Synchronous Machine Design

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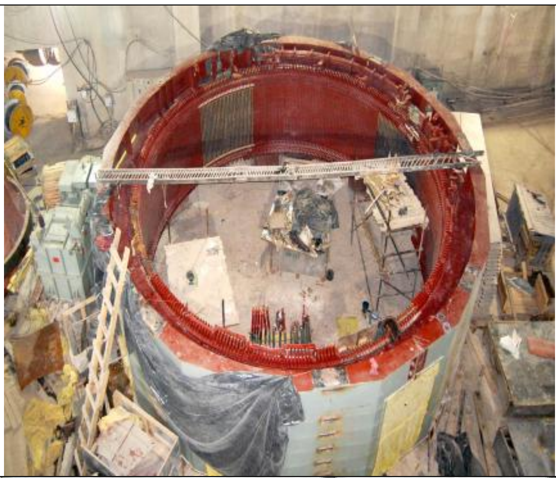
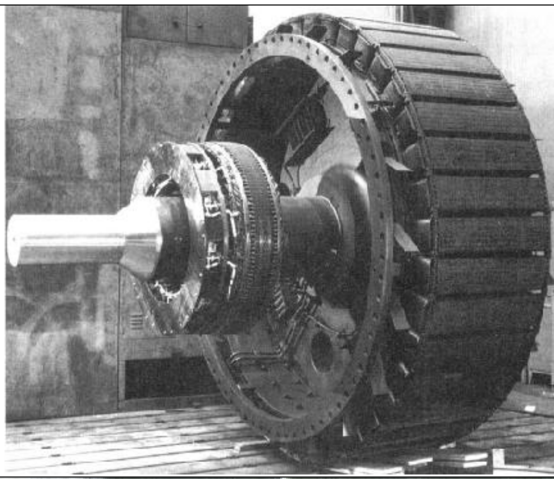
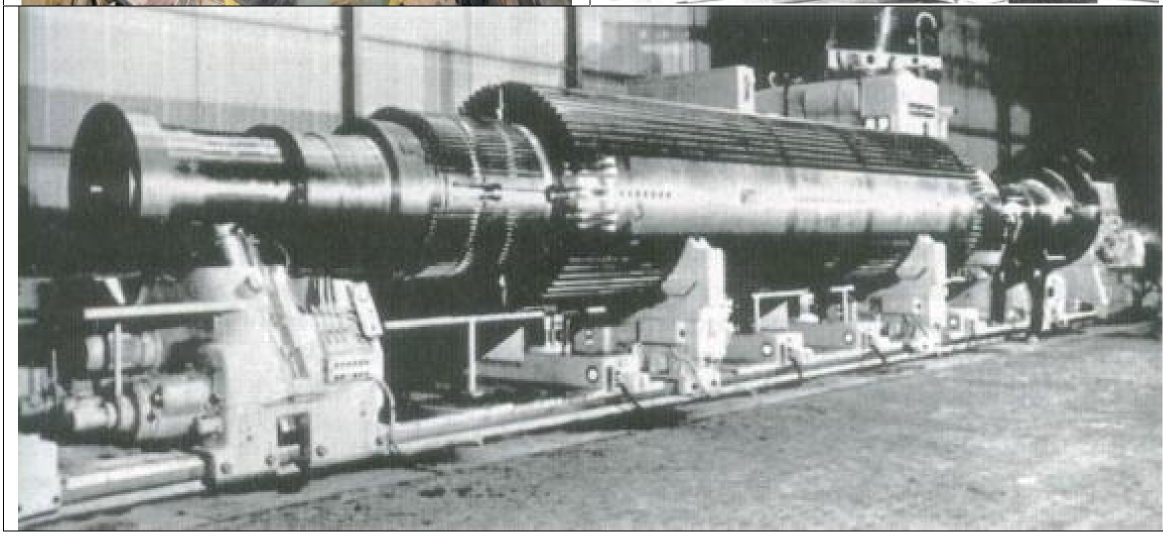






By

Nafees Ahmed

Asstt. Prof. Department of Electrical Engineering
DIT, University, Dehradun, Uttarakhand

References:

1. **Notes by Dr. R. C. Goel**
2. **Electrical Machine Design by A.K. Sawhney**
3. **Principles of Electrical Machine Design by R.K Agarwal**
4. **VTU e-Learning**
5. **www.goole.com**
6. **www.wikipedia.org**

Synchronous Machines Design

OUTPUT EQUATION: - It gives the relationship between electrical rating and physical dimensions (Quantities)

The rating is given by

$$Q = 3V_{Ph} \times I_{Ph} \times 10^{-3} \qquad KVA ------------------(1)$$

$$Q = 3\left(4.44K_{pd1} f\phi_1 N_{Ph}\right) \times I_{Ph} \times 10^{-3} \qquad KVA ------------------(1)$$

$$\because \; V_{Ph} = 3.33K_{d1} f\phi_1 N_{Ph}$$

Where

K_{pd1}= 0.955 For a short pitched (chorded) distributed winding

$f = \dfrac{PN}{120}$ Frequency of output voltage

N = Speed in rpm

$$\phi_1 = \frac{2}{\pi} B_{\delta 1}\left(\frac{\pi D}{P} L\right)$$

D = Inner diameter of stator

L = Length of the machine

Total electrical loading

$$6N_{Ph1}I_{Ph1} = \overline{ac}\;\pi\; D$$

$$N_{Ph1}I_{Ph1} = \frac{\overline{ac}\pi\; D}{6}$$

Putting the values of K_{d1}, f, ϕ_1 & $N_{Ph}I_{Ph}$ in equation (2) we get

$$Q = 3 \times 4.44 \times 0.955 \times \left(\frac{NP}{120}\right) \times \left(\frac{2}{\pi} B_{\delta 1} \frac{\pi D}{P} \times L\right) \times \left(\frac{\overline{ac}\;\pi\; D}{6}\right) \times 10^{-3} \quad KVA$$

$$Q = (11.1 \times 10^{-5} B_{\delta 1}\; \overline{ac})D^2LN$$

Or $\quad Q = CD^2LN \quad KVA$

Where

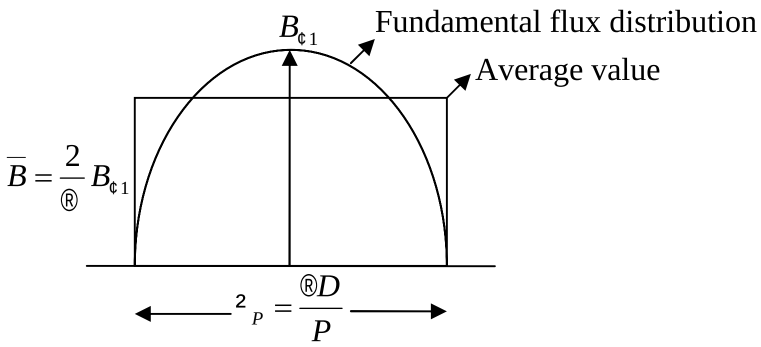
$$C = Output\ Co-efficient = 11.1 \times 10^{-5} B_{\delta 1}\; \overline{ac}$$

$$\left(\begin{array}{l} \text{Note}:-\text{For Induction Motor} \\ \qquad Q = CD^2LN\ \ KW \\ \text{Where} \quad C = 17.4 \times 10^{-5}\, \bar{B}\; \overline{ac}\; \cos\phi\; \eta \\ \qquad\qquad = 17.4 \times 10^{-5} \dfrac{2}{\pi} B_{\delta 1}\; \overline{ac}\; \cos\phi\; \eta \\ \qquad\qquad = 11.1 \times 10^{-5} B_{\delta 1}\; \overline{ac}\; \cos\phi\; \eta \end{array}\right)$$

CHOICE OF MAGNETIC LOADING ($B_{\delta 1}$):

($B_{\delta 1}$ is maximum value of fundamental flux density in the air gap)

Range of $B_{\delta 1}$ = 0.8 to 1 Tesla



$$\left(Average\ Flux\ Density\quad \bar{B}\, \frac{2}{\pi} B_{\phi 1} \approx 0.5\ to\ 0.65 \right)$$

CHOICE OF SPECIFIC ELECTRIC LOADING $\bar{ac}$**:**

1. Water wheel alternator (Hydro Alternator): Salient pole machines

   $\bar{ac}$ =20,000 to 40,000 A/m

2. Turbo Alternator: Non-Salient pole machines

   $\bar{ac}$ =50,000 to 75,000 A/m

MINI AND MAXI VALUE OF C:

We know $C = 11.1 \times 10^{-5} B_{\phi 1}\ \bar{ac}$

1. Water wheel alternator (2 to 4.5)

$$C_{\min} = 11.1 \times 10^{-5}\, 0.8 \times 20000$$
$$\approx 2$$
$$C_{\max} = 11.1 \times 10^{-5}\, 1.0 \times 40000$$
$$\approx 4.5$$

2. Turbo alternator (5 to 8)

$$C_{\min} = 11.1 \times 10^{-5}\, 0.8 \times 50000$$
$$\approx 5$$
$$C_{\max} = 11.1 \times 10^{-5}\, 1.0 \times 75000$$
$$\approx 8$$

PERIPHERAL SPEED: -

$$V_{peri} = \frac{\pi D N}{60} \quad m/s$$

1. Water Wheel alternator

   30 to 80 m/s

   Maxi limit 140 m/s

2. Turbo alternator

   150 m/s

   Maxi limit 175 m/s

RUNAWAY SPEED: - If an alternator is delivering rated load and the load is suddenly through-off, the speed of the runner becomes abnormally high, this abnormal high speed is called as runaway speed.

