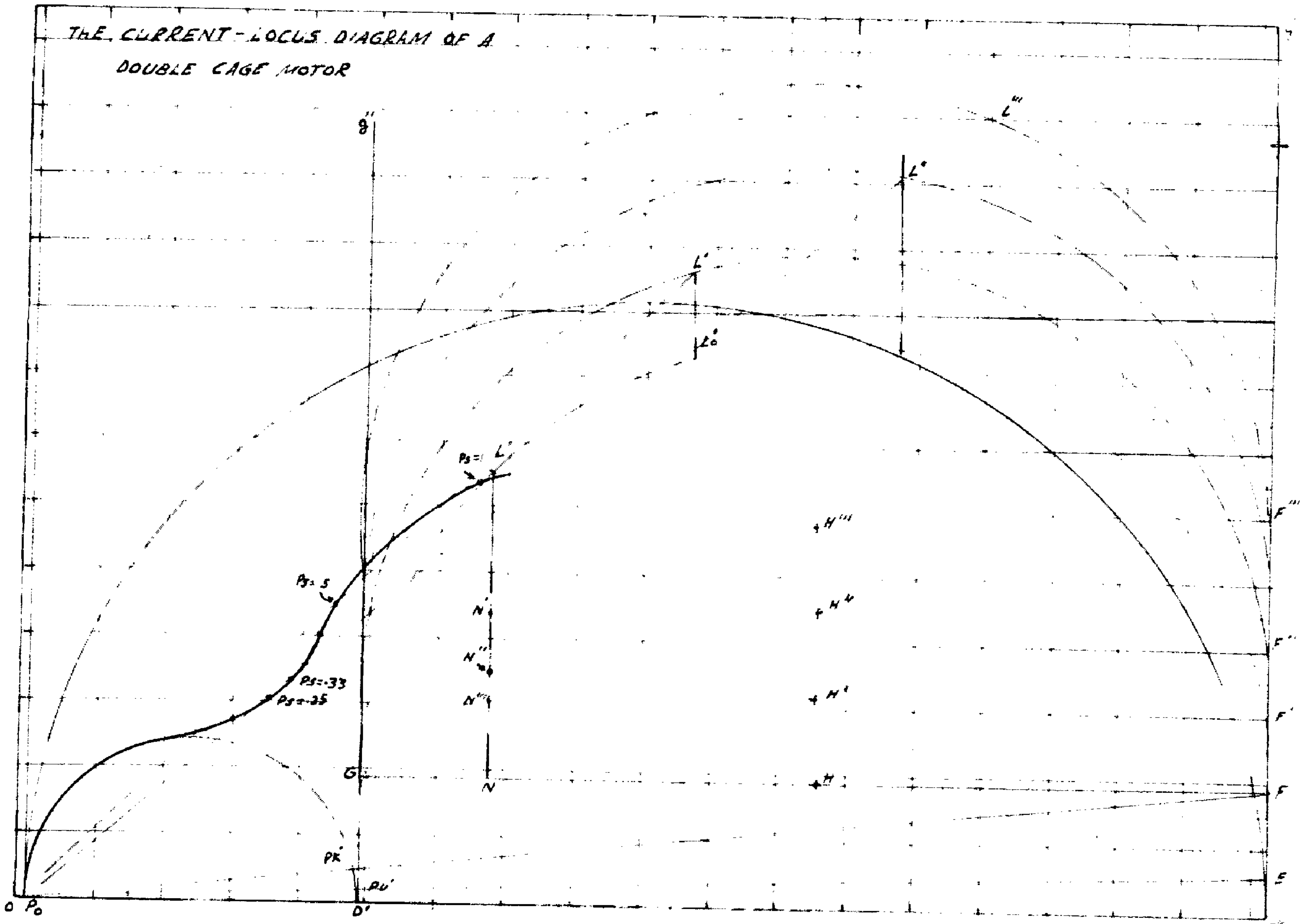

THE CURRENT-LOCUS DIAGRAM OF A
DOUBLE CAGE MOTOR
Ps=1
Ps=5
Ps=-.33
Ps=-.35
G
N
PK
D'
O
Po
E
F
F'
F''
F'''
H
H'
H''
H'''
L'
L''
L'''
Lo
D''

Fig. 2.9

The radiating lines $P_o\,P'_u$ and $P_o\,P_k'$ will on g' cut out the length EF = a. A horizontal line through F which cuts g" in G is drawn, about the center H of the line FG a circle k is drawn. The point of contact L of a tangent from P_o to k is the point corresponding to s = 1, for the max torque per unit current condition, in the inverte diagram.

