DESIGN AND ANALYSIS OF SYNCHRONOUS MACHINE (ALTERNATOR)

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING
(Electrical Power Systems)

By

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CERTIFICATE

This is to certify that the Major Project Report entitled **"Design And Analysis Of Synchronous Machine (Alternator)"** submitted by **Mr.Prashant Kanaiyalal Bhavsar (10MEEE02)**, towards the partial fulfillment of the requirements for the award of degree in Master of Technology (Electrical Engineering) in the field of Electrical Power Systems of Nirma University is the record of work carried out by him under my supervision and guidance. The work submitted has in my opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of my knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

Today most of the electrical power in the world is generated by synchronous machine (alternator). Regarding to cost, durability, stability and security; a design of synchronous machine is very important. The reliability of power system and quality of power can also be improved by improving the performance. The performance can be improved by proper design of synchronous machine. Various constrains like processes, availability of magnetic material, quality aspects and cost aspects are considered during the manufacturing of the synchronous machine. By using advance technology and power of the computer software, the design and performance of the synchronous machine is improved. In practical design, a number of designed parameter of the machine is so high such that hand calculation is so tough and takes a long time. To satisfy all constrain and get realistic design, an iterative approach is required.This can be done by computer programming. Flowcharts for analytical calculations of design parameters are developed for computer programming. The selection of magnetic material decides the iron losses of synchronous machine and hence, it is an important parameter by which efficiency can be improved. Synchronous machine is designed with the different number of stator slots to getting optimum and realistic design by comparing with the manufacturing company. After getting the optimum and realistic design, the designed parameters are implemented to the MAGNET software(V.6.16) for finite element analysis. Static, time harmonic and transient analysis are carried out by MAGNET software. Further,design is verified by the matching the analytically calculated parameters with the result of MAGNET software. Reactance of the synchronous machine under the various condition are calculated by the result of MAGNET software.

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Abbreviations

EMF .... Electro Motive Force
FEM .... Finite Element Method
MMF .... Magneto Motive Force
OCC .... Open Circuit Charasteristic
SCR .... Short Circuit Ratio
TEL .... Total Electric Loading
TML .... Total Magnetic Loading

Nomenclature

B_{av}	Average Value of Flux Density	[$\frac{Wb}{m^2}$]
D	Armature Diameter	[M]
E	Back EMF	[V]
E_{ph}	Induced EMF Per Phase	[V]
I_a	Armature Current	[A]
I_{ph}	Current Per Phase	[A]
I_z	Current in Each Conductor	[A]
K_w	Winding Factor	[ ]
P	Rating of machine	[kW]
P_a	Power Developed by Armature	[kW]
N_s	Speed	[R.P.M]
T_{ph}	Turn Per Phase	[]
L	Stator Core Length	[M]
Q	Rating of machine	[KVA]
a	Number of Parallel Paths	[ ]
ac	Ampere Conductor	[A/M]
f	Frequency	[Hz]
m	Number of Phases	[ ]
p	No of Poles	[ ]
τ	Pole Pitch	[mm]

Suffixes

av	av-Average value
d	d- Direct axis
ph	ph-Phase value
q	q- Quadrature axis

Contents

Chapter 1

Introduction

1.1 Introduction

A synchronous machine is an A.C. rotating machine whose speed under steady state condition is depends on the frequency of armature current and number of field poles. So rotating machine that rotates at the speed according to the supply frequency and the number of poles are called synchronous machine and speed at which they rotate is called synchronous speed. The magnetic field created by the armature currents rotates at the same speed as that created by the field current on the rotor, which is rotating at the synchronous speed, and a steady torque as results.

$$N_S = \frac{120 \times f}{p} \tag{1.1}$$

where,

N_S=synchronous speed of the rotor in R.P.M
f=frequency in hertz (Hz)
p=no of poles
Synchronous machines are commonly used as generators especially for large power

systems,such as turbine generators and hydroelectric generators in the grid power supply. A.C. generator are generally know as alternators.They are also know as synchronous generator,and are universal employed for the generation of the three phase power. Alternator may have either rotating field poles and stationary armature or rotating armature and stationary field poles.

A 3-ϕ synchronous machine is doubly excited A.C machine. The field winding is always energized by a D.C source. The armature winding of synchronous generator supplies A.C power to the external circuit. The rotor of synchronous generator is being rotated with help of prime mover.

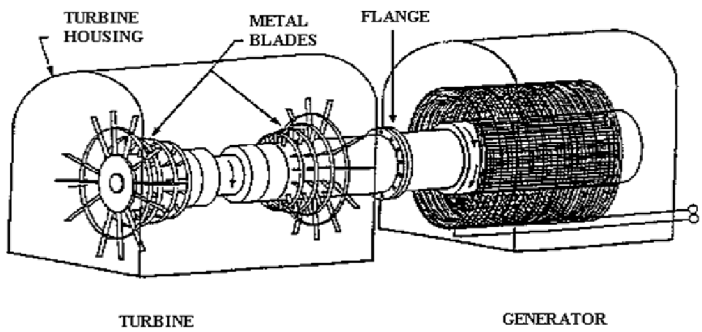


Figure 1.1: Turbine Generator Set

1.2 Structure of Synchronous Machine

The armature winding of a conventional synchronous machine is almost invariably on the stator and is usually a three phase winding. The field winding is usually on the rotor and excited by D.C current, or permanent magnets. The D.C power supply required for Excitation usually is supplied through a D.C generator known as exciter, which is often mounted on the same shaft as the synchronous machine. Various excitation systems using A.C exciter and solid state rectifiers are used with large turbine generators.

There are two types of rotor structures, salient pole rotor and round or cylindrical rotor. As illustrated schematically in the diagram below. Generally,round rotor structure is used for high speed synchronous machines,such as steam turbine generators,while salient pole Structure is used for low speed applications, such as hydroelectric generators. The pictures below show the stator and rotor of a hydroelectric generator and the rotor of a turbine Generator.

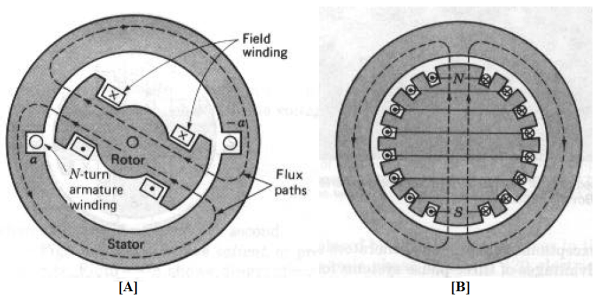


Figure 1.2: [A] Salient pole Rotor , [B] Cylindrical Rotor

1.3 Objective of Project

The project work is aimed at analytical design of synchronous machine of typical ratings by computer programming with due verification from manufacturer. Further, the analytical results of design parameters are need to be compared with simulated results of Finite Analysis carried out using software package-MAGNET. After assured preliminary design, scope of realistic design is also targeted by considering different number of stator slots.

1.4 Problem Identification

During designing of synchronous generator, for higher output power rating the requirement of magnetic loading and electric loading is higher. When increasing the loading of the machine for the same output power the dimension (diameter and length) are decreasing, so cost of the machine is decrease, but during design of synchronous machine the cost is not only important because by increasing the electrical loading of the machine copper cost is increased and copper loss was also increased so heating in the generator is more and problem of cooling is occur to maintain the temperature rise in within limit. Also efficiency is decreasing with increasing in losses. High voltage synchronous generator high electrostatic stress between the stator terminal and stator winding so require thicker and higher class of insulation between the conductor and its layer with maintain the eddy current loss factor should within limit. Mainly problem is occurring during the design to select the proper value of magnetic and electric loading of machine to get optimum and realistic design.

1.5 Planning of The Project Work

- Know the concept of project.
- Literature survey.
- Problem identification
- Manually design
- Develop flowcharts and computer program for the analytical calculation.
- Compare with actual design of manufacturing company
- Modified the design and get realistic design
- Implementation of designed parameter on FEM (Finite Element Method) software (MAGNET V 6.16)
- Analysis of the designed machine and compare the analytical designed parameter with the MAGNET software results.

1.6 Outline of Thesis

Chapter.1 introduce the synchronous machine by its structure and rotating speed of the machine. This chapter also contains the objective of the project work, problem occurring at the starting of the design and planning of the project work.

Chapter.2 containing the literature serve which gives the idea about the current trend in the design of turbo alternator and application of advance technology to improve the performance and operation of the synchronous machine.

Chapter.3 gives the relation between the size of synchronous machine and the out pot power rating of the machine. It also gives the idea for the selection of magnetic loading and electrical loading of the synchronous machine, which helps to starting the design of synchronous machine.

Chapter.4 contains various flow chart for the various parameter calculation and this flow chart gives the basic idea to make computer program for the analytical calculation.

Chapter.5 gives the detail of stator and rotor winding through which current flow in the distributed winding and alternating voltage is available at the armature terminal.

