Design of Synchronous Machine

Output Equation

Let

V_{ph} = phase voltage ;

I_{ph} = phase current

Z_{ph} = no of conductors/phase;

T_{ph} = no of turns/phase

N_s = Synchronous speed in rpm;

n_s = synchronous speed in rps

p = no of poles ;

ac = Specific electric loading

Φ= air gap flux/pole;

B_{av} = Average flux density

K_w = winding factor ;

D = Diameter of the stator;

L = Gross core length

C_o = Output coefficient;

Output of the 3 phase synchronous generator is given by

Output of the machine $Q = 3V_{ph} I_{ph} \times 10^{-3}$ kVA

Assuming Induced emf $E_{ph} = V_{ph}$

Output of the machine $Q = 3E_{ph} I_{ph} \times 10^{-3}$ kVA

Induced emf $E_{ph} = 4.44 f \Phi T_{ph} K_w$

$= 2.22 f \Phi Z_{ph} K_w$

Frequency of generated emf $f = PN_S/120 = Pn_s/2$,

$P\Phi = B_{av}\,\pi DL$, and $\quad 3I_{ph}\,Z_{ph}/\,\pi\,D = ac$

$Q = 3*\,2.22*Pn_s/2*\,\Phi Z_{ph}\,K_w\,I_{ph} * 10^{-3}$ kVA

Output to motor $= 1.11 * B_{av}\,\pi\,D\,L * \pi\,D\,ac * n_s\,K_w\,10^{-3}$ kVA

$$Q = (1.11\,\pi^2\,B_{av}\,ac\,K_w\,10^{-3})\,D^2\,L\,n_s \text{ kVA}$$

$$Q = (11\,B_{av}\;ac\;K_w\;10^{-3})\,D^2\,L\,n_s \text{ kVA}$$

Therefore Output $Q = C_o\,D^2\,L\,n_s$ kVA

where $Co = (11\,B_{av}\,ac\,K_w\,10^{-3})$ = Output coefficient

Choice of Specific loadings: From the output equation it is seen that choice of higher value of specific magnetic and electric loading leads to reduced cost and size of the machine.

Specific magnetic loading: Following are the factors which influences the performance of the machine.

(i) *Iron loss:* A high value of flux density in the air gap leads to higher value of flux in the iron parts of the machine which results in increased iron losses and reduced efficiency.

(ii) *Voltage:* When the machine is designed for higher voltage space occupied by the insulation becomes more thus making the teeth smaller and hence lower value of gap density should be used.

(iii) *Transient short circuit current:* A high value of gap density results in decrease in leakage reactance and hence increased value of armature current under short circuit conditions.

(iv) *Stability:* The maximum power output of a machine under steady state condition is inversely proportional to synchronous reactance. If higher value of flux density is used it leads to smaller number of turns per phase in armature winding. This results in reduced value of leakage reactance and hence increased value of power and hence increased steady state stability.

(v) *Parallel operation:* The satisfactory parallel operation of synchronous generators depends on the synchronizing power. Higher the synchronizing power higher will be the ability of the machine to operate in synchronism. The synchronizing power is inversely proportional to the synchronous reactance and hence the machines designed with higher value air gap flux density will have better ability to operate in parallel with other machines.

Following are the usual B_{av} assumed

Cylindrical rotor machine : 0.55 to 0.65 wb/m^2

Salient pole machine : 0.50 to 0.65 wb/m^2

Specific Electric Loading: Following are the some of the factors which influence the choice of specific electric loadings.

(i) *Copper loss*: Higher the value of ‘ac’, larger will be the number of armature conductors which results in higher copper loss. This will result in higher temperature rise and reduction in efficiency.

(ii) *Voltage:* A higher value of ‘ac’ can be used for low voltage machines since the space required for the insulation will be smaller.

(iii) *Synchronous reactance*: High value of ‘ac’ leads to higher value of leakage reactance and armature reaction and hence higher value of synchronous reactance. Such machines will have poor voltage regulation, lower value of current under short circuit condition and low value of steady state stability limit and small value of synchronizing power.

iv) *Stray load losses*: With increased value of ‘ac’ stray load losses will increase.

