Design of Synchronous Machines

Introduction

Synchronous machines are AC machines that have a field circuit supplied by an external DC source. Synchronous machines are having two major parts namely stationary part stator and a rotating field system called rotor.

In a synchronous generator, a DC current is applied to the rotor winding producing a rotor magnetic field. The rotor is then driven by external means producing a rotating magnetic field, which induces a 3-phase voltage within the stator winding.

Field windings are the windings producing the main magnetic field (rotor windings for synchronous machines); armature windings are the windings where the main voltage is induced (stator windings for synchronous machines).

Types of synchronous machines

1. Hydrogenerators : The generators which are driven by hydraulic turbines are called hydrogenerators. These are run at lower speeds less than 1000 rpm.
2. Turbogenerators: These are the generators driven by steam turbines. These generators are run at very high speed of 1500rpm or above.
3. Engine driven Generators: These are driven by IC engines. These are run at aspeed less than 1500 rpm.

Hence the prime movers for the synchronous generators are Hydraulic turbines, Steam turbines or IC engines.

Hydraulic Turbines: Pelton wheel Turbines: Water head 400 m and above
                    Francis turbines: Water heads up to 380 m
                    Keplan Turbines: Water heads up to 50 m

Steam turbines: The synchronous generators run by steam turbines are called turbogenerators or turbo alternators. Steam turbines are to be run at very high speed to get higher efficiency and hence these types of generators are run at higher speeds. Diesel Engines: IC engines are used as prime movers for very small rated generators.

Construction of synchronous machines

1. Salient pole Machines: These type of machines have salient pole or projecting poles with concentrated field windings. This type of construction is for the machines which are driven by hydraulic turbines or Diesel engines.
2. Nonsalient pole or Cylindrical rotor or Round rotor Machines: These machines are having cylindrical smooth rotor construction with distributed field winding in slots. This type of rotor construction is employed for the machine driven by steam turbines.

1. Construction of Hydro-generators: These types of machines are constructed based on the water head available and hence these machines are low speed machines. These machines are constructed based on the mechanical consideration. For the given frequency the low speed demands large number of poles and consequently large

diameter. The machine should be so connected such that it permits the machine to be transported to the site. It is a normal to practice to design the rotor to withstand the centrifugal force and stress produced at twice the normal operating speed.
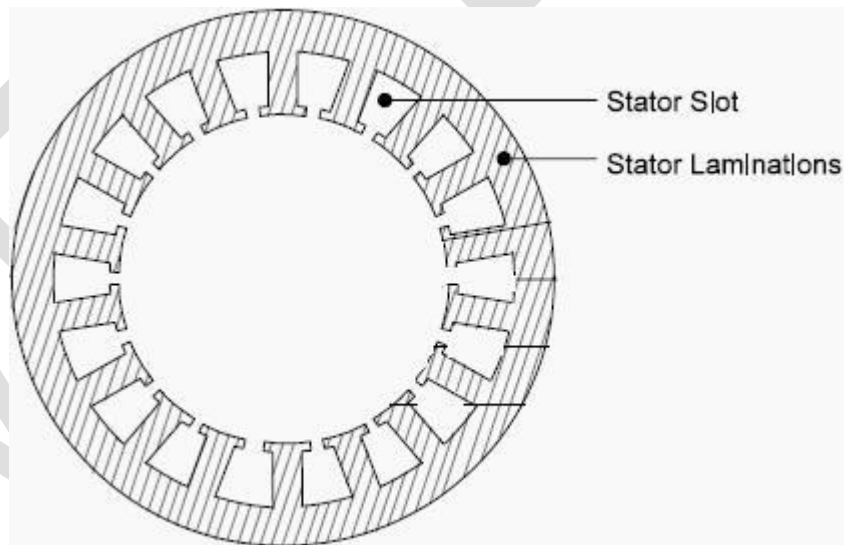
Stator core:

The stator is the outer stationary part of the machine, which consists of

- The outer cylindrical frame called yoke**,** which is made either of welded sheet steel, cast iron.
- The magnetic path**,** which comprises a set of slotted steel laminations called stator core pressed into the cylindrical space inside the outer frame. The magnetic path is laminated to reduce eddy currents, reducing losses and heating. CRGO laminations of 0.5 mm thickness are used to reduce the iron losses.