The point L' corresponding to s = 0,5 may be found in the following manner: it lies immediately on a circle k' whose center H' lies higher than H by the distance 'a' i.e. H H' = a N is the vertical projection of L on FG, and N' is the center of LN. A straight line GN' intersects k in Lo'. L' is the point of intersection with k' of a verticle line, passing through Lo'. In the same manner the point L" is obtained for s= 1/3 and L"' for s =1 The point L, L', L", L"' are inverted as follows: The power of inversion is equal to

$$P_oD'.\ P_oD'' = 18,25.\ 4,82 = 88,5$$

$$\therefore\ P_oP(s = 1).\ P_oL = P_oP(s = 1/2).\ P_oL' = P_oP(s = 1/3).\ P_oL' = P_oD'.\ P_oD''$$

Thus the points $P(s = 1)$; $P(s = 1/2)$, $P(s = 1/3)$, $P(s = 1/4)$ etc. are determined

$$\therefore t = \sqrt{\frac{FN}{NG}} = \sqrt{\frac{11,4}{1,9}} = 2,49$$

In order to determine λ first the value of λ_2 and then μ ($= \frac{\lambda_2}{r_2}$) is to be determined

$$\lambda_1 + \lambda_2 = \frac{2890}{1000} = 2,89$$

$$\lambda_1 = 0,791$$

$$\therefore \quad \lambda_2 = 2,89 - 0,791 = 2,099$$

r_2' is taken as 0,247 ohms per phase

$$\mu = \frac{\lambda_2}{r_2} = \frac{2,099}{0,247} = 8,5$$

and $\lambda = 1 + \frac{\mu}{t} = 1 + \frac{8,5}{2,45} = 3,47$

In this way the resistances of the inner and outer cages are determined, namely

$$r' = \frac{\lambda}{\lambda - 1} \cdot r_2' = \frac{3,47}{2,47} \cdot 0,247 = 0,347 \text{ ohm}$$

$$r'' = \lambda \cdot r_2' = 3,47 \cdot 0,247 = 0,855 \text{ ohm}$$

It is desirable to have relatively small losses in the end rings, since the bars are placed uninsulated in the slots and this causes currents to flow through the end laminations which act in the same way as a decrease of the resistance in the end rings. Furthermore the heat generated in the bars of the outer cage during starting can be more quickly trans-

-ferred by conduction to the rotor iron then the hea generated in the end rings.

For these reasons only 40 percent of the secondary resistance is placed in the end rings of the outer cage while for the inner cage this value is increased to 60 percent.

Thus for the outer cage

$$r_b = \frac{0,6.\ 0,855}{635} = 1,315.10^{-3} \text{ ohm}$$

$$r_r = \frac{0,4.\ 0,855.\ 2.\pi^2.\ 2^2}{635\ .\ 70^2\ .\ 2^2} = 2,16.10^{-6} \text{ om}$$

and for the inner cage

$$r_b = \frac{0,4\ .\ 0,347}{635} = 0,219.10^{-3} \text{ ohm}$$

$$r_r = \frac{0,6\ 0,347\ .\ 2.\ \pi^2}{635.\ 70^2} = 1,325 \text{ ohms}$$

The length of the bar is 52 cm. The mean diameter of outer end ring is taken as 600 mm. and that of the inner ring is taken as 550 mm.
Then,

$$\text{Bar cross-section of outer cage} = \frac{52\ .\ 10^{-2}}{56.\ 1,315.\ 10^{-3}}$$

$$= 7,07 \text{ sq. mm.}$$

Bar cross-section of inner cage

$$= \frac{52.\ 10^{-2}}{56.\ 0,219.\ 10^{-3}} = 40 \text{ sq. mm.}$$

End ring X-section of the outer cage:

Length of each segment of outer ring

$$\frac{\pi.600}{70} = 26,9\text{mm.}$$

$$\therefore \text{X-section of outer end. ring} = \frac{0,6\ 2,69.10^{-2}}{2,16.10^{-6}}$$

$$= 0,748.10.4 \text{ sq. mm.}$$

Length of each segment of inner cage

$$= \frac{0,6\ \pi.550}{70} = 24,7 \text{ mm.}$$

$$\therefore \text{X section of inner cage} = \frac{0,6.2,47.10^{-2}}{1,325.10^{-6}}$$

$$= 1,12.10\ 4 \text{ sq.}$$

Hence for the outer cage circular Bars of 8 mm. dia are used and a ring of 98 mm. wide and 80 deep is used. While for the inner cage ring of 100X sq. mm. is used.