The usual values of ‘ac’:

Turbo machines : 50000 to 100000 amp-cond/m

Salient pole machines : 20000 to 50000 amp-cond/m

Salient Pole Machine: In case of salient pole machines either round or rectangular pole construction is employed. In these types of machines the diameter of the machine will be quite larger than the axial length.

Round Poles: The ratio of pole arc to pole pitch may be assumed varying between 0.6 to 0.7 and pole arc may be taken as approximately equal to axial length of the stator core. Hence

$$\text{Axial length of the core/ pole pitch} = L/\tau_p = 0.6 \text{ to } 0.7$$

Rectangular poles: The ratio of axial length to pole pitch may be assumed varying between 0.8 to 3 and a suitable value may be assumed based on the design specifications.

$$\text{Axial length of the core/ pole pitch} = L/\tau_p = 0.8 \text{ to } 3$$

Using the above relations D and L can be separated. However once these values are obtained diameter of the machine must satisfy the limiting value of peripheral speed so that the rotor can withstand centrifugal forces produced.

Limiting values of peripheral speeds are as follows:

Bolted pole construction = 50 m/s

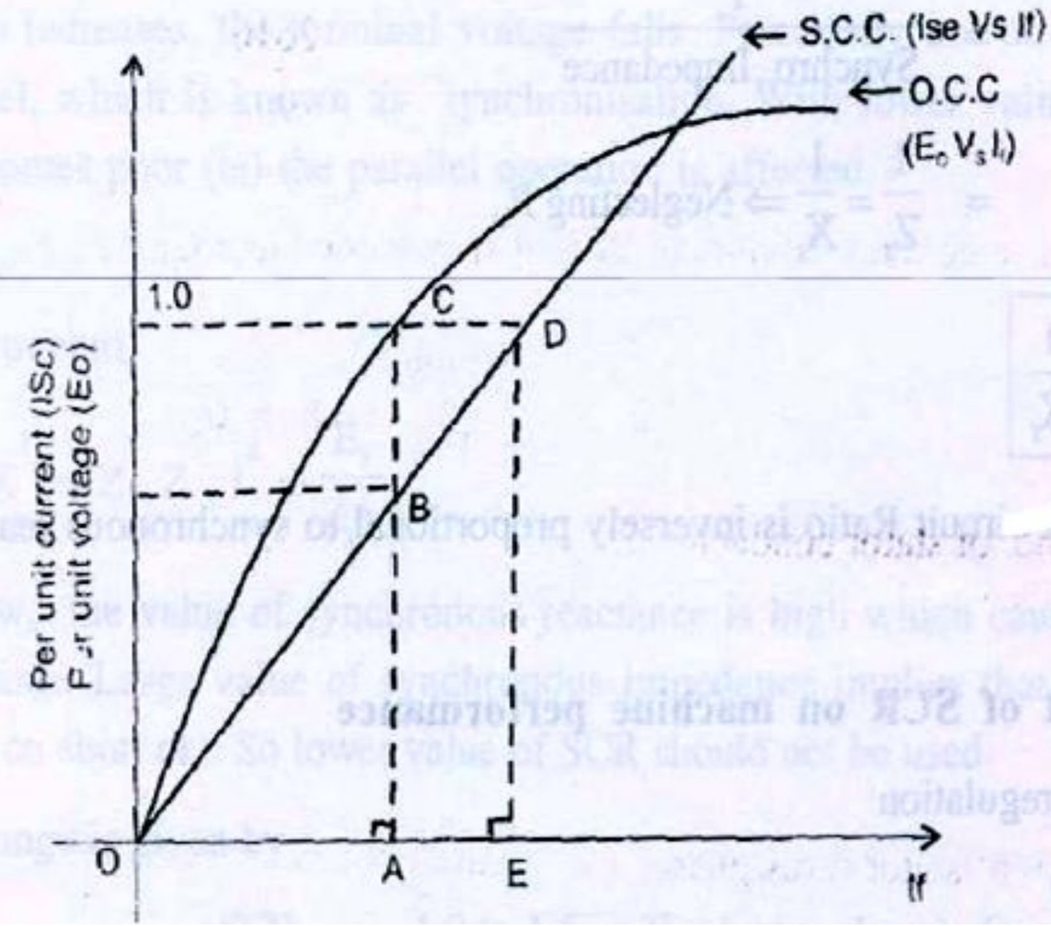
Dove tail pole construction = 80 m/s

Normal design = 30 m/s

Turbo alternators: These alternators will have larger speed of the order of 3000 rpm. Hence the diameter of the machine will be smaller than the axial length. As such the diameter of the rotor is limited from the consideration of permissible peripheral speed limit. Hence the internal diameter of the stator is normally calculated based on peripheral speed. Peripheral speed for these alternators must be below 175 m/s.