1. Water Wheel alternator

Pelton wheel turbine:	1.8	times of rated speed
Frances Turbine:	2 to 2.2	times of rated speed
Kaplan Turbine:	2.5 to 2.8	times of rated speed

2. Turbo alternator 1.25 times of rated speed

ESTIMATION OF MAIN DIMENSIONS (D, L):

We know $$D^2L = \frac{Q}{CN} \quad ----------------------- \quad (1)$$

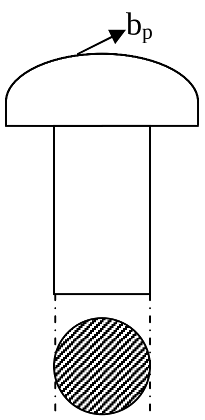
1. Water Wheel alternator: It is of two types

   a. Round Pole or Circular Pole: $\frac{b_P}{2_P} = 2/3$

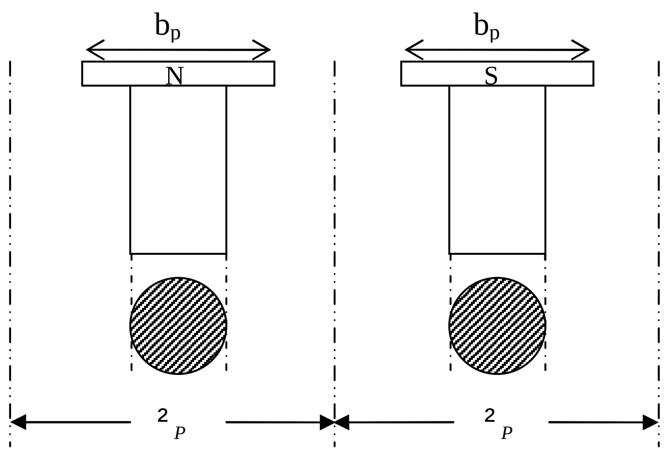
   b_P = Pole arc or width of pole shoe
   = Length of the pole
   = L (for round pole with square pole shoe)-

   b. Long Pole: $\frac{L}{2_P} = 1 \; to \; 5$

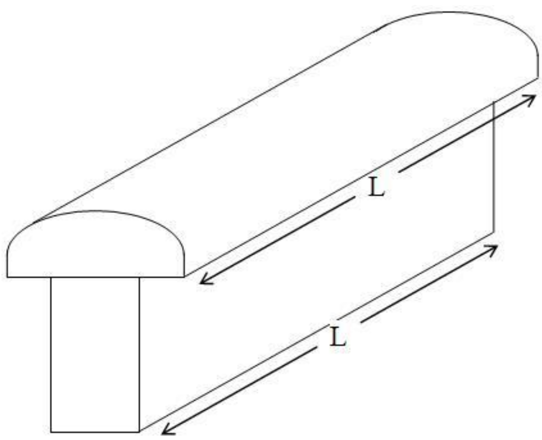
---------- (2)



Round or circular Pole



Round or circular Pole
(With square pole shoe)



Long Pole

Solving equation (1) & (2) we can find out D & L. Finally check the peripheral speed.

2. Turbo alternator:

$\rightarrow$ For large rating machines $(\geq 25 \text{ MVA})$ we use peripheral speed as limit

$$V_{peri} = 150\, m/s = \frac{® \, D N}{60} \qquad \text{------------------ (2)}$$

From above equation taking N=3000 rpm

$$D = \frac{150 \times 60}{® \times 3000} \approx 1 \; m$$

So for large rating machines dia of alternator is determined by maximum permissible peripheral speed. Thus for peripheral speed of 150 m/s, the maximum permissible dia D =1 meter

Now put D = 1 in equation (1) and solve for L

Note:

Output/meter of length

$Q = CD^2LN$	KVA	
$= 8 \times 1^2 \times 1 \times 3000$	KVA	for L = 1 meter
$= 24$	MVA/meter	

Hence we can say

For Q = 48 MVA M/C	L = 2 m	D = 1 m
For Q = 96 MVA M/C	L = 4 m	D = 1 m

<u>DETERMINATION OF AIR GAP LENGTH: -</u>

$$\frac{¢}{2_P} = 0.01 \; to \; 0.015 \qquad \text{Water wheel}$$

$$= 0.02 \; to \; 0.025 \qquad \text{Turbo}$$

Where $\quad 2_P = \dfrac{® \, D}{P}$

<u>ESTIMATION OF NO OF STATOR SLOTS (S): -</u>

$2_{sg} \leq 20 \; mm$	Up to 1KV
$\leq 40 \; mm$	Up to 6.6 KV
$\leq 60 \; mm$	Up to 16 KV

No of stator slots

$$S = \frac{®D}{2_{sg}}$$

$$q = \frac{S}{3P} \;= \text{Slots per pole per phase}$$

May be an integer or fractional (say $\frac{x}{y}$)

For symmetrical winding, no of pole pairs should be divisible by y

(I.e. $\dfrac{x}{y} = \dfrac{7}{3} = 2\dfrac{1}{3}$ if P=4 $\Rightarrow$ no of pole pairs = 2, so change $\dfrac{x}{y} = 2\dfrac{1}{2}$)

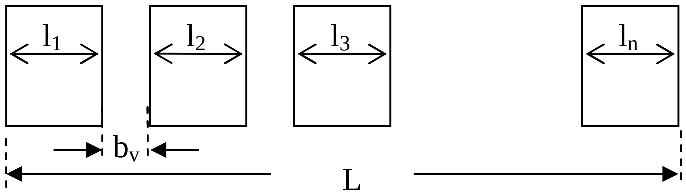
Hence find out the corrected value of q $\Rightarrow$ $q_{corrected}$ and $S_{corrected} = 3Pq_{corrected}$

EFFECTIVE, OVERALL & GROSS IRON LENGTH OF MACHINE:

(Note: - Same as for induction motor)

Generally

$l_1 = l_2 = l_3 = \ldots\ldots\ldots = l_n$



Let

n_v =No of ventilating ducts

b_v = Width of one ventilating duct

(Generally for every 10 cm of core length there used to be 1 cm ventilating duct)

Gross Iron length

$$l = l_1 + l_2 + l_3 + \ldots\ldots\ldots + l_n$$

Actual Iron length

$$l_i = K_i * l$$

Where K_i =Stacking factor

=0.90 to 0.92

Overall length

$$L = l + n_v * b_v$$

Effective length

$$L_e = L - n_v \times b_v^{'}$$

Where $b_v^{'} = b_v \dfrac{5}{5 + \dfrac{b_v}{\delta}}$ =Effective width of ventilating duct (< b_v due to fringing)

ESTIMATION OF NO OF TURNS N_{Ph}, TOTAL NO CONDUCTORS Z, CONDUCTORS PER SLOTS N_C, FUNDAMENTAL FLUX Φ_1 AND MAXIMUM VALUE OF FUNDAMENTAL FLUX DENSITY $B_{\delta 1}$: -

$$V_{Ph} = 3.33 K_{d1} f \Phi_1 N_{Ph} \quad \text{------------------------------ (1)}$$

So $$N_{Ph} = \frac{V_{Ph}}{4.44 K_{pd1} f \Phi_1} \quad \text{------------------------------ (2)}$$

$$\Phi_1 = \frac{2}{\pi} B_{\delta 1} \left(\frac{\pi D}{P} l_e \right) \quad \text{------------------------------ (3)}$$

$K_{pd1} = 0.955$

$$Z = 6 N_{Ph} \quad \text{------------------------------ (4)}$$

$$N_c = \frac{Z}{S} \qquad \text{-----------------------------} \ (5)$$

It should be an integer, if not make an integer and divisible by 2 for double layer winding.