A set of insulated electrical windings are placed inside the slots of the laminated stator. The cross-sectional area of these windings must be large enough for the power rating of the machine. For a 3-phase generator, 3 sets of windings are required, one for each phase connected in star. Fig. 1 shows one stator lamination of a synchronous generator. In case of generators where the diameter is too large stator lamination can not be punched in on circular piece. In such cases the laminations are punched in segments. A number of segments are assembled together to form one circular laminations. All the laminations are insulated from each other by a thin layer of varnish.

Details of construction of stator are shown in Figs 2 -

. Stator lamination
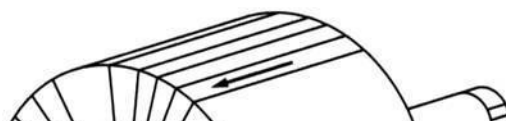
Rotor of a Non salient pole alternator

Rotor of water wheel generator consists of salient poles. Poles are built with thin silicon steel laminations of 0.5mm to 0.8 mm thickness to reduce eddy current laminations. The laminations are clamped by heavy end plates and secured by studs or rivets. For low speed rotors poles have the bolted on construction for the machines with little higher peripheral speed poles have dove tailed construction as shown in Figs. Generally rectangular or round pole constructions are used for such type of alternators. However the round poles have the advantages over rectangular poles.

Generators driven by water wheel turbines are of either horizontal or vertical shaft type. Generators with fairly higher speeds are built with horizontal shaft and the generators with higher power ratings and low speeds are built with vertical shaft design. Vertical shaft generators are of two types of designs (i) Umbrella type where in the bearing is mounted below the rotor. (ii) Suspended type where in the bearing is mounted above the rotor.

In case of turbo alternator the rotors are manufactured form solid steel forging. The rotor is slotted to accommodate the field winding. Normally two third of the rotor periphery is slotted to accommodate the winding and the remaining one third unslotted portion acts as the pole. Rectangular slots with tapering teeth are milled in the rotor. Generally rectangular aluminum or copper strips are employed for filed windings. The field windings and the overhangs of the field windings are secured in place by steel retaining rings to protect against high centrifugal forces. Hard composition insulation materials are used in the slots which can with stand high forces, stresses and temperatures. Perfect balancing of the rotor is done for such type of rotors.

Damper windings are provided in the pole faces of salient pole alternators. Damper windings are nothing but the copper or aluminum bars housed in the slots of the pole faces. The ends of the damper bars are short circuited at the ends by short circuiting rings similar to end rings as in the case of squirrel cage rotors. These damper windings are serving the function of providing mechanical balance; provide damping effect, reduce the effect of over voltages and damp out hunting in case of alternators. In case of synchronous motors they act as rotor bars and help in self starting of the motor.

Relative dimensions of Turbo and water wheel alternators:

Turbo alternators are normally designed with two poles with a speed of 3000 rpm for a 50 Hz frequency. Hence peripheral speed is very high. As the diameter is proportional to the peripheral speed, the diameter of the high speed machines has to be kept low. For a given volume of the machine when the diameter is kept low the axial length of the machine increases. Hence a turbo alternator will have small diameter and large axial length.

However in case of water wheel generators the speed will be low and hence number of poles required will be large. This will indirectly increase the diameter of the machine. Hence for a given volume of the machine the length of the machine reduces. Hence the water wheel generators will have large diameter and small axial length in contrast to turbo alternators.

Introduction to Design
Synchronous machines are designed to obtain the following informations.
- (i) Main dimensions of the stator frame.
- (ii) Complete details of the stator windings.
- (iii) Design details of the rotor and rotor winding.
- (iv) Performance details of the machine.