Chapter.6 gives basic of the FEM and MAGNET software. It also contain the creation of model of synchronous machine and result of the FEM analysis. Here the design is verified by comparing the analytical design and the FEM results.

Chapter.7 gives the conclusion and future scope for the project.

Chapter 2

Literature Survey

PAPER[1]:- In this paper present most economical design of turbo alternator by choosing high speed wit smallest diameter and maximum ratio of length/diameter is approximately nearly equal to 6:1. The weight and dimensions of largest 2-pole rotor are such that reliable forging can be secured, but in the case of large 4-pole rotor, in excess of 100 MVA, it is considered necessary by most firm to build the three or more single forging.

Insulation properties affecting the design whether it is use for stator or rotor. If it is used for stator, dielectric properties are the most important, particularly in the view of high electrostatic stress and while it is used for the rotor due to centrifugal forces of rotor necessitate of good mechanical properties. Thermal considerations are equaled important for both stator and rotor.

According to the development describe in this paper result has been a reduction in size of generator and increases the efficiency. In 1922 the efficiency of 20 MW generators was 95% and in 1926 are increases to the 96%. Today of the order of 97% with hydrogen cooling.

PAPER[2]:- This paper represents the overall design criteria. The output power of the alternator is given by P=K·V·B·A·N Where, K= constant,V=active volume of the machine,B=flux density in Wb/m^2,A=stator current in ampere, N=rotational speed. The active volume and rotational speed are determined by mechanical consideration. Such as the turbine design, critical speed and strength of the material when these are reached to the maximum limit, the output power only increases by increasing the flux density, but flux density is directly proportional to the losses. This paper comparing the iron loss of grain oriented silicon steel and non oriented silicon steel and get result losses in the grain oriented silicon steel is less with higher flux density compare to the non oriented silicon steel. The thermal properties of the grain oriented silicon steel are also important. The heat generated by the loss must be conducted away to the surface, which are cold and temperature gradients must be low enough to ensure that the maximum temperature is not high. So material would have higher thermal conductivity and low conductivity.

The magnetic material require for stator of large alternator for public and private utilities will continue to require soft magnetic material.The demand will be 0.3 to 0.35 tons/MW of installed capacity with a present world annual growth in electricity of over 9% will require $5 * 10^6$ tons of material by the end of the century.

PAPER[3]:- In generator rotor winding having a often shorted turn occurs, it expand to the several failure such as vibration increases performance reduction and power limitation by deteriorating winding insulation of the generator rotor. This paper represent the application of flux sensor and is placed at the stator winding. Recently adopted flux sensor method of diagnosing generator rotor shorted turn, it shows voltage waveform induced by flux probe sensor permanently installed in generator stator winding, if there is shorted turn in rotor the induced voltage at the sensor decreases because the current path is shorted and then density of magnetic field become weak. This voltage wave form can be seen by flux sensor connected to data acquisition system through Ethernet or communication port to display on the computer screen. It is also indicate the number of turns of the rotor at which it is shorted circuited.

PAPER [4]:- In this paper hybrid excitation synchronous generator which can operate constant voltage over wide range of speed is describe. It has same stator structure as general synchronous generator, but the rotor of generator has two part (1) permanent magnet part and (2) electrically excited part. The output voltage can be kept constant by regulating the magnetic field of the electrically excited part when the speed is varied. The magnetic field can change easily by adjusting the excitation current of the auxiliary electrically excited part to keep the output voltage constant when the speed of generator is varied. This type of generator which can maintain constant output voltage in a wide speed range. It has small voltage regulation, wide load adaption and a strong overload capacity. It improves the quality of supply and reliability of the power supply system.

PAPER [5]:- This paper represent with the help of phasor diagram of the electrical magnetic potential in cylindrical rotor of synchronous generator. The mathematical model of synchronous generator introduces and development the relationship between the temperature of stator end region, active power, reactive power and armature voltage.

$$P^2 + (Q + \frac{b}{2a})^2 = \frac{\Delta T}{a} \tag{2.1}$$

where,

P=Active power

Q=Reactive power

Δ T= Difference between normal operating temperature and temperature rise a, b are the constant

Keep the output reactive power and cooling condition of turbine generator unchanged the temperature of end region will increase, so active power output should be increases in order to cause the overheating of stator end region.

PAPER[6]:- This paper present the facts of how such a engineering problem at Heysham-2 nuclear power station namely the cracking of 660 MW generator rotor and how this problem being solved. Investigation of cracked rotors evaluated that the mechanism of initial cracking was fretting fatigue between the pole slot filler blocks and the slot wall. The initial crack growth was associated by the two filler blocks adjacent to the crack being pressed against the slot wall by magnetic forces. Once the crack had grown to be 6-12 mm deep, it continue to grow during normal operation of machine due to tensile axial stress and the stress due to self weight bending.
It was decided that fretting could be eliminated by insulating the steel filler blocks from the slot wall. It is now hoped that the area of generator rotor cracking is at an end.

PAPER[7]:- The recent high growth of power of computer system and development of the software to solve complicated problems made it possible to use precise method of calculation in electric machinery to obtain magnetic field analysis As the bases of permeance network method (Tooth Counter Method). TCM gives fast calculation of magnetic circuit and therefore high performance calculation of steady state and dynamic characteristic and transient analysis. This feature allows TCM to be used in CAD system. In this paper represent the basic of TCM and TURBO TCM software.
The main advantage of this approach is good compromise between the accuracy of field calculation and the computing time. The TCM represent one approach of permeance network. It is based on a theoretically validated representation of the total magnetic field in the air gap as the sum of local magnetic fields of the particular element, so called tooth counter method. The software has been designed to perform both calculations in dynamic and steady state modes. The input data of the software are alternator specification, stator and rotor size, stator and rotor number of slots and

characteristic of the material. Based on that information, the software automatically generates the parameterized magnetic equivalent circuit, electric circuit and the coupling equation. The first results of the simulation were compared and validated with those of the experimental for no load case. The comparison show good correspondence between the calculation results and the experimental data. Good compromise between accuracy and commutating time, this open the way to optimal design of turbo alternator.

PAPER[8]:-This paper represents calculation of various reactance of synchronous machine under the saturated and unsaturated condition of magnetic material. The calculation of steady-state,transient and sub-transient reactance by using both magnetostatic and time harmonic simulation with help of magnet software based on finite element analysis. The result obtained by using FEM are compared to the measured values from the test carried out by the manufacture. The discrepancy between the computed and measured value is in the 10 % range. This paper also represents the calculation of direct-axis synchronous reactance and quadrature-axis synchronous reactance under the steady-state, transient and sub-transient condition.

Chapter 3

Design Concepts

The purpose of this section is to try to relate the rating of rotating machine to their main dimensions. A few general equations are developed which are applicable to all type of rotating machines, i.e, D.C. machine, induction machine, synchronous machine. However, it may be emphasized here that design is a complex process and many factor which affect design of different types of machine cannot be incorporated into a set of few general equation.Some design concepts and constraints are being introduce.

3.1 Relation Between Rating and Dimensions of Rotating Machine

Consider an m phase machine having one circuit(parallel path) per phase,
kVA rating of machine is given by;
Q=Number of phase×Output voltage per phase×Current per phase×m

$$Q = m \cdot E_{ph} \cdot I_{ph} \cdot 10^{-3} \tag{3.1}$$

Terminal voltage of each may be taken equal to the induced EMF per phase,
We have,

Induced EMF per phase is given by;

$$E_{ph} = 4.44 \cdot f \cdot \Phi \cdot T_{ph} \cdot K_w \tag{3.2}$$

$$Q = 4.44 \cdot f \cdot \Phi \cdot T_{ph} \cdot K_w \cdot I_{ph} \cdot 10^{-3} \tag{3.3}$$

There fore we can write,

$$Q = m \cdot 4.44 \cdot \frac{p \cdot N_s}{2} \cdot \Phi \cdot T_{ph} \cdot K_w \cdot I_{ph} \cdot 10^{-3} \tag{3.4}$$

$$Q = 1.11 \cdot K_w \cdot (p \cdot \Phi) \cdot 2 \cdot m \cdot I_{ph} \cdot T_{ph} \cdot N_s \cdot 10^{-3} \tag{3.5}$$

Now current in each conductor,I_z=I_{ph}

Total No. of armature conductors is given by;

$$Z = Numberofphases \cdot (2 \cdot Turnperphase) = 2 \cdot m \cdot T_{ph} \tag{3.6}$$