Short Circuit Ratio

It is defined as the ratio of field current required to produce rated voltage on open circuit to the field current reqd. to circulate rated current on short circuit.



Explanation

The fig shows open Circuit and short Circuit characteristics of an alternator.

According to definition,

$$\boxed{SCR = \frac{OA}{OE}}$$

Triangles OAB and OED are similar

$$\text{Since} \quad \angle OAB = \angle OED$$

$$\angle OBA = \angle ODE$$

$$\angle AOB = \angle EOD$$

$$\text{Now,} \; \frac{OA}{OE} = \frac{AB}{ED} = \frac{OB}{OD}$$

$$\therefore SCR = \frac{AB}{ED}$$

$$= \frac{AB}{AC} \Rightarrow \frac{1}{\left(\frac{AC}{AB}\right)} \Rightarrow \frac{1}{\frac{\text{open ckt voltage}}{\text{short ckt. current}}}$$

$$= \frac{1}{\text{Synchro Impedance}}$$

$$= \frac{1}{Z_s} = \frac{1}{X_s} \Rightarrow \text{Neglecting } R_a$$

Effect of SCR on Machine performance

1. Voltage regulation
2. Stability
3. Parallel operation
4. Short circuit Current

Voltage regulation:- A high value of SCR means that the synchronous reactance has a low value resulting in to good voltage regulation.

Stability:- A machine with high value of SCR. i.e. lower value of X_d, will lead to higher synchronizing power and thus giving a higher stability limit.

Parallel operation:- A machine with low value of SCR means a large value of X_d giving a small value of synchronizing power. Such a machine have problem during parallel operation.

Short circuit current:- A small value of SCR means a large value of X_d which will limit the short circuit current during fault conditions.

For salient pole machines SCR value varies from 0.9 to 1.3

For turbo alternators SCR value varies from 0.7 to 1.1

Length of the air gap: Length of the air gap is a very important parameter as it greatly affects the performance of the machine. Air gap in synchronous machine affects the value of SCR and hence it influences many other parameters. Hence, choice of air gap length is very critical in case of synchronous machines.

Following are the advantages and disadvantages of larger air gap.

Advantages:

(i) Stability: Higher value of stability limit

(ii) Regulation: Smaller value of inherent regulation

(iii) Synchronizing power: Higher value of synchronizing power

(iv) Cooling: Better cooling

(v) Noise: Reduction in noise

(vi) Magnetic pull: Smaller value of unbalanced magnetic pull

Disadvantages:

(i) Field mmf: Larger value of field mmf is required

(ii) Size: Larger diameter and hence larger size

(iii) Magnetic leakage: Increased magnetic leakage

(iv)Weight of copper: Higher weight of copper in the field winding

(v) Cost: Increase over all cost.

The approximate value of air gap length can be expressed in terms of pole pitch.

For salient pole alternators: lg = (0.012 to 0.016) x pole pitch

For turbo alternators: lg = (0.02 to 0.026) x pole pitch

Synchronous machines are generally designed with larger air gap length compared to that of Induction motors.

Estimation of length of air gap:

Length of the air gap is usually estimated based on the ampere turns required for the air gap.

Armature ampere turns per pole required

$$AT_a = 1.35\ I_{ph}\ T_{ph}\ K_w / p$$

Where T_{ph} = Turns per phase, I_{ph} = Phase current,

K_w = winding factor, p = pairs of poles

No load field ampere turns per pole

AT_{fo} = SCR x Armature ampere turns per pole

AT_{fo} = SCR x At_a

Ampere turns required for the air gap will be approximately equal to 80% of the no load field ampere turns per pole.

Mmf for air gap is also equal to $800000 B_g K_g l_g$

$$0.8\ AT_{fo} = 800000\ B_g K_g l_g$$

$$l_g = 0.8\ AT_{fo} / 800000\ B_g K_g$$

Selection of number of slots:

Following factors are considered for selection of number of slots.