To proceed with the design and arrive at the design information the design engineer needs the following information.
- (i) Specifications of the synchronous machine.
- (ii) Information regarding the choice of design parameters.
- (iii) Knowledge on the availability of the materials.
- (iv) Limiting values of performance parameters.
- (v) Details of Design equations.

Specifications of the synchronous machine:
Important specifications required to initiate the design procedure are as follows:

Rated output of the machine in kVA or MVA, Rated voltage of the machine in kV, Speed, frequency, type of the machine generator or motor, Type of rotor salient pole or non salient pole, connection of stator winding, limit of temperature, details of prime mover etc.

Main Dimensions:
Internal diameter and gross length of the stator forms the main dimensions of the machine. In order to obtain the main dimensions it is required to develop the relation between the output and the main dimensions of the machine. This relation is known as the output equation.

Output Equation:
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 $E_{ph} = 4.44 f \Phi T_{ph} K_{W}$

$\qquad = 2.22 f \Phi Z_{ph} K_{W}$

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

Air gap flux per pole $\Phi = B_{av}\pi DL/p$, and Specific electric loading $q = 3I_{ph} Z_{ph}/ \pi D$

Output of the machine $Q = 3 \times (2.22 \times Pn_s/2 \times B_{av}\pi DL/p \times Z_{ph} \times K_w) I_{ph} \times 10^{-3}$ kVA

Output $Q = (1.11 \times B_{av}\pi DL \times n_s \times K_w)(3 \times I_{ph}Z_{ph}) \times 10^{-3}$ kVA

Substituting the expressions for Specific electric loadings

Output $Q = (1.11 \times B_{av}\pi DL \times n_s \times K_w)(\pi D q) \times 10^{-3}$ kVA

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

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

Therefore Output $Q = C_O D^2 L n_s$ kVA

$$\text{or } D^2L = Q/C_o n_s \text{ m}^3$$

where $C_o = (11 B_{av} q K_w \times 10^{-3})$

V_{ph} = phase voltage ; I_{ph} = phase current E_{ph} = induced emf per phase

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

T_{ph} = no of turns/phase

N_S = Synchronous speed in rpm

n_s = synchronous speed in rps

p = no of poles, q = Specific electric loading

Φ = air gap flux/pole; B_{av} = Average flux

density k_w = winding factor

From the output equation of the machine it can be seen that the volume of the machine is directly proportional to the output of the machine and inversely proportional to the speed of the machine. The machines having higher speed will have reduced size and cost. Larger values of specific loadings smaller will be the size of the machine.

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 higher flux density in teeth and core.

(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 indirectly 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.

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 q larger will be the number of armature of conductors which results in higher copper loss. This will result in higher temperature rise and reduction in efficiency.

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

(iii)   Synchronous reactance: High value of q 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 increase of q stray load losses will increase.

Values of specific magnetic and specific electric loading can be selected from Design Data Hand Book for salient and nonsalient pole machines.

Separation of D and L: Inner diameter and gross length of the stator can be calculated from D^2L product obtained from the output equation. To separate suitable relations are assumed between D and L depending upon the type of the generator.

Salient pole machines: 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

Axial length of the core/ pole pitch = L/τ_p = 0.6 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 = 45 m/s
Dove tail pole construction = 75 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. The peripheral speed in case of turbo alternators is much higher than the salient pole machines. Peripheral speed for these alternators must be below 175 m/s.

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.
Hence length of the air gap must be selected considering the above factors.

Calculation 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 $AT_a = 1.35\ T_{ph}k_w\ /p$

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

$$AT_{fo} = SCR\ x\ AT_a$$

Suitable value of SCR must be assumed.

Ampere turns required for the air gap will be approximately equal to 70 to 75 % of the no load field ampere turns per pole.

$$AT_g = (0.7\ to\ 0.75)\ AT_{fo}$$

Air gap ampere turns $AT_g = 796000\ B_gk_gl_g$

Air gap coefficient or air gap contraction factor may be assumed varying from 1.12 to 1.18.