Therefore

$$TEL = I_z \cdot Z = 2 \cdot m \cdot I_{ph} \cdot T_{ph} \tag{3.7}$$

$$TML = (p \cdot \Phi) \tag{3.8}$$

Hence,

$$Q = 1.11 \cdot K_w \cdot (p \cdot \Phi) \cdot (I_z \cdot Z) \cdot N_s \cdot 10^{-3} \tag{3.9}$$

$$Q = 1.11 \cdot K_w \cdot (TML) \cdot (TEL) \cdot (n_s) \cdot 10^{-3} \tag{3.10}$$

but,

$$p \cdot \Phi = \pi \cdot D \cdot L \cdot B_{av} \tag{3.11}$$

$$I_z \cdot Z = \pi \cdot D \cdot ac \tag{3.12}$$

now substituting the equation.3.11 and 3.12 are substituting in equation.(3.9)

$$Q = 1.11 \cdot K_w \cdot (\pi \cdot D \cdot L \cdot B_{av}) \cdot (\pi \cdot D \cdot ac) \cdot N_s \cdot 10^{-3} \tag{3.13}$$

$$Q = (1.11 \cdot \pi^2 \cdot B_{av} \cdot ac \cdot K_w \cdot 10^{-3}) \cdot D^2 \cdot L \cdot N_s \tag{3.14}$$

$$Q = (11 \cdot B_{av} \cdot ac \cdot K_w \cdot 10^{-3}) \cdot D^2 \cdot L \cdot N_s \tag{3.15}$$

$$Q = C_0 \cdot D^2 \cdot L \cdot N_s \tag{3.16}$$

Where,

$$C_0 = 11 \cdot B_{av} \cdot ac \cdot K_w \cdot 10^{-3} \tag{3.17}$$

Equation.3.16 is known as the output Equation of A.C machine and equation.3.17 represent C_0 is called output co-efficient.[9]

3.2 Factor Affecting to the Size of Rotating Machine

From above derivation the product of D^2 L will decrease with increase of speed and/or increases the output co-efficient. The volume of active parts of the rotating machine is $\frac{\pi}{4}$*D^2*L and therefore the volume of active parts and hence the size and cost of machine decreases with increases in speed and/or in the value of output co-efficient.

1].Speed:- It is clearly from the equation.3.16, that the volume of active parts is varies inversely proportional to the speed. Thus for the same output of machine designed with greater speed will have smaller size and hence lesser cost compared to a machine designed with low speed. Therefore, whenever a choice has to be made highest practical speed rating should be selected.

2]. Output Co-efficient:- From equation.3.16 we gather that the volume of active part is inversely proportional to the value of output co-efficient. Thus an increase in the value of output coefficient result in reduction in size and cost of machine and so looking from the economic point of view the value of output co-efficient should be as high as possible.

3.3 Choice of Specific Magnetic Loading

Factor affecting to the choice of magnetic loading

1].Iron Loss:- A high value of flux density in air gap leads to a high value flux density in stator core and teeth, resulting high iron loss with consequent decreases in efficiency and increases in temperature rise.

2].Voltage:- In case of machine designed for high voltage, space required for the insulation is greater and small space is left for teeth. Therefore, lower value of flux density should be used in high voltage machine to avoid the excessive value of flux density in the stator teeth and core.

3].Transient Short Circuit Current:- A high value of gap density results in decrease in the leakage reactance of the machine with increase in initial value of armature under short circuit condition. Therefore, low value of gap density should be used to limit the initial electromagnetic forces under short circuit condition.

4].Stability:- The maximum power which a cylindrical rotor machine can deliver under steady state condition is $P_{max}=\frac{E*V}{X_S}$ where, E is the excitation voltage, V is the terminal voltage and X_S is the synchronous reactance. Therefore, the maximum power or steady state stability limit of a machine is inversely proportional to its synchronous reactance. If a high value of gap density is used, the flux per pole is large and therefore a smaller number of turn is required for armature winding. This result in reduction in the value of synchronous reactance. Therefore a high value of gap density should be used to improve the steady state stability limit.

5].Parallel Operation:- All synchronous generator, expect those required to feed isolated loads, are connected in parallel with the other synchronous generator. The satisfactory parallel operation of synchronous generator is dependent on the synchronizing power, higher this power, the higher the capability to keep the machine in synchronism. The synchronizing power is inversely proportional to the synchronous reactance and therefore machine designed with high value of gap density to operate satisfactory in parallel.

Following are the normal range of gap density (magnetic loading)
Turbo alternator 0.54 to 0.65 $\frac{Wb}{m^2}$
Salient pole machine 0.52 to 0.65 $\frac{Wb}{m^2}$[9]
Take a lower value for small size machine.

3.4 Choice of Electric Loading

Factor affecting to the choice of specific electric loading
1].Copper Loss and Temperature Rise:- A high value of ac gives higher copper loss resulting in lower efficiency and higher temperature rise. The values of ac used depend upon the cooling techniques employed. Higher value of ac is used in machine which employs cooling techniques that effectively dissipate the generated heat.

2].Voltage:- A higher value of ac can be used for low voltage machine since the space required for the insulation is small.

3].Synchronous reactance:- The value of ac affects the leakage reactance and armature reaction of the machine. A high value ac leads to high value of leakage reactance and armature reaction and consequently higher value of the synchronous reactance. Therefore machine designed with a high value of ac will have 1) poor inherent voltage regulation, 2) low current under the short circuit condition and therefore many large unit especially turbo alternator are designed with high value of ac in order that they may be able to withstand momentary short circuit without mechanical injury and 3) low value for steady state stability limit and small synchronizing power and consequently leads to instability.

4].Stray load Loss:- The stray load losses increase steeply with increasing the value of ac.

Following are the normal range of electric loading (ac)
Turbo alternator 50,000 to 75,000 $\frac{A}{M}$
Salient pole machine 20,000 to 40,000 $\frac{A}{M}$[9]

3.5 Effect of S.C.R. on Machine Performance

1]Voltage Regulation:- Low value of S.C.R means a large value of synchronous reactance.Synchronous machine with a lower value of S.C.R, thus greater change in the voltage under fluctuations of load.So voltage regulation of the machine is poor.

2]Stability:- A machine with a low value of S.C.R (and thus high value of X_d) has a lower stability limit as the maximum power output of the machine is inversely proportional to X_d.

3]Short Circuit current:- A small value of S.C.R indicates a smaller value of current under short circuit condition owing to large value of synchronous reactance.The short circuit current can be limited by controlling the excitation and thus synchronous generator need not be designed with large value of synchronous reactance.(low value of S.C.R.)

4]Self Excitation:- Machine feeding a long transmission lines should not be designed with a small S.C.R(high X_d) as this would lead to large voltage on open circuit produce by self excitation owing to large capacitive currents drawn by the transmission

lines.
So, the machine with higher value of S.C.R higher the stability limit and low value of voltage regulation.On the other hand higher value of S.C.R higher the short circuit current.Also machine designed with higher value of S.C.R. has long air gap which means that the MMF required by the field is large.

Present trends is to designed the machine with a low value of S.C.R. This is due to the recent advancement in fast acting control and excitation system.

Modern turbo alternator having S.C.R. normally 0.5 to 0.7.[9]

3.6 Summary

This chapter will gives relation between output power rating and size of the machine. Here also describe various parameter like magnetic and electric loading of the machine which will affect the performance of the machine. Next chapter will give the basic idea for the making of the computer program for analytical calculation.

Chapter 4

Design Procedure

A designed problem has to be formulated considering the various constraints, processes,availability of the material, quality aspects etc. Constraints can be from technical, cost or availability aspects. Technical constraints can be from calculation method, available process system, skilled labors, manufacturing facilities, machinery or tools etc.

The practical method in case of bigger machine is to established a computer program for the total design incorporating the constraint parameter and running the programm for various alternatives from which final designed is selected.

In any practical design the number of variable is to high that hand calculation are impossible. The number of constraint is also large and for these to be satisfied by final design, a lengthly iterative approach is required. This is only possible with the help of computer programs.

Here the different flowchart is given for the different parameter calculation which required for the design of synchronous machine.

4.1 Main Dimensions Calculation

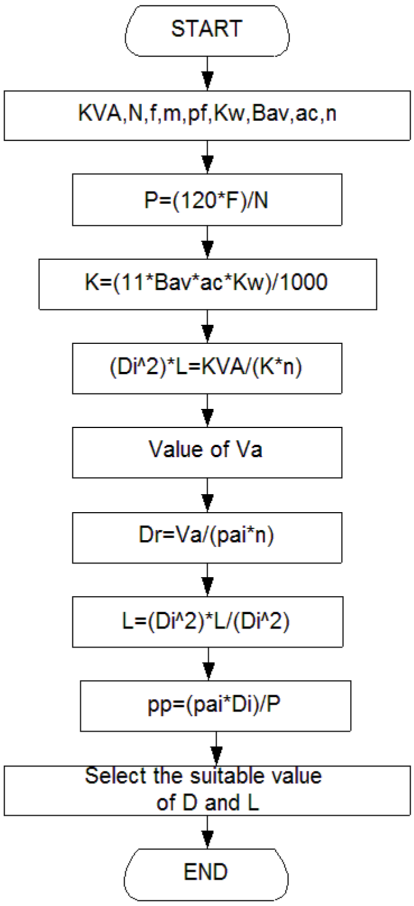


Figure 4.1: Flow Chart for the Calculation of Main Dimensions

1. If the peripheral speed much higher, than run away speed is above then change the type of pole of R.P.M

2. The value of maximum peripheral speed is 175 m/sec.

This flow chart represent the calculation of main dimension of the machine like D and L by assuming suitable value of magnetic loading and electric loading of the machine.It also calculate the pole pitch (τ).