Balanced winding:- The number of slots are so selected that a balanced 3-phase winding is obtained. Unbalance winding will leads to generation of space harmonics and over heating.

Tooth flux density:- selection of large number of slots will lead to narrower teeth resulting in to increased tooth flux density beyond permissible limits.

Leakage reactance:- With less number of slots, the conductors are nearer leading to increased leakage flux and thereby increased leakage reactance.

Tooth ripples:- With large number of slots tooth ripples and therefore pulsation loss decreases.

Temperature rise and cost:- Selection of too small a number of slots will lead to crowding of conductors, disturbance in air circulation and hence developing high internal temperature. Also, smaller number of slots result in saving in labour because of less number of coils to wind, insulate, place in to slots and connect.

Considering all the above points number of slots per pole phase for salient pole machines may be taken as 3 to 4 and for turbo alternators it may be selected as 7 to 9 slots per pole per phase.

Slot pitch must be with in the following limitations

(i) Low voltage machines $\leq$ 2.5 cm

(ii) Medium voltage machines up to 6kV $\leq$ 4.0 cm

(iv) High voltage machines up to 15 kV $\leq$ 6.0 cm

Turns per phase:

Turns per phase can be calculated from emf equation of the alternator.

$$\text{Induced emf } E_{ph} = 4.44\, f\, \Phi\, T_{ph} K_w$$

$$\text{Hence turns per phase } T_{ph} = Eph / 4.44\, f\, \Phi K_w$$

E_{ph} = induced emf per phase

Z_{ph} = no of conductors/phase in stator

T_{ph} = no of turns/phase

k_w = winding factor may assumed as 0.955

Conductor section:

$$\text{Current per phase} = (\text{kVA} \times 1000)/\ 3^*\ E_{ph}$$

The conductor current $I_z = I_{ph}$, when all the turns per phase are connected in series.

But $I_z = I_{ph}/A$, if there are 'A' number of parallel paths per phase.

Sectional area of the stator conductor $a_s = I_s / \delta_s$ where δ_s is the current density in stator windings and I_s is stator current per phase. A suitable value of current density has to be assumed considering the advantages and disadvantages.

Advantages of higher value of current density:

(i) reduction in cross section

(ii) reduction in weight

(iii) reduction in cost

Disadvantages of higher value of current density

(i) increase in resistance

(ii) increase in cu loss

(iii) increase in temperature rise

(iv) reduction in efficiency

Hence higher value is assumed for low voltage machines and small machines. Usual value of current density for stator windings is 3 to 5 amps/mm^2.

Stator slot dimensions: Because parallel sided slots are used the teeth are tapered having minimum width at the gap surface. The flux density in teeth at the air gap surface at no load does not exceed about 1.7 to 1.8 wb/m^2 .

$$w_{t(\min)} = \frac{\emptyset}{\psi \frac{S_s}{p} L_i * 1.8}$$

Where ψ = ratio of pole arc to pole pitch

The depth of the slot d_s is now determined by the space requirement for copper and insulation. The depth of slot is normally about 3 times the width.

The length of mean turn:

$L_{mt} = 2L + 2.5\ \tau_p + 0.06\ kV + 0.2\ m$

Design of field system - Salient pole rotor

Dimension of the pole:

(i) ***Axial Length of the pole***: Axial length of the pole may be assumed 1 to 1.5 cm less than that of the stator core.

(ii) ***Width of the pole***: Leakage factor for the pole is assumed varying between 1.1 to 1.15.

Thus the flux in the pole body = 1.1 to 1.15 Φ

Area of the pole = Flux in the pole body/ Flux density in the pole body.

Flux density in the pole body is assumed between 1.4 to 1.6 wb/m^2.

Area of the pole = width of the pole x net axial length of the pole.

Net axial length of the pole = gross length x stacking factor

Stacking factor may be assumed as 0.93 to 0.95.

Hence width of the pole = Area of the pole / net axial length of the pole.

(iii) ***Height of the pole***:

Height of the pole is decided based on the mmf to be provided on the pole by the field winding at full load. Hence it is required to find out the mmf to be provided on the pole at full load before finding the height of the pole. Full load field ampere turns required for the pole can be calculated based on the armature ampere turns per pole.