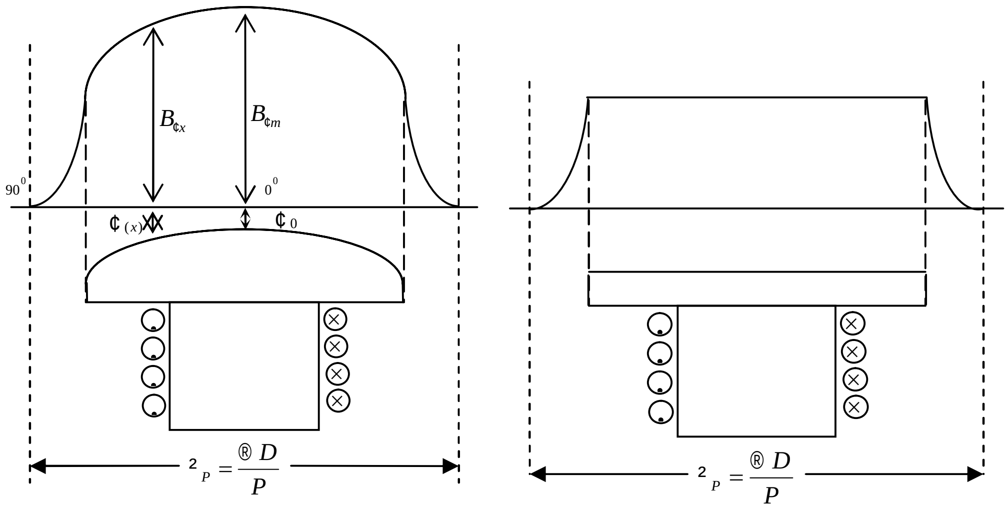
So find

$N_{c,corrected}$	
$Z_{corrected}$	using equation (5)
$N_{Ph,corrected}$	using equation (4)
$¤_{1,corrected}$	using equation (2)
$B_{¢1,corrected}$	using equation (3)

ESTIMATION OF FLUX DENSITY DISTRIBUTION CURVE IN THE AIR GAP: -

- Shape of the voltage generated depends on shape of air gap flux. If air gap flux is sinusoidal then generated emf will be sinusoidal.
- Hence aim is to get sinusoidal flux in the air gap.
- Synchronous machines may be

1. Salient pole rotor : Projected Poles
   a. Sinusoidal air gap
   b. Constant air gap
2. Cylindrical rotor



(a) Sinusoidal air gap (b) Constant air gap

For sinusoidal air gap

$$¢_{(x)} = \frac{¢_0}{\cos\_}$$

θ is taken from centre of pole, at pole centre $\theta = 0^0$ & at interpolar axis $\theta = 90^0$

1. **Estimation of air gap flux for salient pole:** Sinusoidal Air gap

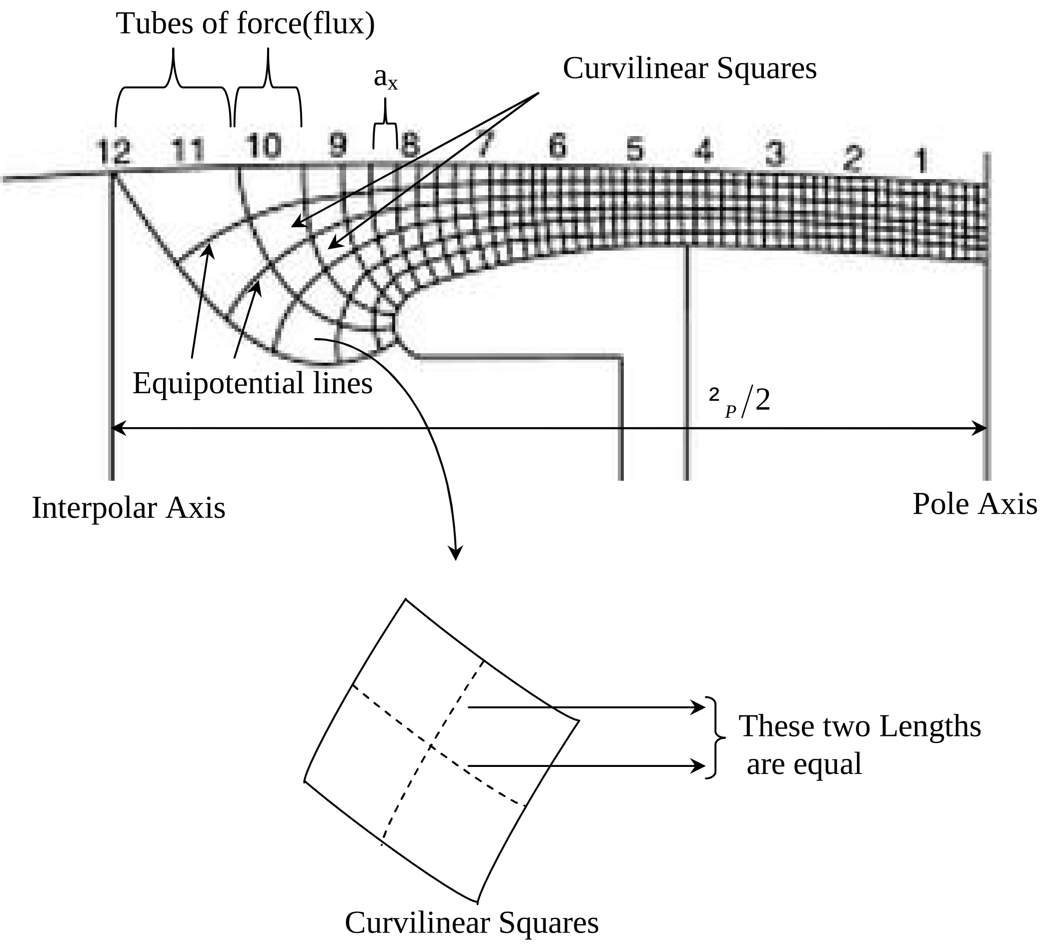
There are three methods

a. Wiesemann method of curvilinear square:
b. Simplified method (Developed in Germany):
c. Carter's fringe curve method:

a. Wiesemann method of curvilinear square:

Consider half pole pitch of sinusoidal air gap

The flux path in the air gap under the pole may be divided into tubes of flux as shown in following figure.



Assumptions are

i. The line of force (flux) and equipotential line intersects at right angle and form curvilinear square.
ii. Flux enters and emerges at perpendicular to the equipotential surface. It is possible if permeability of iron is infinity.
iii. Stator & rotor surface are assumed at equipotential.
iv. Each tube of force caries equal number of flux lines.
v. Each tube of force is divided into equal number of curvilinear squares.
vi. The depth of each tube being unity in a direction parallel to shaft.

The flux density plot shown in above figure can be used to determine

i. Permeance of air gap
ii. Form factor
iii. Percentage of harmonics. This then help in shaping the pole correctly to obtain sinusoidal flux distribution in air gap and reducing the harmonics and eliminating the more pronounced ones when necessary.

- Permeance of each square

$$= \mu_0 \frac{A}{L} = \mu_0 \frac{\text{Width of square} \times \text{Unit depth of pole (Machine)}}{\text{Length along air gap path}}$$

Here width and length of each square are made equal as far as possible so that each square will have same permeance i.e

$$Permeance = \mu_0$$

Permeance in series m= no of squares along the air gap =6
Permeance in parallel n= no of squares along the pole pitch =52x2
(x2 for full pole pitch)

Thus the permeance of air gap path under each pole

$$Permeance / pole = \mu_0 \frac{m}{n}$$

- For flux density distribution curve

Let W_x=mean width of a flux tube
l_{gx}=mean length of flux tube

Then permeance of this tube considering unit depth

$$= \mu_0 \frac{W_x \times 1}{l_{gs}} = \mu_0 \frac{W_x}{l_{gs}}$$

Flux $\phi_x = \text{MMF} \times \text{Permeance} = \text{AT}_f \times \mu_0 \frac{W_x}{l_{gx}}$ (AT_f= Filed MMF/ Pole)

Flux density at armature surface where width of tube is a_x,

$$B_x = \frac{\phi_x}{a_x \times 1} = \text{AT}_f \times \mu_0 \frac{W_x}{a_x l_{gs}} \quad \text{---------- (1)}$$

Now at the centre of the pole: $a_x=W_x$ & $l_g=l_{gx}$

So flux density at the pole centre

$$B_{\delta m} = \text{AT}_f \times \frac{\mu_0}{l_g} \quad \text{---------- (2)}$$

(1) ÷ (2)

$$B_x = B_{\delta m} \times \mu_0 \frac{W_x l_g}{a_x l_{gs}} \quad \text{---------- (3)}$$