4.2 Length of Air Gap Calculation

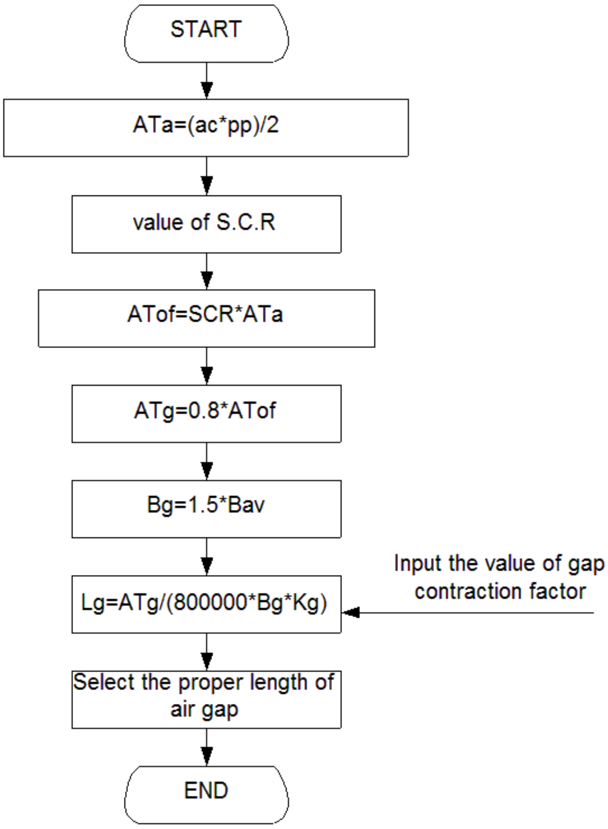


Figure 4.2: Flow Chart for the Calculation of Length of Air Gap

1. The short circuit ratio(S.C.R) of the machine is about 0.5 to 0.7.

2.The ratio of air gap MMF to load MMF is commonly constant value.

3. The gap contraction factor is always around 1.0.

This flow chart represents calculation of the length of air gap by calculating the armature MMF and air gap MMF with suitable value of SCR.

4.3 Stator Parameter Calculation

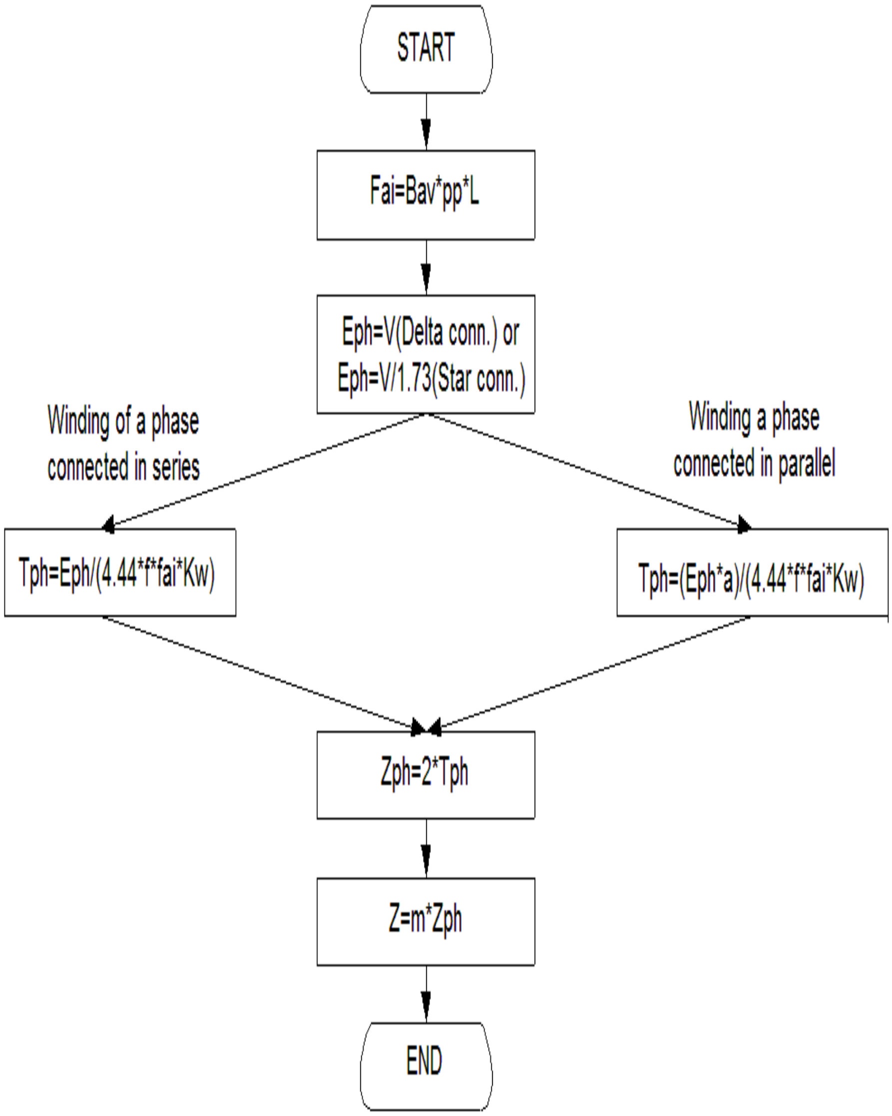


Figure 4.3: Flow Chart for the Calculation of Stator Parameter

This flow chart represent the calculation of the various stator parameter like stator core flux, stator terminal voltage, turns per phase and total number of stator conductor by considering either winding of the phase connected in series or parallel.

4.4 Number of Stator Slot Calculation

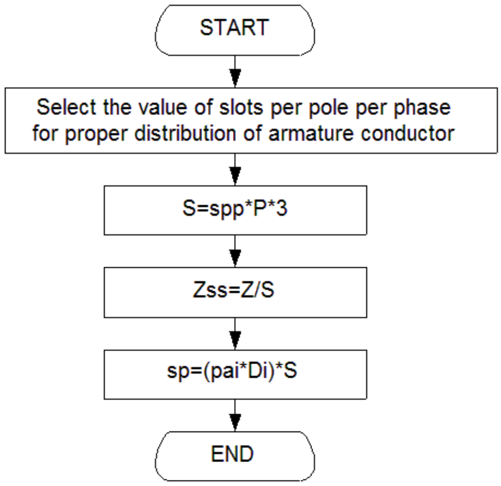


Figure 4.4: Flow Chart for the Calculation of Number of Stator Slot

This flow chart represent the calculation of total number of stator slot and slot pitch of stator by assuming suitable value for the slot per pole per phase.

4.5 Ventilating Arrangement Calculation

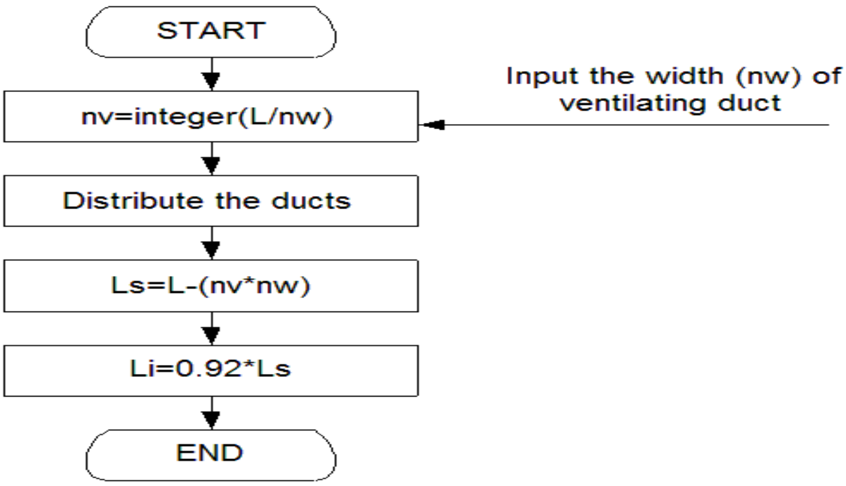


Figure 4.5: Flow Chart for the Calculation of Ventilating Arrangement

This flow chart represent the calculation of total gross length and net iron length by considering the proper distribution and suitable number of ventilating ducts.