As a guide line, the approximate value of air gap length can be expressed in terms of pole pitch

For salient pole alternators: l_g = (0.012 to 0.016) x pole pitch
For turbo alternators: l_g = (0.02 to 0.026) x pole pitch
Synchronous machines are generally designed with larger air gap length compared to that of Induction motors.

Design of stator winding:

Stator winding is made up of former wound coils of high conductivity copper of diamond shape. These windings must be properly arranged such that the induced emf in all the phases of the coils must have the same magnitude and frequency. These emfs must have same wave shape and be displaced by 120^0 to each other. Single or double layer windings may be used depending on the requirement. The three phase windings of the synchronous machines are always connected in star with neutral earthed. Star connection of windings eliminates the 3rd harmonics from the line emf.

Double layer winding: Stator windings of alternators are generally double layer lap windings either integral slot or fractional slot windings. Full pitched or short chorded windings may be employed. Following are the advantages and disadvantages of double layer windings. Advantages:

(i)   Better waveform: by using short pitched coil
(ii)   Saving in copper: Length of the overhang is reduced by using short pitched coils
(iii)   Lower cost of coils: saving in copper leads to reduction in cost
(iv)   Fractional slot windings: Only in double layer winding, leads to improvement in waveform Disadvantages:
(i)   Difficulty in repair: difficult to repair lower layer coils
(ii)   Difficulty in inserting the last coil: Difficulty in inserting the last coil of the windings
(iii)   Higher Insulation: More insulation is required for double layer winding
(iv)   Wider slot opening: increased air gap reluctance and noise

Number of Slots:
The number of slots are to be properly selected because the number of slots affect the cost and performance of the machine. There are no rules for selecting the number of slots. But looking into the advantages and disadvantages of higher number of slots, suitable number of slots per pole per phase is selected. However the following points are to be considered for the selection of number of slots.
(a)
Advantages:
(i)   Reduced leakage reactance
(ii)   Better cooling
(iii)   Decreased tooth ripples

Disadvantages:
(i)   Higher cost
(ii)   Teeth becomes mechanically weak
(iii)   Higher flux density in teeth

(b) Slot loading must be less than 1500 ac/slot

(c) Slot pitch must be with in the following limitations
(i)   Low voltage machines ≤ 3.5 cm
(ii)   Medium voltage machines up to 6kV ≤ 5.5 cm
(iv)   High voltage machines up to 15 kV ≤ 7.5 cm

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 much higher of the order of 7 to 9 slots per pole per phase In case of fractional slot windings number of slots per pole per phase may be selected as fraction 3.5.

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

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

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

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 cross section: Area of cross section of stator conductors can be estimated from the stator current per phase and suitably assumed value of current density for the stator windings.

Sectional area of the stator conductor $a_S = I_S / \delta_S$ where δ_S is the current density in stator windings

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 coils:

Two types of coils are employed in the stator windings of alternators. They are single turn bar coils and multi turn coils. Comparisons of the two types of coils are as follows

(i)   Multi turn coil winding allows greater flexibility in the choice of number of slots than single turn bar coils.
(ii)   Multi turn coils are former wound or machine wound where as the single turn coils are hand made.
(iii)   Bending of top coils is involved in multi turn coils where as such bends are not required in single turn coils.
(iv)   Replacing of multi turn coils difficult compared to single turn coils.
(v)   Machine made multi turn coils are cheaper than hand made single turn coils.
(vi)   End connection of multi turn coils are easier than soldering of single turn coils.
(vii)   Full transposition of the strands of the single turn coils are required to eliminate the eddy current loss.
(viii)   Each turn of the multi turn winding is to be properly insulated thus increasing the amount of insulation and reducing the space available for the copper in the slot.

From the above discussion it can be concluded that multi turn coils are to be used to reduce the cost of the machine. In case of large generators where the stator current exceeds 1500 amps single turn coils are employed.