Before the rotor slot is dimensioned the magneties resistance of the slit is to be determined

$$X^1 = \left(\frac{\lambda}{\lambda - 1}\right)^2 X_2' = \left(\frac{3,47}{2,47}\right)^2 2,099 = 4,12$$

$$L' = 4,12/635.100.\pi = 2,06.10^{-5}$$

Taking $L_r = 1,55.10^{-6}$ (as in the normal cage)

$$\therefore L_b = (20,6-1,55).10^{-6} = 19.10^{-6}\ h$$

$$\therefore \lambda s = \frac{19\ .\ 10^{-6}}{0,4\pi\ .\ 49.\ 10^{-8}} = 30,8$$

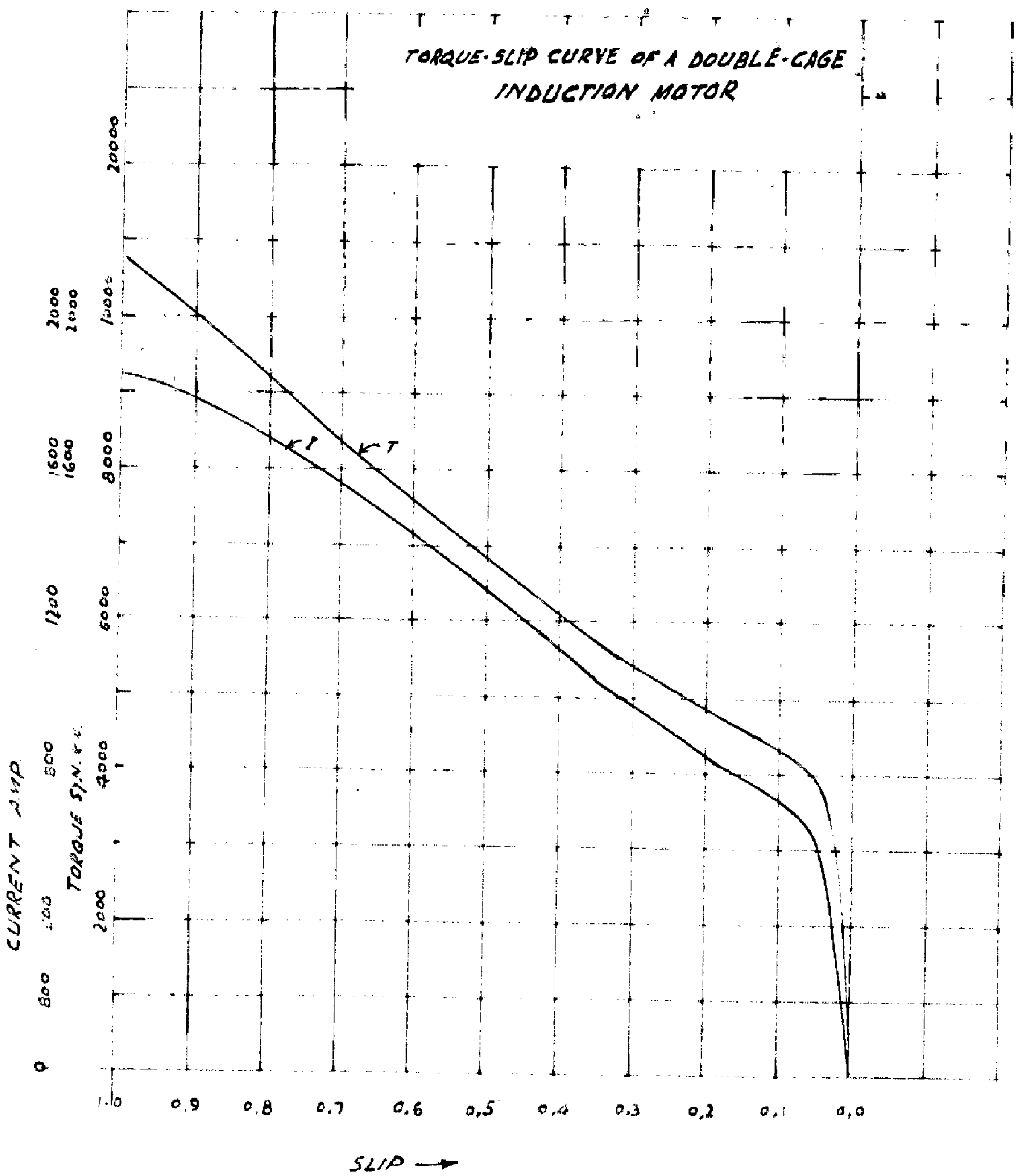

TORQUE-SLIP CURVE OF A DOUBLE-CAGE INDUCTION MOTOR
CURRENT AMP
TORQUE SYN. KW
SLIP →
I
T
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2000
4000
6000
8000
10000
20000
0
800
1200
1600
2000

Fig. 2.11

In the dimensioning of the slot provision must also be made to secure λ s = 30,8.

If at the narrowest part of the tooth B_{t_b} = 19000 G then

$$b_t = \frac{7150}{19000} .0,94. 29 = 10,25 \text{ mm}$$

The slot of dimensions as shown in fig. 2.14 is used.

From the circle diagram the following quantities are obtained:

Full load:

slip	2,57 %
I_1	360 A.
Cos φ 1	0,929
Torque	2930 syn. kW.
η	93,5 %

At standstill:

I_1	=	1840
Cos φ1	=	0,694
Torque	=	10650 syn. kW.

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