4.6 Stator Core Parameter Calculation

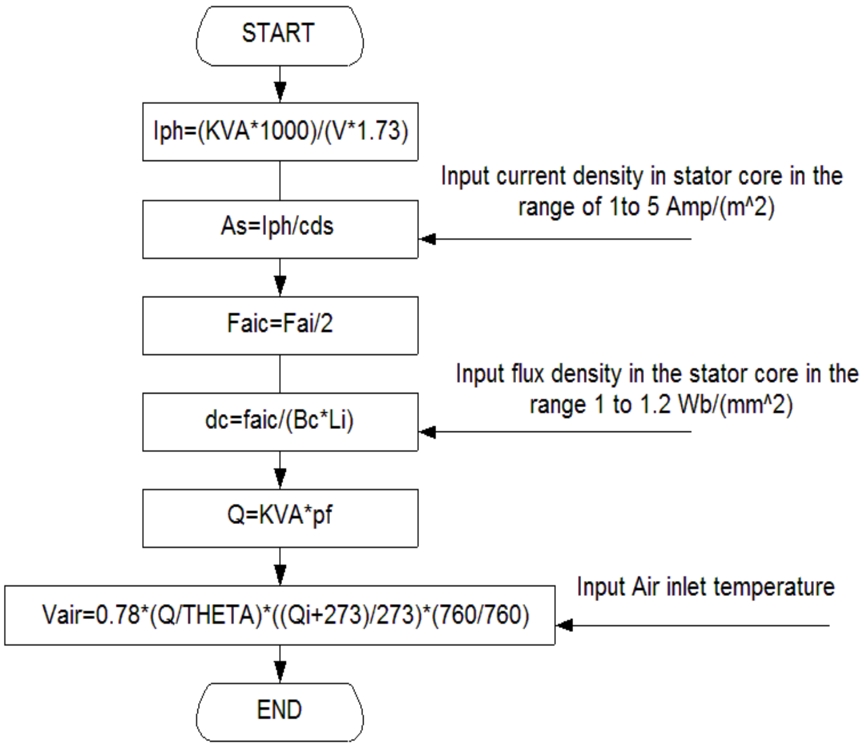


Figure 4.6: Flow Chart for the Calculation of Stator Core Parameter

This flow chart represent the calculation of the various stator core parameter like area of stator conductor,flux in core and depth of core.

4.7 Stator Slot Dimensions Calculation

This flow chart represent the calculation of stator slot dimensions by assuming suitable value of flux density in stator teeth, accordance to the stator conductor size and parallel path of the stator winding.

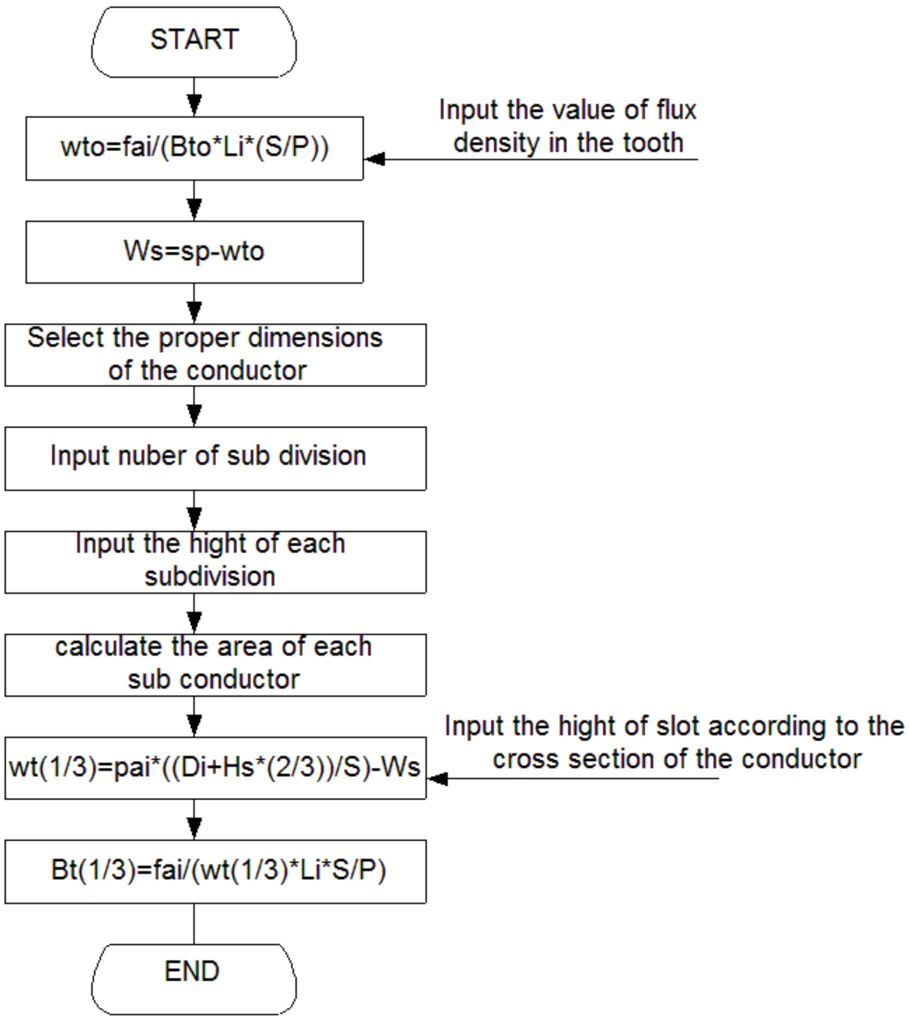


Figure 4.7: Flow Chart for the Calculation of Stator Slot Dimensions

4.8 Rotor Parameter Calculation

This flow chart represent the calculation of the all detail rotor parameter like MMF for the rotor ,by selecting number of rotor slot also calculated the slot pitch for rotor,length of mean turns,total no of rotor conductor and turns per pole,resistance of the rotor winding and current under the loaded condition. Table.4.1 show list of symbols used in flow chart.