Calculate flux density at various points using equation (3) each 10^0 or 15^0 apart on armature surface and draw the curve.

$$Form\ factor = \frac{B_{rms}}{B_{av}}$$

b. Simplified method (Developed in Germany):

Assumption:

i. Permeability of iron is infinity

We know $B = \mu_o H = \mu_o \dfrac{MMF / Pole}{Air\ gap\ length}$

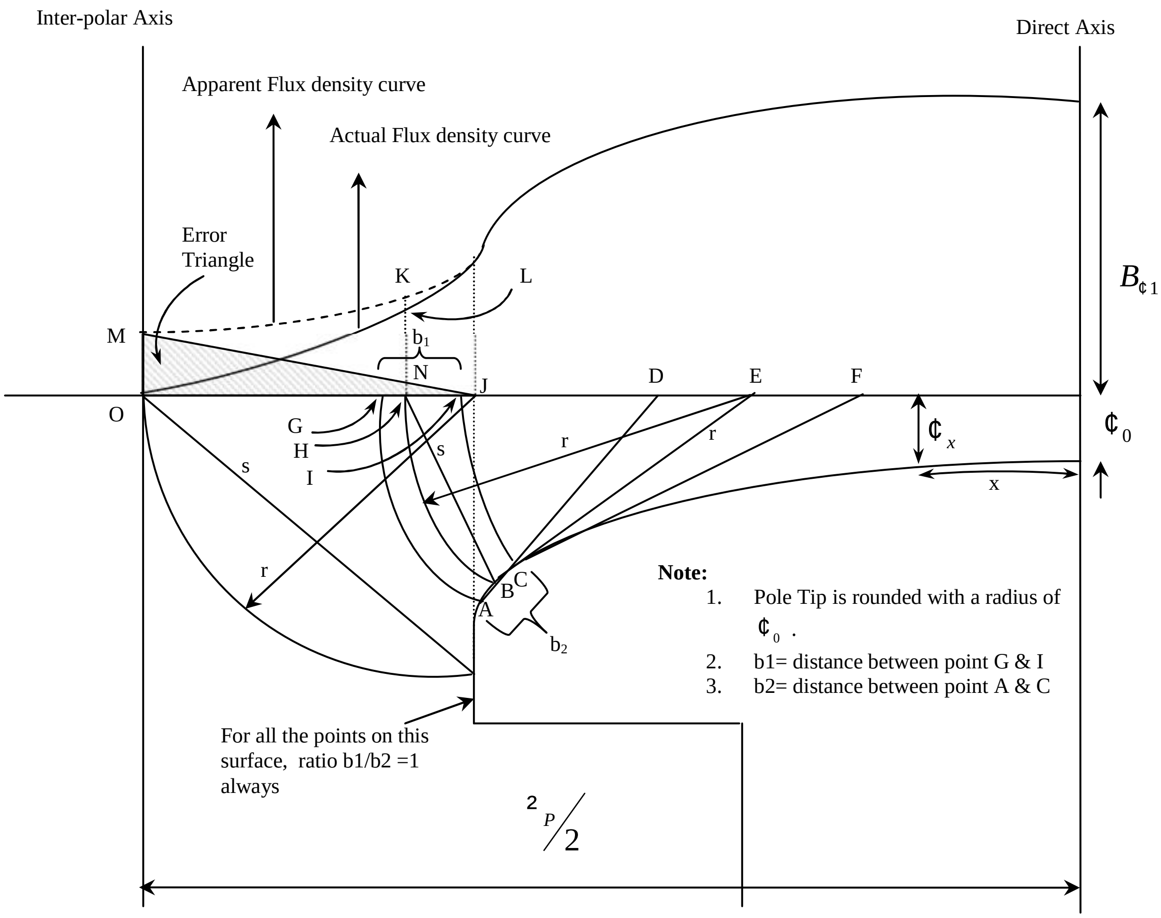
So flux density at pole centre

$$B_{\delta m} = \mu_o \frac{MMF}{\delta_o} \quad \text{------------ (1)}$$

Flux density at distance “x” from the pole centre

$$B_{¢x} = «o\frac{MMF}{¢_x} \qquad \text{------------ (2)}$$

(2) / (1) $$B_{¢x} = B_{¢m}\frac{¢_0}{¢_x} \qquad \text{------------ (3)}$$



Flux Density Distribution Curve

Under the pole flux density can be find out by using the equation (3) but between pole tip and inter-polar axis we have to apply another method to find out flux density.

Steps to find out flux density between pole tip to Interpolar axis:

(i) Assume three points A, B & C on the curve portion of the pole tip.

(ii) Draw tangents AD, BE & CF from points A, B & C respectively.

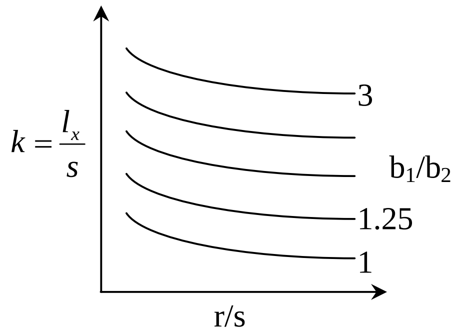
(iii) With D, E & F as centers, draw arcs of circle with radius of AD, BE & CF respectively. They intersect horizontal line at points G, H & I.

(iv) Join H & B, let Chord HB = s
Radius BE = r

(v) So flux density corresponding to point H

$$B_{¢x}\left(\text{at point H}\right) = HK = B_{¢m}\frac{¢_0}{¢_x} = B_{¢m}\frac{¢_0}{k \times s}$$

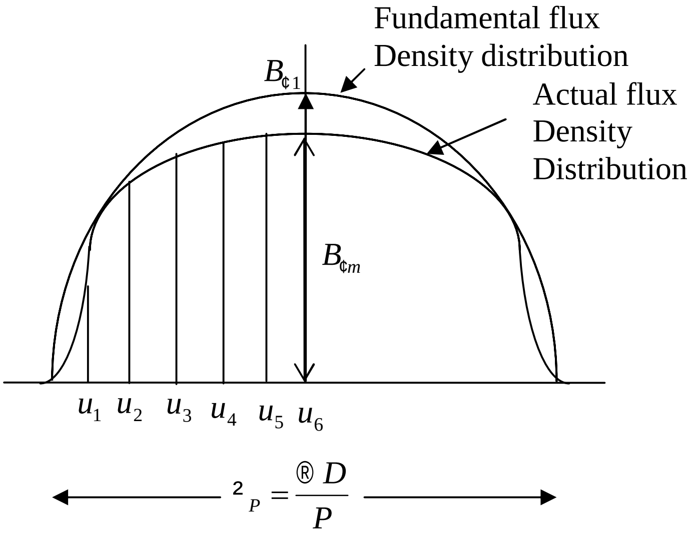
Where k is a constant and its value can be find out from graph (See reference notes figure 16 page 16.)



(vi) Similarly we can find out flux density at each and every point on the pole tip.
(vii) Draw the flux density curve. It is known as apparent flux density curve.
(viii) The value of flux density at inter-polar axis must be zero but it is not zero in above calculated graph. So it is not the actual flux density curve. To get actual flux density curve.
(ix) Draw triangle MJO, known as error triangle.
(x) For point K
Calculated flux density (Apparent flux density) = HK
Error = HN
Actual flux density HL = HK-HN.

(ix) Similarly we can find out point of actual flux density curve after subtracting the error value.
➢ The actual flux density distribution curve so obtained has a fundamental as well as odd harmonics.