Single turn bar windings:

The cross section of the conductors is quite large because of larger current. Hence in order to eliminate the eddy current loss in the conductors, stator conductors are to be stranded. Each slot of the stator conductor consists of two stranded conductors. The dimensions of individual strands are selected based on electrical considerations and the manufacturing requirements. Normally the width of the strands is assumed between 4 mm to 7 mm. The depth of the strands is limited based on the consideration of eddy current losses and hence it should not exceed 3mm. The various strand of the bar are transposed in such a way as to minimize the circulating current loss.

Multi turn coils:

Multi turn coils are former wound. These coils are made up of insulated high conductivity copper conductors. Mica paper tape insulations are provided for the portion of coils in the slot and varnished mica tape or cotton tape insulation is provide on the over hang portion. The thickness of insulation is decided based on the voltage rating of the machine. Multi turn coils are usually arranged in double layer windings in slots.

Dimensions of stator slot:

Width of the slot = slot pitch – tooth width

The flux density in the stator tooth should not exceed 1.8 to 2.0 Tesla. In salient pole alternators internal diameter is quite large and hence the flux density along the depth of the tooth does not vary appreciably. Hence width of the tooth may be estimated corresponding to the permissible flux density at the middle section of the tooth. The flux density should not exceed 1.8 Tesla. However in case of turbo alternators variation of flux density along the depth of the slot is appreciable and hence the width of the tooth may be estimated corresponding to the flux density at the top section of the tooth or the width of the tooth at the air gap. The flux density at this section should not exceed 1.8 Tesla.

For salient pole alternator:

Flux density at the middle section =
Flux / pole /(width of the tooth at the middle section x iron length x number of teeth per pole arc)
Number of teeth per pole arc = pole arc/slot pitch

For turbo alternators:
Flux density at the top section =
Flux / pole /(width of the tooth at the top section x iron length x number of teeth per pole pitch)
As the $2/3^{rd}$ pole pitch is slotted the number of teeth per pole pitch =
2/3 x pole pitch/(slot pitch at top section)
Slot width = slot pitch at the top section – tooth width at the top section.
Once the width of the slot is estimated the insulation required width wise and the space available for conductor width wise can be estimated.

Slot insulation width wise:
(i)   Conductor insulation
(ii)   Mica slot liner
(iii)   Binding tape over the coil
(iv)   Tolerance or clearance

Space available for the conductor width wise = width of the slot – insulation width wise
We have already calculated the area of cross section of the conductor. Using above data on space available for the conductor width wise depth of the conductor can be estimated. Now the depth of the slot may be estimated as follows.

Depth of the slot:
(i)   Space occupied by the conductor = depth of each conductor x no. of conductor per slot
(ii)   Conductor insulation
(iii)   Mica slot liner
(iv)   Mica or bituminous layers to separate the insulated conductors
(v)   Coil separator between the layers
(vi)   Wedge
(vii)   Lip
(viii)   Tolerance or clearance

Mean length of the Turn:

The length of the mean turn depends on the following factors

(i)   Gross length of the stator core: Each turn consists of two times the gross length of stator core.
(ii)   Pole pitch: The over hang portion of the coils depend upon the coil span which in turn depends upon the pole pitch.
(iii) Voltage of the machine: The insulated conductor coming out of the stator slot should have straight length beyond the stator core which depends upon the voltage rating of the machine.
(iv)   Slot dimension: Length per turn depends on the average size of the slot.