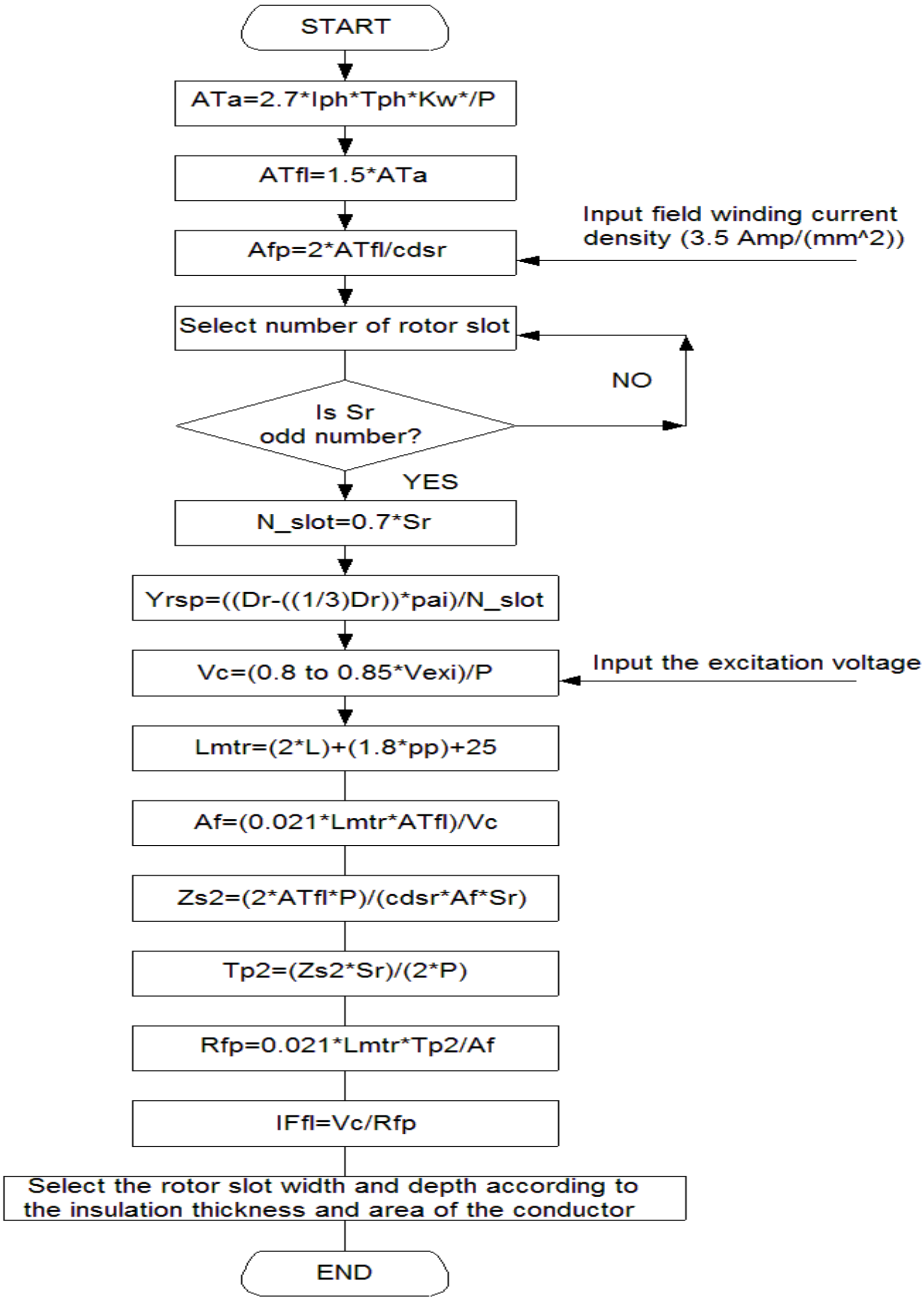


Figure 4.8: Flow Chart for the Calculation of Rotor Parameter

Table 4.1: Various Symbols for Flow Chart

kVA	Power rating	nw	Width of ventilating duct
N	Speed in R.P.M	Ls	Gross iron length
m	Number of phase	Li	Net iron length
p.f	Power factor	Iph	Phase current
Kw	Winding factor	cds	Current density in the stator winding
Bav	Average flux density	As	Area of stator conductor
ac	Ampere conductor per meter	Faic	Flux in core
n	Speed in R.P.S	dc	Depth of core
P	Number no pole	Bc	Flux density in core
K	Output co-efficient	Q	Rated output power in kW
Di	Stator inner diameter	Vair	Air required for the cooling of the machine
L	Length of core	θ	Temperature raise of the machine
Va	Peripheral	Qi	Air inlet temperature
Dr	Diameter of rotor	wto	Tooth width width at air gap
pp	Pole pitch	Ws	Width of stator slot
ATa	Armature MMF per pole	wt(1/3)	Tooth width at 1/3 height from the tooth tip
S.C.R	Short circuit ratio	ATfl	Full load field MMF
ATof	No load MMF	Afp	Area of the field winding per pole
ATg	MMF for air gap	cdsr	Current density in the rotor winding
Bg	Maximum flux density at air gap	Sr	Number of rotor slot
Kg	Gap contraction factor	$N_s lot$	Number of wound slot
Lmts	Length of mean turns of stator winding	Yrsp	Rotor slot pitch
Fai	Flux per pole	Vexi	Excitation voltage
Eph	Phase voltage	Vc	Voltage across each field coil
V	Voltage rating of the machine	Zs2	Conductor per slot
Tph	Turns per phase	Lmtr	Length of mean turns of the field winding
Zph	Conductor per phase	Af	Area of the each field conductor
Z	Total number of armature conductor	Lg	Length of air gap
S	Total number of stator slot	Tp2	Turns per pole
spp	Slot per pole per phase	nv	Number of ventilating duct
Zss	Conductor per slot	Rfp	Resistance of field winding per pole
sp	Stator slot pitch	IFfl	Field current at full load

4.9 Summary

This chapter describe the various flow chart for the calculation of all parameter of stator and rotor by assuming certain value which is necessary for the starting of designing of synchronous machine. Next chapter will give the arrangement for the stator and rotor winding.

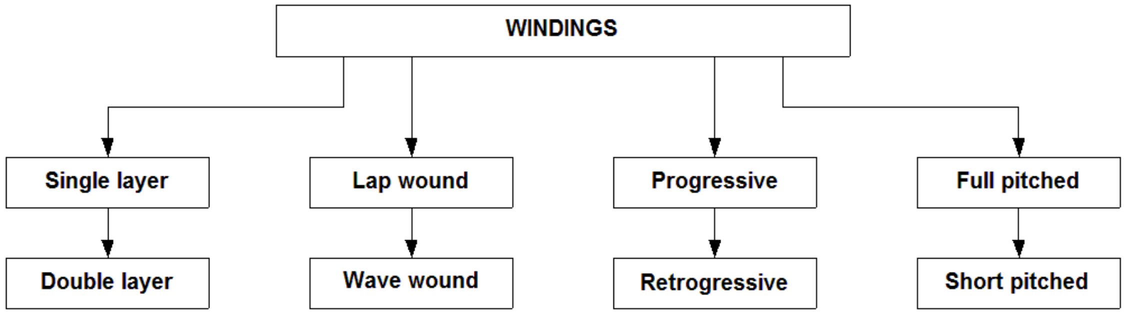
Chapter 5

Machine Windings

Winding of the machine is defined as an arrangement of conductor designed to produce EMF by relative motion in a magnetic field. The action of rotating electromagnetic machine is dependent upon the conversion of power that takes place through the medium of magnetic field; an EMF being induced int he winding that experiences a charge of flux linkages.

Electrical machine employ group of conductor distributed in slot over the periphery of stator and rotor. The groups are connected in various types of series-parallel combination to from a Winding. The conductors are connected in series so as to increase the voltage rating while they are connected in parallel to increase the current rating.

5.1 Classification of Winding



The winding used in synchronous machine may be single layer or double layer type. Machines having large values of flux per pole have small number of turns per phase and therefore a double layer bar winding is used for them.For high voltage machine with small values of flux per pole have a large number of turns per phase. Therefore, multi-turn coils are used for such machines. For machines using multi turn coils the choice lies between double layer lap winding and single layer concentric winding.

5.2 Choice Between Single and Double Layer Winding

Double layer windings in open slots have the following advantages over the single layer windings in semi enclosed slots:

1] Easy in manufacture of coils and lower cost of winding.

2] Less number of coils are required as spare in the case of winding repairs.

3] Fractional slot windings can be used.

4] Fractional pitch coil can be used.

The single layer windings have the following advantages:

1] Higher efficiency and quieter operation because of narrow slot openings.

2] Space factor for slots is higher owing to absence of inter layer separator.

5.3 Stator Winding

The double layer integral lap short pitch winding is used for the stator winding

An armature of a 4 pole, 3 phase, 84 slots, double layer, short pitched by 3 slots, lap wound alternator.

Pole pitch=84/4=21 slots/pole

Coilsapn=Pole pitch-3=18 Slots

Electrical angle=Pair of poles×Mechanical angle=2×90=180

In one full revolution of the rotor a conductor in any slot travels by 360 degree mechanical=(2×360=720),since there are 84 slots,

Slot angle=720/84=8.57 degree electrical

There are three phase R, Y and B separated by 120 degree. If R phase start at 0 degree, then Y phase start at 120 degree and B phase start 240 degree behind. Since slot angle is 8.57 degree, B phase start at 120/8.57=14^{th} slots later and Y phase start 28^{th} slots later.

In terms of slots, if R phase start at slot No.1,

then B phase start at slot No.1+14=15,

and Y phase start at slot No.15+14=29,

Science we are using short pitch winding,

We designed top conductors in slots are 1,3,5,.......167(Odd), and bottom conductors in slots are 2,4,6,.......168(Even).

R PHASE

Top conductor No.1 in first slot is to be connected to bottom conductor No.38 in slot (1+18)=19th slot.

Therefore,Back pitch=38-1=37 Conductor. The other end of this bottom conductor No.38 is to be connected to top conductor No.3 in slot 2.

Therefore,front pitch=38-3=35 conductor.

In the same way winding scheme for total **R Phase** is completed.

B PHASE

B Phase start slot No 8.

Top conductor No 15 in 8th slot is connected to bottom conductor No.52 in slot No=26th slot.

The another and of this bottom conductor No.52 is connected to top conductor No.17 in slot 9.

In the same way winding scheme for total **B Phase** is completed.

Y PHASE

Y Phase start behind 14 slots from R PHASE starting, it start at (1+14)=15th slots.

Top conductor No 29 in 15th slot is connected to bottom conductor No.66 in slot (15+18)=33st slot.

The another and of this bottom conductor No.66 is connected to top conductor No.21 in slot 16.

In the same way winding scheme for total **Y Phase** is completed.