Hence full load field ampere turns per pole can be assumed 1.7 to 2.0 times the armature ampere turns per pole.

Armature ampere turns per pole $AT_a = 1.35\ I_{ph}\ T_{ph}\ K_w\ /p$

And

$AT_{fl} = (1.7 \text{ to } 2.0)\ AT_a$

Height of the pole is calculated based on the height of the filed coil required and the insulation.

Height of the filed coil:

I_f = current in the field coil; a_f = area of the field conductor

T_f = number of turns in the field coil; R_f = resistance of the field coil

l_{mt} = length of the mean turn of the field coil

s_f = copper space factor; h_f = height of the field coil

d_f = depth of the field coil

p_f = permissible loss per m^2 of the cooling surface of the field coil

ρ = specific resistance of copper

qf = heat generated per unit volume

Watts radiated from the field coil = External surface in cm^2 x watts/cm^2

= External periphery of the field coil x Height of the field coil x watts/cm^2

Total loss in the coil = $(I_f^{\,2} \text{ x } R_f) = (I_f^2 \text{ x } \rho \text{ x } l_{mt} \text{ x } T_f / a_f)$

Total copper area in the field coil = $a_f \text{ x } T_f = s_f h_f d_f$

Hence $a_f = s_f d_f h_f / T_f$

Thus watts lost per coil = $(I_f^2 \text{ x}\rho \text{ x } l_{mt} \text{ x } T_f) T_f / s_f h_f d_f$

$= (I_f T_f)^2 \text{ x } l_{mt} / s_f h_f d_f$

Loss dissipated form the field coil = q_f x cooling surface of the field coil

Normally inner and outer surface of the coils are effective in dissipating the heat. The heat dissipated from the top and bottom surfaces are negligible.

Cooling surface of the field coil = $2 \text{ x } l_{mt} \text{ x } h_f$

Hence loss dissipated from the field coil = $2 \text{ x } l_{mt} \text{ x } h_f \text{x } q_f$

For the temperature rise to be with in limitations

Watts lost per coil = watts radiated from the coil

$(I_f T_f)^2 \rho \times l_{mt} / s_f h_f d_f = 2 \times l_{mt} \times h_f \times q_f$

Hence $h_f = (I_f T_f) / [10^4 \times \sqrt{(sf\ df\ qf)}]$

$= AT_{fl} \times 10^{-4} / (s_f d_f q_f)$

Depth of the field coil is assumed from 3 to 5 cm,

Copper space factor may be assumed as 0.6 to 0.8,

Loss per m^2 may be assumed as 700 to 750 w/m^2

Hence the height of the pole =

$= h_f$ + height of the pole shoe + height taken by insulation

Design of field winding

(i) Generally the exciter voltage will be in the range of 110 volts to 440 volts. 15-20 % of voltage is kept as drop across the field controller.

Hence voltage per coil Vc = (0.8 to 0.85) exciter voltage / Number of field coils

(ii) Assume suitable value for the depth of the field coil

(iii) Mean length of the turn in field coil is estimated from the dimensions of the pole and the depth of the field windings. Mean length of the turn = $2(l_p + b_p) + \pi(d_f + 2t_i)$ where t_i is the thickness of insulation on the pole.

(iv) Sectional area of the conductor can be calculated as follows

Resistance of the field coil $R_f = \rho \times l_{mt} \times T_f / a_f$ = voltage across the coil/ field coil

$$V_c / I_f = \rho \times l_{mt} \times T_f / a_f$$

Hence $a_f = \rho \times l_{mt} \times I_f T_f / V_c$

(v) Field current can be estimated by assuming a suitable value of current density in the field winding. Generally the value of current density may be taken as 3.5 to 4 amp/mm^2.