Actual flux density distribution curve:
Divide half of the pole pitch into 6 equal's parts as shown bellow.



$$B_{\delta 1} = 0.086u_1 + 0.167u_2 + 0.236u_3 + 0.289u_4 + 0.323u_5 + 0.167u_6$$
$$B_{\delta 3} = 0.236u_1 + 0.333u_2 + 0.236u_3 + 0.289u_4 - 0.236u_5 - 0.167u_6$$
$$B_{\delta 5} = ...$$
$$B_{\delta 7} = ...$$

- Equation for actual flux density

$$B_{\text{¢}m} = B_{\text{¢}1}Sin\text{¯} + B_{\text{¢}3}Sin3\text{¯} + B_{\text{¢}5}Sin5\text{¯} + B_{\text{¢}7}Sin7\text{¯}$$

It Average value

$$B_{av} = \frac{2}{\text{®}}\left(B_{\text{¢}1} + \frac{1}{3}B_{\text{¢}3} + \frac{1}{5}B_{\text{¢}5} + \frac{1}{7}B_{\text{¢}7} + \ldots\right)$$

Its RMS value

$$B_{av} = \sqrt{\frac{1}{2}\left(B_{\text{¢}1}^2 + B_{\text{¢}3}^2 + B_{\text{¢}5}^2 + B_{\text{¢}7}^2 + \ldots\right)}$$

- Ratio

$$\frac{B_{\text{¢}1}}{B_{\text{¢}m}} = K_{\text{¢}} \Rightarrow B_{\text{¢}1} = K_{\text{¢}}B_{\text{¢}m}$$

- Flux per pole

$$\text{¤}_1 = \frac{2}{\text{®}}B_{\text{¢}1}\text{²}_P l_e$$

- Actual flux per pole

$$\text{¤}_p = B_{av}\text{²}_P l_e$$

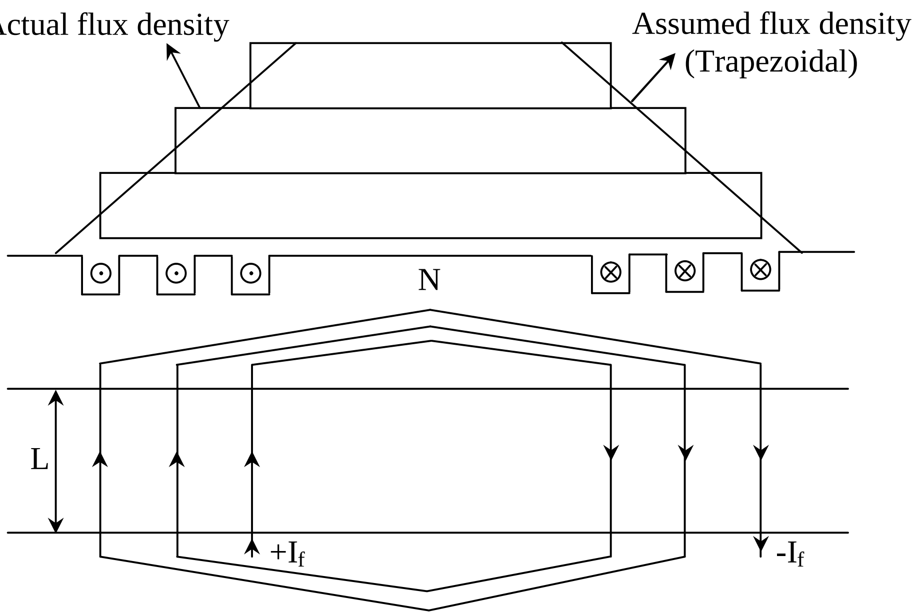
$$\Rightarrow \frac{\text{¤}_1}{\text{¤}_P} = \frac{B_{\text{¢}1}}{\frac{\text{®}}{2}B_{av}} = \frac{B_{\text{¢}1}}{B_{\text{¢}m}} = K_{\text{¢}} \Rightarrow \left[\frac{\text{¤}_1}{\text{¤}_P} = K_{\text{¢}}\right]$$

Note:

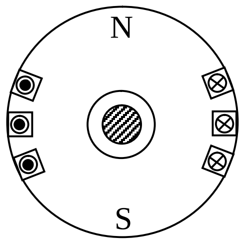
1. $B_{\text{¢}1}$ & ¤_1 are used for calculation in electrical circuit design and $B_{\text{¢}m}$ & ¤_P are used in magnetic circuit calculation.
2. Pole tip is rounded by an arc of radios ¢_0.

2. Estimation of flux density distribution curve for cylindrical rotor:

- In cylindrical rotor synchronous machine 1/3rd portion of rotor is left unslotted.
- Length of air gap is constant
- Flux is assumed to be trapezoidal

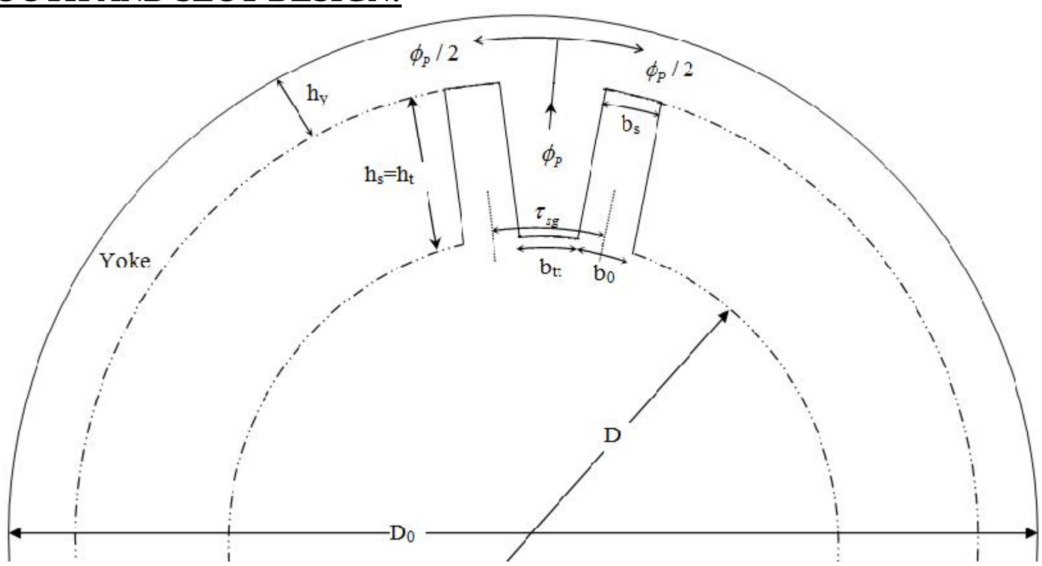


$$B_{¢m} = «_o \frac{MMF / Pole}{Air\ \ gap\ length}$$



Cylindrical Rotor

TOOTH AND SLOT DESIGN:



In alternators generally open slots are used.

Slot pitch $$2_{sg} = \frac{®D}{P}$$

Flux through a slot pitch

$$¤_{2_{sg}} = B_{¢m} 2_{sg} l_e$$

We know $$K_¢ = \frac{B_{¢1}}{B_{¢m}}$$

So $$B_{¢m} = \frac{B_{¢1}}{K_¢}$$

Flux through the tooth (we assume that entire flux per slot pitch passes through tooth)

$$¤_{2_{sg}} = B_t . b_{tt} .. l_e$$

Permissible value of flux density in tooth

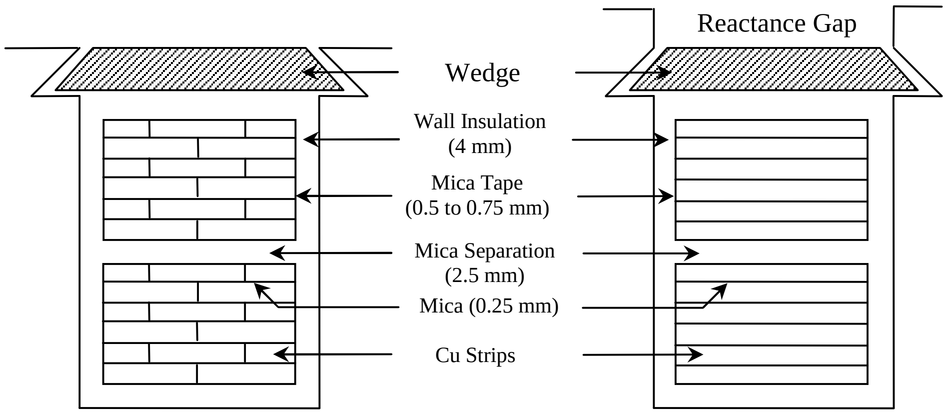
B_t = 1.6 to 1.8 T

If flux density B_t > 1.7 T in stator tooth, magnetic unloading will take place: A part of the flux enters through the slot.

So $$b_{tt} = \frac{¤_{2_{sg}}}{B_t .. l_e}$$

So width of slot $$b_o = b_s = 2_{sg} - b_{tt}$$

Height of slot $$h_s = (2\ to\ 5) b_o$$



Slot for Water Wheel Alternator
(11 KV-Brick Construction)

Slot for Turbo Alternator
(11 KV)

Thickness of insulation

With mica or leatheroid as a wall insulation

KV	0.4	1.1	3.3	6.6	11	15	22
mm	0.5	0.75	1.5	2.5	4	5.5	6.5

With improved insulation (Semica Therm)

KV	2	3	6	10	16	25
mm	1.1	1.4	1.8	2.8	4.0	6.0

Thickness = 0.215 KV +0.7 mm

Advantages of Semica Therm:

(a) Much better heat is dissipated for higher rating machines due to less thickness of wall insulations.

(b) Insulation occupies little less space in the slot.