Table 5.1: Details of **R PHASE** Winding

Phase group (R)	Sr No.	No. of top conductor (Zt)	No. of bottom conductor(Zb) Zb=Zt+37	No. of top conductor(Zt) Zt=Zb-35
1	1	1(Beginning)	1+37=38	38-35=3
1	2	3	3+37=40	40-35=5
1	3	5	5+37=42	42-35=7
1	4	7	7+37=44	44-35=9
1	5	9	9+37=46	46-35=11
1	6	11	5+37=48	48-35=13
1	7	13	13+37=50	50(Ending)
2	1	43(Ending)	43+37=80	80-35=45
2	2	45	45+37=82	82-35=47
2	3	47	47+37=84	84-35=49
2	4	49	49+37=86	86-35=51
2	5	51	51+37=88	88-35=53
2	6	53	53+37=90	90-35=55
2	7	55	55+37=92	92(Beginning)
3	1	85(Beginning)	85+37=122	122-35=87
3	2	87	87+37=124	124-35=89
3	3	89	89+37=125	126-35=91
3	4	91	91+37=128	128-35=93
3	5	93	93+37=130	130-35=95
3	6	95	95+37=132	132-35=97
3	7	97	97+37=134	134 (Ending)
4	1	127(Ending)	127+37=164	164-35=129
4	2	129	129+37=166	166-35=131
4	3	131	131+37=168	168-35=79
4	4	133	133+37=170(170-168=2)	170-35=135
4	5	135	135+37=172(172-168=4)	172-35=137
4	6	137	137+37=174(174-168=6)	174-35=139
4	7	139	139+37=176(176-168=8)	8 (Beginning)

Table 5.2: Details of **B PHASE** Winding

Phase group (Y)	Sr No.	No. of top conductor (Zt)	No. of bottom conductor(Zb) Zb=Zt+37	No. of top conductor(Zt) Zt=Zb-35
1	1	15(Beginning)	15+37=52	52-35=17
1	2	17	27+37=54	54-35=19
1	3	19	29+37=56	56-35=21
1	4	21	31+37=58	58-35=23
1	5	23	33+37=60	60-35=25
1	6	25	35+37=62	62-35=27
1	7	27	27+37=64	64 (Ending)
2	1	57(Ending)	57+37=94	94-35=59
2	2	59	59+37=96	96-35=61
2	3	61	61+37=98	98-35=63
2	4	63	63+37=100	100-35=65
2	5	65	65+37=102	102-35=67
2	6	67	67+37=104	104-35=69
2	7	69	69+37=106	106 (Beginning)
3	99	99(Beginning)	99+37=136	136-35=101
3	2	101	101+37=138	138-35=103
3	3	103	103+37=140	140-35=105
3	4	105	105+37=142	142-35=107
3	5	107	107+37=144	144-35=109
3	6	109	109+37=146	146-35=111
3	7	111	111+37=148	148(Ending)
4	1	141(Ending)	141+37=178(178-168=10)	178-35=143
4	2	143	143+37=180(180-168=12)	180-35=145
4	3	145	145+37=182(182-168=14)	182-35=147
4	4	147	147+37=184(184-168=16)	184-35=149
4	5	149	149+37=186(186-168=18)	186-35=151
4	6	151	151+37=188(188-168=20)	188-35=153
4	7	153	153+35=190(190-168=22)	22 (Beginning)

Table 5.3: Details of **Y PHASE** Winding

Phase group (B)	Sr No.	No. of top conductor (Zt)	No. of bottom conductor(Zb) Zb=Zt+37	No. of top conductor(Zt) Zt=Zb-35
1	1	29(Ending)	29+37=66	66-35=31
1	2	31	31+37=68	68-35=33
1	3	33	33+37=70	70-35=35
1	4	35	35+37=72	72-35=37
1	5	37	37+37=74	74-35=39
1	6	39	39+37=76	76-35=41
1	7	41	41+37=78	78(Beginning)
2	1	71(Beginning)	71+37=108	108-35=73
2	2	73	73+37=110	110-35=75
2	3	75	75+37=112	112-35=77
2	4	77	77+37=114	114-35=79
2	5	79	79+37=116	116-35=81
2	6	81	81+37=118	118-35=83
2	7	83	83+37=120	120 (Ending)
3	1	113(Ending)	113+37=150	150-35=115
3	2	115	115+37=152	152-35=117
3	3	117	117+35=154	154-35=119
3	4	119	119+37=156	156-35=121
3	5	121	121+37=158	158-35=123
3	6	123	123+37=160	160-35=125
3	7	125	125+37=162	162 (Beginning)
4	1	155(Beginning)	155+37=192(192-168=24)	182-35=157
4	2	157	157+37=194(194-168=26)	194-35=159
4	3	159	159+37=196(196-168=28)	196-35=161
4	4	161	161+37=198(198-168=30)	198-35=163
4	5	163	163+37=200(200-168=32)	200-35=165
4	6	165	165+37=202(202-168=34)	202-35=167
4	7	167	167+37=204(204-168=36)	36(Ending)

5.4 Rotor Winding

The double layer Simplex lap winding is used for the rotor winding

No. of poles(P)=4,

Total No.of conductor is given by;

$$Z = Slots \cdot Conductor/Slots = 24 \cdot 2 = 48 \tag{5.1}$$

For progressive winding,Back pitch is give by;

$$Yb = \frac{Z}{P} + 1 = \frac{48}{4} + 1 = 13 \tag{5.2}$$

And Front pitch is given by;

$$Yf = \frac{Z}{P} - 1 = \frac{48}{4} - 1 = 11 \tag{5.3}$$

In double layer winding, top conductor in slot are 1,3,5,.........47(Odd), and bottom conductors in slot are 2,4,6.........48(Even).

To start with top conductor in slot No.1 is connected to bottom conductor No. (1+Yb)=(1+13)=14 on one end. The other end of conductor No.14 is connected to (14-Yf)=(14-11)=3 and it goes on according as per the following table.

Table 5.4: Details of Rotor winding

Sr No.	No. of top conductor (Zt)	No. of bottom conductor(Zb) Zb=Zt+Yb	No. of top conductor(Zt) Zt=Zb-Yf
1	1	1+13=14	14-11=3
2	3	3+13=16	16-11=5
3	5	5+13=18	18-11=7
4	7	7+13=20	20-11=9
5	9	9+13=22	22-11=11
6	11	11+13=24	24-11=13
7	13	13+13=26	26-11=15
8	15	15+13=28	28-11=17
9	17	17+13=30	30-11=19
10	19	19+13=32	32-11=21
11	21	21+13=34	34-11=23
12	23	23+13=36	36-11=25
13	25	25+13=38	38-11=27
14	27	27+13=40	40-11=29
15	29	29+13=42	42-11=31
16	31	31+13=44	44-11=33
17	33	33+13=46	46-11=35
18	35	35+13=48	48-11=37
19	37	37+13=50(50-48=2)	50-11=39
20	39	39+13=52(52-48=4)	52-11=41
21	41	41+13=54(54-48=6)	54-11=43
22	43	43+13=56(56-48=8)	56-11=45
23	45	45+13=58(58-48=10)	58-11=47
24	47	47+13=60(60-48=12)	60-11=49(49-48=1)

Table 5.5: Brush and Commutator Segments Arrangement

Pole No.	1	2	3	4
Polarity Slots No. under the pole	North 1,2,3,4,5, 6	South 11,12,13,14,15, 16	North 21,22,23,24,25, 26	South 31,32,33,34,35, 36
Conductors No.	1 to 12 (12 nos)	13 to 24 (12 nos)	25 to 36 (12 nos)	37 to 48 (12 nos)
Polarity of induced EMF	+Ve	-Ve	+Ve	-Ve
No. of coils	6	16	16	16
No. of commutator segments	6	6	6	6
No. of brush	1	1	1	1

5.5 Summary

This chapter describe advantages of double layer winding and winding scheme for the stator and rotor with coilspan, front pitch, back pitch, through which current can pass and alternating voltage is available at the stator terminal. Next chapter will introduction about MAGNET software and FEM analysis of the synchronous machine model.

Chapter 6

Finite Element Analysis

6.1 Basics of FEA

The finite element analysis (FEA) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equation. The Finite Element Method is a good choice for solving partial differential equations over complicated domains, when the domain changes, when the desired precision varies over the entire domain, or when the solution lacks smoothness.[10]

The finite element method is essentially based on subdivision the whole domain in a fixed number of sub-domains. Because of small dimensions of these domains, the function is approximated by simple interpolating functions whose coefficients are unknown quantities. The solution of the field problem is obtained when these unknown coefficients are found. The finite element analysis is organized in following steps:

1 . Partition of the domain

2 . Choice of the interpolating functions

3 . Formulation of the system to resolve the field problem

4 . Solution of the problem

Modern finite element packages use advanced graphical displays which are usually menu-driven to make the process of solving problems as easy as possible. All packages have three main components:

- Pre-processor
- Solver
- Post-processor

Pre-processoris a module where the finite element model is created by the user.This module allows new models to be created and old models to be altered. The different parts of any finite element model are:

- **Drawing:** Drawing the geometry outline of the model using graphical drawing tools like, line, circle, arc,etc
- **Material:** The different regions of the geometry model are assigned by magnetic material properties. The materials can have linear or nonlinear magnetic characteristics. Materials can be defined by their different properties like conductivity, permeability, flux density, coercive force etc.
- **Electrical Circuits:** Regions which contain coils are linked to current or voltage sources. Specifying the number of turns per coil and the current magnitude.
- **constrains:** The edges of the model usually need constraints and this is done by defining constraints graphically.

Solver module solves numerically the field equations. The pre-processor module sets which solver (electrostatic, magneto static, eddy-current) should be used. Mostly, adaptive meshing is implemented to ensure efficient mesh discretization. The solver starts by creating a coarse finite element mesh and solving it. An error estimate is produced from this solution, and the mesh is refined and solved again. This is repeated until the mesh is refined sufficiently to produce an accurate result.