Hence $I_f = \delta_f \times a_f$

(vi) Number of turns in the field winding

$$T_f = \text{Full load field ampere turns / field current}$$

$$= AT_{fl} / I_f$$

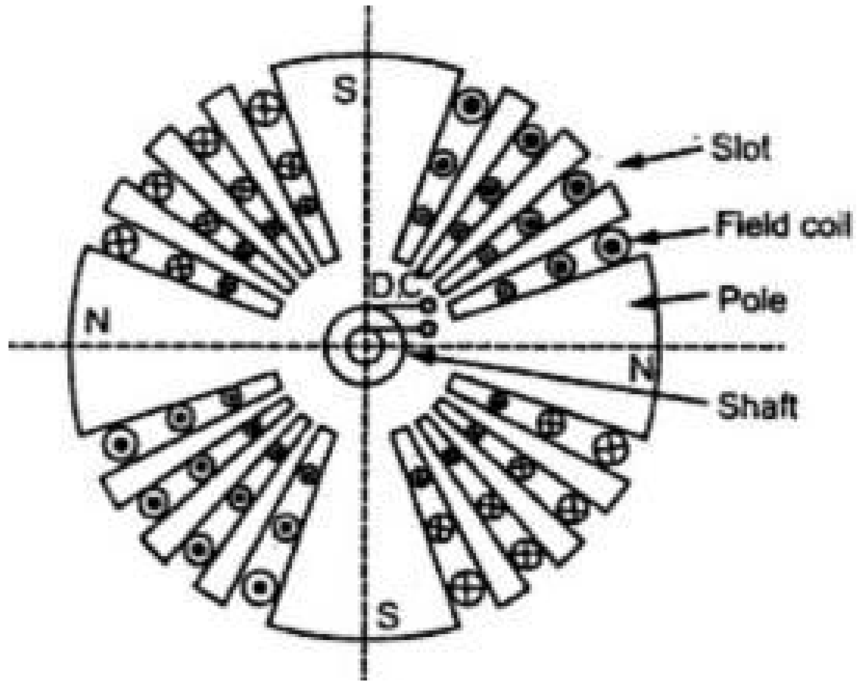
(vii) Height of the field winding $h_f = AT_{fl} \times 10^{-4} / \sqrt{(sf\ df\ qf)}$

(viii) Resistance of the field winding $R_f = \rho \times l_{mt} \times T_f / a_f$

(ix) Copper loss in the field winding $= If^2 \times R_f$

Design of the field System: Non-Salient pole Alternator

In case of turbo alternators, the rotor windings or the field windings are distributed in the rotor slots.



Normally 70% of the rotor is slotted and remaining portion is unslotted in order to form the pole.

The design of the field can be explained as follows.

(i) ***Selection of rotor slots***: Total number of rotor slots may be assumed as 50 – 70 % of stator slots pitch. However the rotor slots must satisfy the following conditions in order to avoid the undesirable effects of harmonics in the flux density wave forms.

(a) There should be no common factor between the number of rotor slot pitches and number of stator slot pitches.

(b) Number of rotor slots should be divisible by 4 for a 2 pole synchronous machine. That means the number of rotor slots must be multiple of 4.

(c) Width of the rotor slot is limited by the stresses developed at the rotor teeth and end rings.

(ii) Design of rotor winding

(a) Full load field mmf can be taken as twice the armature mmf.

$AT_{fl} = 2 \times AT_a = 2 \times 1.35 \times I_{ph} \times T_{ph} \times k_w /p$

(b) Standard exciter voltage of 110 - 220 volts may be taken. With 15-20 % of this may be reserved for field control. Hence voltage across each field coil Vf = (0.8 to 0.85) V/p

(c) Length of the mean turn $l_{mt} = 2L + 1.8\ \tau_p + 0.25$ m

(d) Sectional area of each conductor $a_f = \rho \times l_{mt} \times (I_f \times T_f) / v_f$

(e) Assume suitable value of current density in the rotor winding. 2.5 – 3.0 amp/mm^2 for conventionally cooled machines and 8 – 12 amp/mm^2 for large and special cooled machines.

(f) Find area of all the rotor conductors per pole = $2 \times (I_f \times T_f)/\delta_f$

(g) Find the number of rotor conductors per pole

$$= 2 \text{ x } (I_f \text{ x } T_f) \,/\, (\delta_f \text{ x } a_f)$$

(h) Number of field conductors per slot

$$= 2 \text{ x } (I_f \text{ x } T_f) \,/\, (\delta_f \text{ x } a_f \text{ x } s_r),$$

where s_r is the number of rotor slots.

(i) Resistance of each field coil $R_f = \rho \text{ x } l_{mt} \text{ x } T_f \,/\, a_f$

(j) Calculate the current in the field coil If = v_f / R_f