ESTIMATION OF SECTIONAL AREA OF STATOR CONDUCTOR (F_C):

Per phase stator current

$$I_{Ph} = \frac{Q \times 10^3}{3V_{Ph}}$$

So $$F_C = \frac{I_{Ph}}{\text{¢}} \quad mm^2$$

Where $$\text{¢} = \text{Current density} = 4 \rightarrow 5 \quad A/mm^2$$

STATOR YOKE DESIGN:

Flux through stator yoke is half of the flux per pole

$$\frac{\text{¤}_P}{2} = B_y \times h_y K_i l$$

Where B_y = flux density in yoke

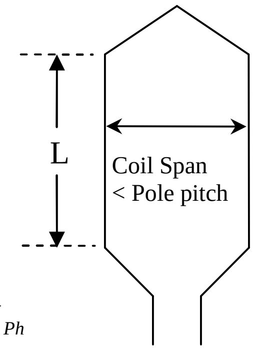
= 1.3 to 1.5 T

So $$h_y = \frac{\text{¤}_P / 2}{B_y K_i l}$$

OUTER DIA OF MACHINE (D_O):

$$D_o = D + 2h_s + 2h_y$$

ESTIMATION OF STATOR RESISTANCE, STATOR CUR LOSS AND WEIGHT OF COPPER:



One Turns

Length of mean turns

$$L_{mt\backslash} = 2\ L + 3\ 2_P$$

Where $$2_P = Pole\ \ pitch = \frac{\Pi D}{P}$$

DC Resistance of stator winding per phase at 75^0 C

$$R_{Ph,\,dc,\,75^0 C} = 0.021 \times 10^{-6} \times \frac{L_{mt}}{F_c} N_{Ph}$$

AC Resistance of stator winding per phase at 75^0 C

$$R_{Ph,\,ac,\,75^0 C} = R_{Ph} = (1.15\ \ to\ \ 1.20) R_{Ph,\,dc,\,75^0 C}$$

Copper loss in the stator winding

$$= 3\ I_{Ph}^2\ \ R_{Ph}$$

Weight of cu used in stator winding

=8900*(3*L_{mt}*N_{Ph}*F_C)

ESTIMATION OF STATOR IRON LOSS: (Same as for Induction Motor)

We find out flux density in the stator tooth at $\frac{1}{3}^{rd}$ of tooth height from narrow end

Slot pitch at $\frac{1}{3}^{rd}$ of tooth height from narrow end

$$2_{sg\frac{1}{3}h_t} = \frac{\Pi\left(D + \frac{1}{3}h_s \times 2\right)}{S_1}$$

Width of the tooth at $\frac{1}{3}^{rd}$ of tooth height from narrow end

$$b_{t\frac{1}{3}h_t} = 2_{sg\frac{1}{3}h_t} - b_s$$

Area of one stator tooth at $\frac{1}{3}^{rd}$ of tooth height from narrow end

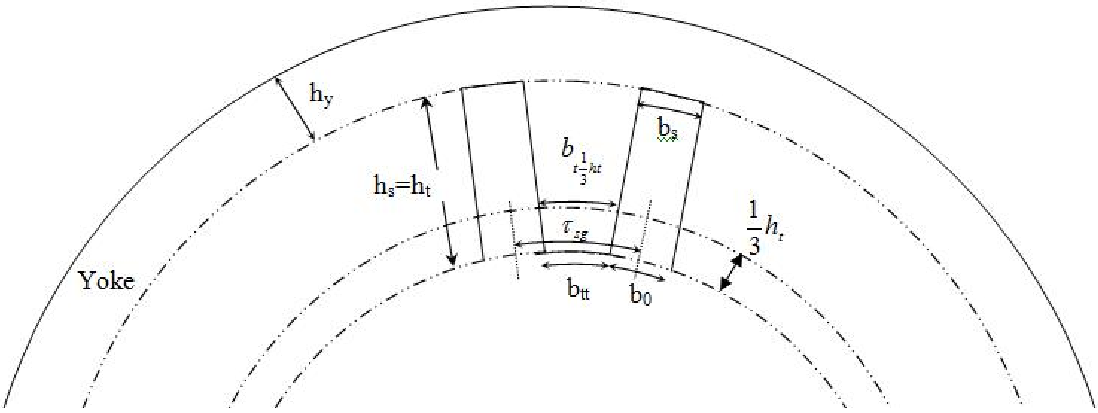
$$= b_{t\frac{1}{3}h_t} \times K_i l$$ (Where l_i = k_i l=Actual iron length)

Area of all the stator teeth under one pole

$$A_{t\frac{1}{3}h_t} = Area\ \ of\ \ one\ \ tooth \times No\ \ of\ \ teeth\ \ per\ \ pole\left(\frac{S_1}{P}\right)$$

$$= b_{t\frac{1}{3}h_t} \times K_i l \times \left(\frac{S_1}{P}\right)$$

$$= \left[\frac{\Pi\left(D + \frac{1}{3}h_s \times 2\right)}{S_1} - b_s\right] \times K_i l \times \left(\frac{S_1}{P}\right)$$



So mean flux density in teeth

$$B_{t\frac{1}{3}h_t} = \frac{\text{¤}_1}{A_{t\frac{1}{3}h_t}}$$

Corresponding to flux density in tooth $B_{t\frac{1}{3}h_t}$ find out iron loss per Kg from the graph given on page 19, fig 18. $So \quad B_{t\frac{1}{3}h_t} \Rightarrow p_{it} \quad W/Kg$

Iron loss in teeth

= p_{it}* density * volume of iron in teeth
= p_{it}* 7600 * volume of iron in teeth

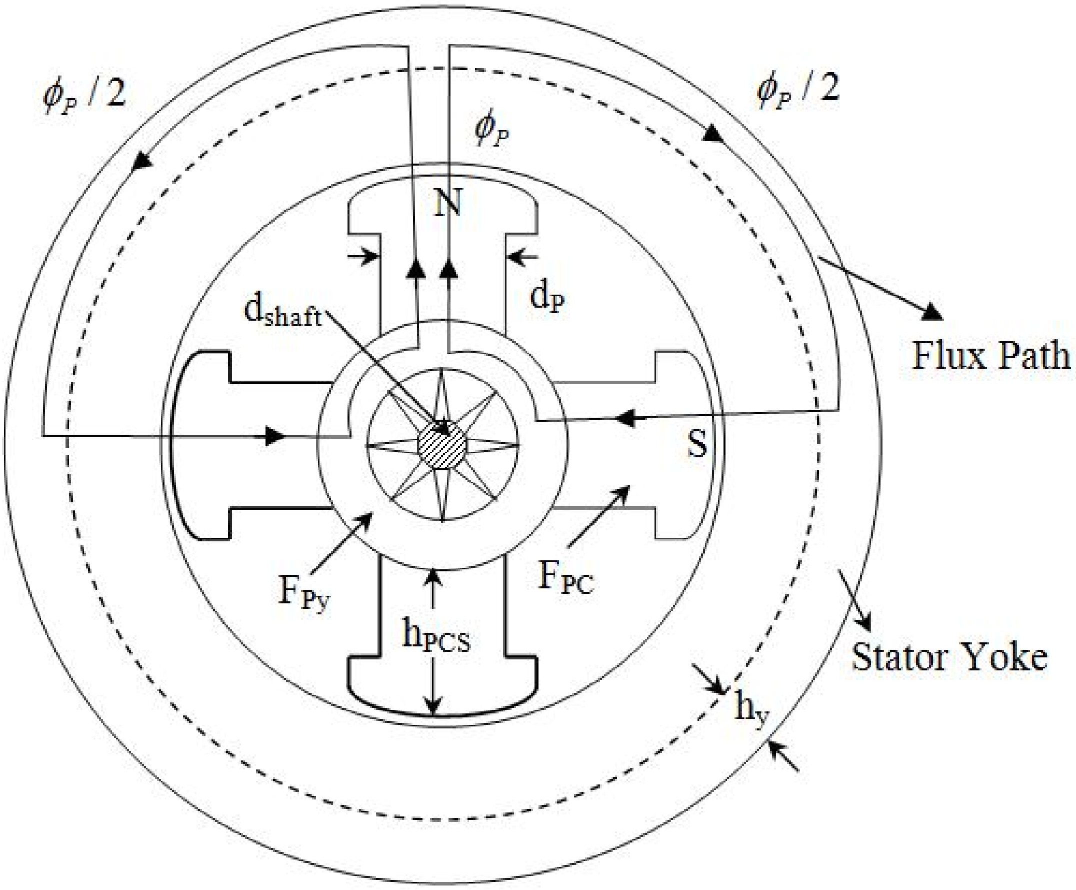
Corresponding to flux density in yoke B_y find out iron loss per Kg from the graph given on page 19, fig 18. $So \quad B_y \Rightarrow p_{iy} \quad W/Kg$