Hence mean length of the turn in double layer windings of synchronous machines is estimated as follows.

$$l_{mt} = 2l + 2.5 \tau_p + 5\, kV + 15 \text{ cm}$$

Design of the field System: Salient pole Alternator:

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

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

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
ζ = specific resistance of copper

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 = $(I_f^2$ x $R_f) = ($ I_f^2 x ζ x l_{mt} x T_f / $a_f)$
Total copper area in the field coil = a_f 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 x ζ x l_{mt} x T_f $)$ T_f / s_f h_f

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

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 x l_{mt} x h_f

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

For the temperature rise to be with in limitations

Watts lost per coil = watts radiated from the coil

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

Hence $h_f = (I_f\ T_f) / [\ 10^4$ x $\sqrt{(s_f\ d_f\ q_f)}]$
$= AT_{fl}$ x $10^{-4}/ \sqrt{(s_f\ d_f\ q_f)}$

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 for salient pole Alternator:

Design of the field winding is to obtain the following information.

(i)   Cross sectional area of the conductor of field winding

(ii)   Current in field winding

   (iii)   Number of turns in field winding
   (iv)   Arrangement of turns
   (v)   Resistance of the field winding
   (vi)   Copper loss in the field winding

Above informations can be obtained following the following steps

(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 V_c = (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 $R_f = \zeta \times l_{mt} \times T_f / a_f$ = voltage across the coil/ field coil

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

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

(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.

(vi)   Number of turns in the field winding T_f = Full load field ampere turns / field current = AT_{fl} / I_f

(vii)   Height of the field winding $h_f = AT_{fl} \times 10^{-4} / \sqrt{(s_f d_f q_f)}$

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

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

Design of the field System: NonSalient pole Alternator:

In case of turbo alternators, the rotor windings or the field windings are distributed in the rotor slots. The rotor construction of the turbo alternator is as shown in fig. below.
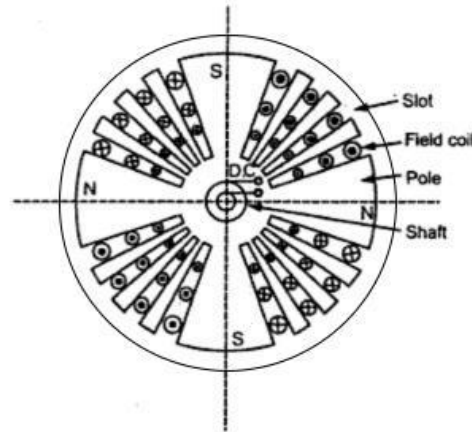
Normally 70% of the rotor is slotted and remaining portion is unslotted in order to form the pole. The design of the field can be explained as follows.

(i) Selection of rotor slots: Total number of rotor slots may be assumed as 50 – 70 % of stator slots pitches. However the so found 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 wound 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 $V_f = (0.8 \text{ to } 0.85) \, V/p$

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

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

(e) Assume suitable value of current density in the rotor winding. $2.5 – 3.0 \text{ amp/mm}^2$ for conventionally cooled machines and $8 – 12 \text{ amp/mm}^2$ 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 $= 2 \times (I_f \times T_f) / (\delta_f \times a_f)$

(h) Number of field conductors per slot $= 2 \times (I_f \times T_f) / (\delta_f \times a_f \times s_r)$, where s_r is the number of rotor slots.

(i) Resistance of each field coil $R_f = \zeta \times l_{mt} \times T_f / a_f$

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

Based on the above data dimensions may be fixed. The ratio of slot depth to slot width may be taken between 4 and 5. Enough insulation has to be provided such that it with stands large amount of mechanical stress and the forces coming on the rotor.

The following insulation may be provided for the field coil.
(i)   All field conductors are provided with mica tape insulation.

(ii)   Various turns in the slots are separated from each other by 0.3 mm mica separators.
(iii)   0.5 mm hard mica cell is provided on all the field coil.
(iv)   Over the above insulation, 1.5 mm flexible mica insulation is provided.
(v)   Lastly a steel cell of o.6 mm is provided on the whole field coil.

(iv)   Field current: Resistance of the field coil $R_f = \zeta \times l_{mt} \times T_f / a_f$
$$= 0.021 \times 7.31 \times 224/ 84$$
$$= 0.41$$

Current in the field winding $I_f = V_c/ R_f = 90/0.41 = 219$ Amps.