Iron loss in yoke

= p_{iy}* density * volume of iron in yoke
= p_{iy}* 7600 * volume of iron in yoke
$\left(Yoke\ volume = h_Y \times K_i \times l \times \text{®}(D_0 - h_Y)\right)$

Total Stator iron losses P_i = Iron loss in teeth + Iron loss in yoke

ROTOR DESIGN:



1. **Sectional area of pole core(F_{PC}):**

$$\text{¤}_1 = \frac{2}{\text{®}} B_{\text{¢}1} \text{²}_P l_e$$ =Useful flux per pole (average value of fundamental flux)

$$\text{¤}_p = B_{av} \text{²}_P l_e$$ = Actual flux per pole (average value of actual flux)

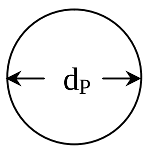
$$\text{¤}_{p(total)} = 1.2\text{¤}_P$$ (Take 20% as leakage flux)

$$F_{PC} = \frac{\text{¤}_{P(total)}}{B_{PC}}$$

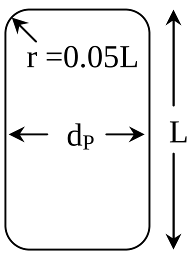
Where B_{PC} = Permissible value of flux density in pole core
= 1.5 to 1.7 T

Diameter corresponding to this area

$$F_{PC} = \frac{\text{®}}{4} d_P^2 \Rightarrow d_P = \sqrt{\frac{4F_{PC}}{\text{®}}}$$



Round Pole



Long (Rectangular) Pole

2. **<u>Sectional are of pole yoke(F_{PY}):</u>**

$$F_{PY} = \frac{\phi_{P(total)}/2}{B_{PY}}$$

Where $\quad B_{PY}$ = Permissible value of flux density in pole yoke
= 1.1 to 1.3 T

3. **<u>Shaft diameter:</u>**

$$d_{shaft} = 0.1\sqrt{\frac{KW}{RPM}} \quad (m)$$

4. **<u>Damper winding design:</u>**

Sectional area of copper in damper bars per pole

$$F_D/Pole = 0.2\frac{\overline{ac} \times 2_P}{\delta_D}$$

(As a thumb rule we provide 20% of stator cu in damper bars)

Where

δ_D = Permissible current density =3 to 4 A/mm^2

No of damper bars

Damper bar slot pitch ≈ 0.8 time the stator slot pitch

$$\Rightarrow N_d = \frac{Pole\ \ Arc}{0.8 \times Stator\ \ Slot\ \ Pitch}$$

5. **<u>Estimation of OCC from design data:</u>** It involves calculation of magnetic circuit (mmf) per pole pair under rated terminal voltage on NO load.

Magnetic circuit for a pole pair consists of

2 air-gaps length
2 stator teeth height
1 stator yoke length
2 rotor pole core and pole shoe length
1 rotor yoke length

MMF required for two air-gaps $(AT_{2\delta'})$**:**

Effective length of air gap

$$\delta' = K_C\delta$$

Where

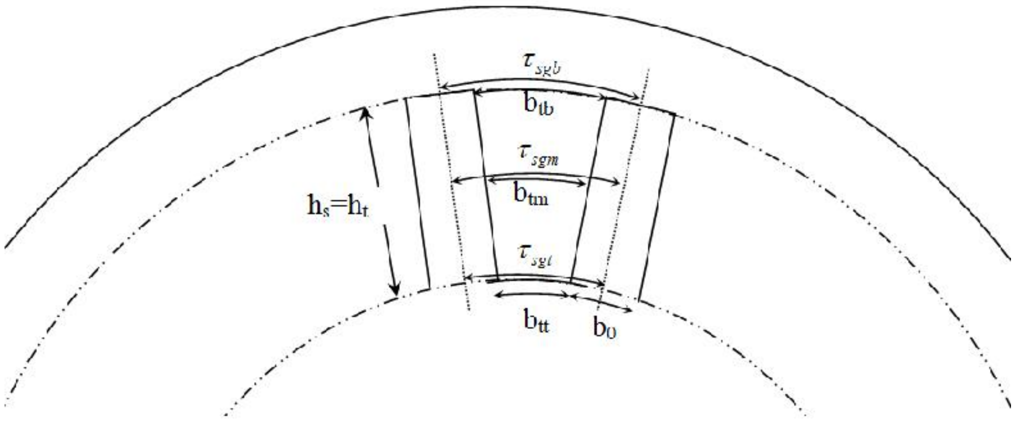
$$K_C = \text{Cartor's gap coefficient } = \frac{2_{sg}}{2_{sg} - r\delta}$$

$$r = \frac{b_0/\delta}{5 + b_0/\delta}$$

We know $H = \frac{1}{\mu_0}B$

So $AT_{2\delta'} = \left(\frac{1}{\mu_0}B\right)2\delta'$

MMF required for 2 teeth heights (AT_{2ht})**:**



Slot pitch at tooth top $\tau_{sgt} = \frac{\pi D}{P}$

Slot pitch at tooth middle $\tau_{sgm} = \frac{\pi (D + h_t)}{P}$

Slot pitch at tooth bottom $\tau_{sgb} = \frac{\pi (D + 2h_t)}{P}$

So

Slot width at tooth top $b_{tt} = \tau_{sgt} - b_0$

Slot width at tooth middle $b_{tm} = \tau_{sgm} - b_0$

Slot width at tooth bottom $b_{tt} = \tau_{sgb} - b_0$

Flux through a slot pitch $\Phi_{\tau_{sg}} = B_{¢m} \tau_{sg} l_e$

So

Flux density at tooth top $B_{tt} = \frac{\Phi_{\tau_{sg}}}{b_{tt} K_i l} \rightarrow at_{tt} \quad (AT/m)$

Flux density at tooth middle $B_{tm} = \frac{\Phi_{\tau_{sg}}}{b_{tm} K_i l} \rightarrow at_{tm} \quad (AT/m)$

Flux density at tooth bottom $B_{tb} = \frac{\Phi_{\tau_{sg}}}{b_{tb} K_i l} \rightarrow at_{tb} \quad (AT/m)$

Note: For calculating the ampere turns per meter corresponding to flux density in stator tooth use figure 14 if $B_t \le 1.7$ and figure 15 if $B_t > 1.7$ of given reference notes.

Average mmf/m for the tooth is given by Simpson's rule

$$at_{ht} = \frac{at_{tt} + 4at_{tm} + at_{tb}}{6}$$

Hence MMF required for 2 teeth heights $AT_{2ht} = at_{ht} \times 2h_t$

MMF required for 1 stator yoke (AT_Y):

$B_y \rightarrow at_y$

So $AT_y = at_{y\times} l_y$

Where

$$l_y = \frac{\text{®}\left(D_0 - h_h\right)}{P} \;\; or \;\; = \frac{\text{®}\left(D + 2h_t + h_y\right)}{P}$$

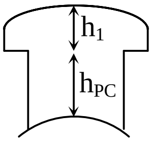
MMF required for 2 pole core and pole shoe (AT_{2PCS}):

$B_P \rightarrow at_{PCS}$

So $\quad AT_{2PCS} = at_{PCS} \times 2h_{PCS}$

Where

$h_{PCS} = h_{PC} + h_1$



MMF required for 1 rotor yoke (AT_{PY}):

$B_{PY} \rightarrow at_{PY}$

So $\quad AT_{PY} = at_{PY} \times l_{PY}$

Where

$$l_{PY} = \frac{\text{®}\left(D - 2\text{¢} - 2h_{PCS} - h_{PY}\right)}{P}$$

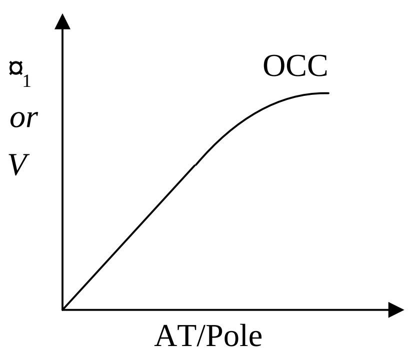
S.No	Part	Length of path	Flux density	at (AT/m)	$AT_{pole\text{-}pair}$
1	Stator Yoke	l_y	B_y	at_y	AT_y
2	Stator Tooth	$2h_{t1}$	$B_{t\frac{1}{3}h_{t1}}$	at_{2ht1}	AT_{2ht1}
3	Air Gap	$2\text{¢}'$	B_{30^0}	$at_{2\text{¢}'}$	$AT_{2\text{¢}'}$
4	Rotor Tooth	$2h_{t2}$	$B_{t\frac{1}{3}h_{t2}}$	at_{2ht2}	AT_{2ht2}
5	Rotor Yoke	l_{ry}	B_{ry}	at_{ry}	AT_{ry}
					$AT_{pole\text{-}pair}$ $= AT_{30} = \sum$

Hence

MMF (AT)/Pole Pair $\quad = \sum ATs = AT_{2\text{¢}'} + AT_{2ht} + AT_Y + AT_{2PCS} + AT_{PY}$

MMF (AT)/Pole $\quad = \dfrac{\sum ATs}{2} = \dfrac{AT_{2\text{¢}'} + AT_{2ht} + AT_Y + AT_{2PCS} + AT_{PY}}{2}$

OCC is graph between terminal voltage at no load and filed mmf per pole i.e. $V\ (or\ \text{¤}_1)\ Vs\ \ AT\,/\,pole$



6. **Estimation of SCC:**

Apply Potier's concept

The excitation required under short circuit donation to circulate rated current consists of two parts

(i) Excitation ΔA required for leakage reactance drop IX_a.

(ii) Excitation (A) required to balance the effect of armature reactance

Total excitation required = $\Delta A + (-A)$

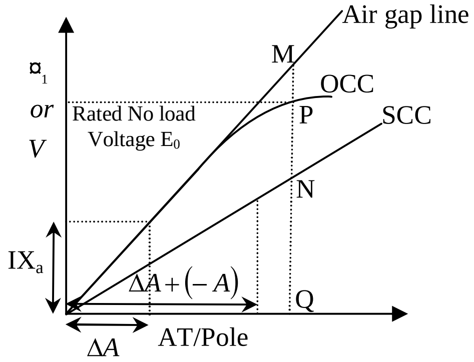
A is given by

$$A = 0.9K_{pd}NI$$

Where N = No of turns for all 3 phases per pole

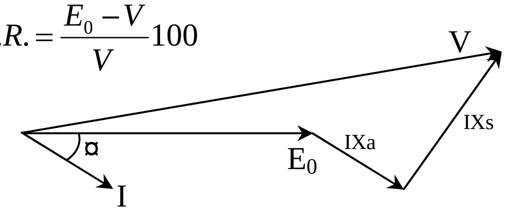
$$N = \frac{3N_{Ph}}{P}$$

So excitation $\Delta A + (-A)$ will circulate rated current under the short circuit condition



7. **Estimation of voltage regulation:**

$$\% \; V.R. = \frac{E_0 - V}{V} 100$$



Phasor Diagram
(Lagging PF)

8. **Design of filed winding:**

- The excitation voltage (V_{dc}) is usually 200 to 600 volts dc.
- About 15% drop is taken in leads and also to provide excess excitation when required.

So

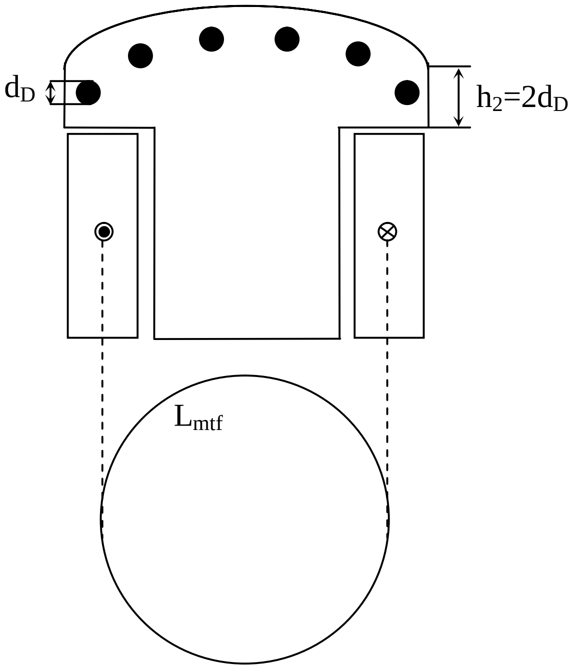
$$0.85V_{dc} = I_f R_{f\,75^0 C} \quad \text{---------- (1)}$$

Where

I_f = Filed current = ¢$_f F_{Cf}$ ---------- (2)

¢$_f$ = Current density in filed winding($3 - 4\ \text{A/mm}^2$)

F_{cf} = Sectional area of field conductor



Pole and filed Winding

$R_{f,75^0C}$ = Filed resistance $= 0.021\times 10^{-6}\dfrac{L_{mtf}N_f}{F_{Cf}}$ ---------- (3)

L_{mtf} = Length of mean turn for field winding

N_f = Total number of field turns

Using equation (2) & (3), equation (1) will become

$$0.85V_{dc} = ¢_f F_{Cf} \times 0.021\times 10^{-6}\frac{L_{mtf}N_f}{F_{Cf}}$$

$$\Rightarrow N_f = \frac{0.85V_{dc}}{0.021\times 10^{-6}¢_f L_{mtf}}$$

Filed current

$$I_f = \frac{AT_{Pole}}{N_{fP}}$$

Where

N_{fP} = No of field turns per pole

Sectional area of filed conductor

$$F_C = \frac{I_f}{¢_f}$$

Note:

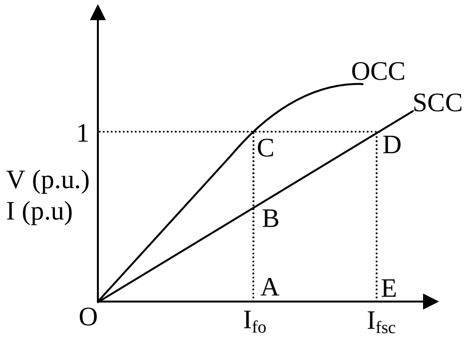
1. Excitation power required

5 KVA to 100 KVA:	2- 5% of the machine rating
50 MVA to 500 MVA:	0.25% to 0.5% of the machine rating

2. Losses and efficiency:
   a. Efficiency of >100 MVA synchronous machine: up to 98.5%

b. Efficiency of >5 MVA synchronous machine: 93% or up to 95%

9. **<u>SCR: Short Circuit Ratio:</u>**



The short circuit ration (SCR) of a synchronous machine is defined as the ratio of filed current required to produce rated voltage on open circuit to filed current required to circulate rated current at short circuit

$$SCR = \frac{I_{fo}}{I_{fsc}} = \frac{OA}{OE}$$

Consider similar triangles ΔOAB and ΔOED

$$SCR = \frac{OA}{OE} = \frac{AB}{ED} = \frac{AB}{AC} = \frac{1}{AC/AB}$$

$$SCR = \frac{1}{pu\ voltage\ on\, open\, circuit/corresponding\ \ pu\, current\ on\ short\ circuit}$$

$$SCR = \frac{1}{X_S}$$

Thus the SCR is the reciprocal of synchronous reactance.

Range of SCR

SCR= 0.5 to 0.9 for turbo alternator

SCR= 0.9 to 1.3 for water wheel alternator

Effect of SCR on performance of alternator:

1. **Stability:** Power developed

$$P_{d,cylindrical} = \frac{E_0 V}{X_s} \sin \delta$$

$$P_{d,salient} = \frac{E_0 V}{X_s} \sin \delta + \frac{V^2}{2} \frac{X_d - X_q}{X_d X_q} \sin 2\delta$$

A machine which can develop more power is more stable.

So lower the value of X_s (or X_d), higher will the stability

$\Rightarrow SCR \uparrow$

2. **Parallel Operation:**

Synchronizing power $\infty \frac{1}{X_s}$

So for higher synchronizing power X_s should be small

$\Rightarrow SCR \uparrow$

3. **Short Circuit Current:**

$$I_{sc} = \frac{V}{X_s}$$

So to limit short circuit current X_s should be high

$\Rightarrow SCR \downarrow$

4. **Voltage Regulation:**

$$E_0 = V + I(R_a + jX_S)$$

$$VR = \frac{E_0 - V}{V}$$

For VR to be low, X_s should be high

$\Rightarrow SCR \uparrow$

5. **Self Excitation:**

Lower the value of Xs, higher will be the current in the filed path due to residual voltage.

$\Rightarrow SCR \uparrow$

Hence

- We see that if SCR is high the machine will have higher stability, better parallel operation, good voltage regulation and more suitable for self excitation.
- The value of X_s is controlled by the length of air gap. By increasing the air gap length we can reduce armature reaction and so decrease synchronous reactance and increase SCR.
- If we increase the air gap, more filed MMF is required and it will result in more cost for the field system.
- For salient pole rotor

  $X_d = X_s$

  $X_q = (0.55 \text{ to } 0.65)\, X_d$