Post-processor is an interactive module that displays field quantities such as magnetic vector potential,flux density, field intensity and permeability. It also gives the user access to a vast amount of information regarding the finite element solution such as energy, force, torque and inductance, which are all built into the module.
In this to study the finite element analysis **MAGNET software** is used.The facility of this software are :

- Static magnetic fields around specified DC/AC current distributions and permanent magnets
- AC magnetic fields and phase differences caused by eddy currents in and around sinusoidal current-carrying conductors at a single frequency in the complex domain.
- Time-varying magnetic fields and time lag effects caused by induced eddy currents in and around current-carrying conductors and permanent magnets
- The effects of motion: multiple components in linear, rotational or arbitrary directions.

6.2 FEA Simulation

Analytical designed of synchronous machine(Alternator) is now verified with the **FEA** by magnet software. The rating of the machine are as follow and Table.A.1:

- Rated power=5000kW
- Rated voltage=11000kV
- No. of poles=4
- Rotor:Cylindrical
- Power factor=0.8 lagging

6.2.1 Creating FE Model

The synchronous machine model is created according to the dimension obtained by the design parameter in Table.A.2,Table.A.3.

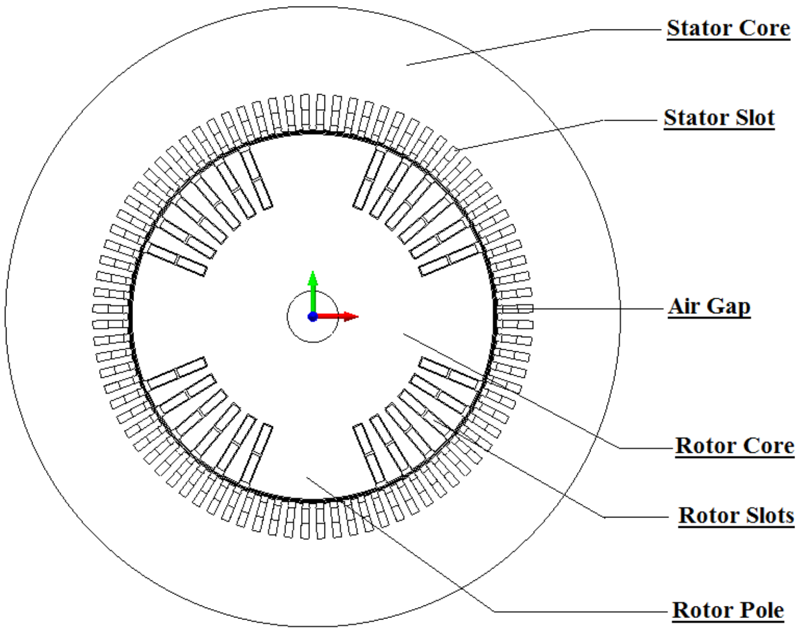


Figure 6.1: Wire Frame Model without Material

The magnetic material are assigned to the different parts of the synchronous machine. Conducting material is assigned to the conductors in the slot. All the electrical and magnetic properties are defined. Then coil at each and every conductor of slot is made. According to winding diagram, these coils are connected in such a way so required polarity is maintained. Coils of the stator winding are supplied by the sinusoidal currents source of the magnitude required to produce rated voltage and each are at 120 degree phase shift and rotor winding is supplied by a D.C Current source of the magnitude of rated full load field current. The 2D and 3D model of the synchronous machine after the modeling is completed is shown in fig.6.2 and fig.6.3 respectively.

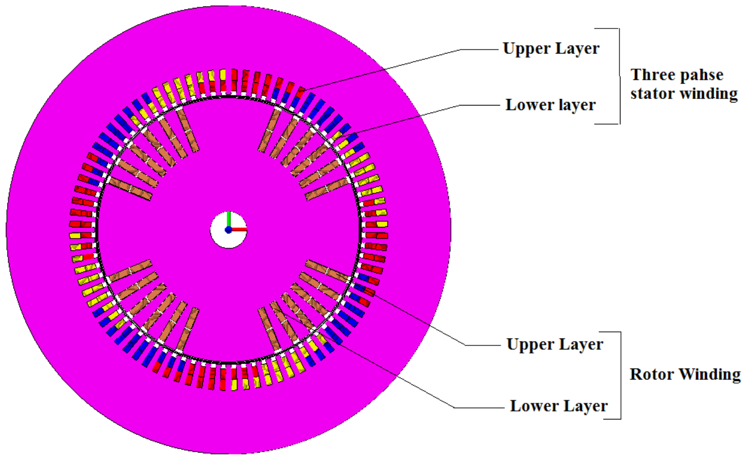


Figure 6.2: 2D model of Synchronous Machine with Material

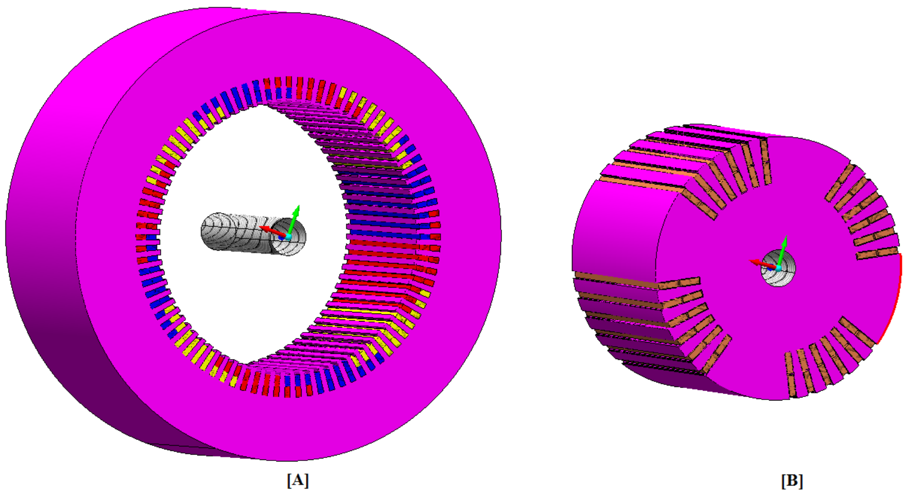


Figure 6.3: 3D View of [A]-Stator Core,Slots,Windings [B]-Rotor Core,Slots,Windings

6.2.2 Meshing of Model

The accuracy of the software result and time for solving the model is also dependent on the meshing of the model.So defining of the mesh is very important parameter to obtain the proper result.Here we have to define the size of the mesh element, so for small size of the element higher the density of the meshing and takes more time for solution but gate accurate result.Whenever a mesh is generated, it is important to consider the requirements of different regions. A fine mesh produces higher accuracy but it takes more time to solve the model. So the regions in which higher accuracy is needed only should be having fine mesh. The automatic mesh generator produces adequate mesh in terms of quality, accuracy and size. However it is better to adjust and control the density of the mesh with a specific region. The generated mesh with refinement is shown in fig.6.4.

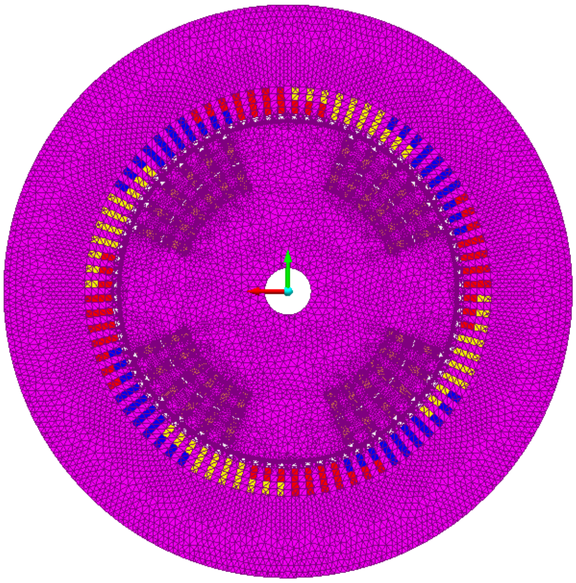


Figure 6.4: Meshing of Synchronous Machine Model

After model is created the static, time harmonic and transient analysis is performed on the model. The values of flux density in the teeth, stator core, rotor core and air gap is analyzed and verified with the analytic design of the synchronous machine as obtained in Design Sheet.A.1.

6.2.3 FEA Simulation Results with Static Analysis

Static analysis results are shown by the flux contour plot, flux density plot and physical creation of the pole in the synchronous machine. The flux plot is shown in the Fig.6.5,Which indicates the physical creation of the pole by positive and negative value of flux at different poles. Fig.6.6 also represent the creation of pole by graphically and its value is 0.1605 Wb, which is very near to the calculated value of flux in stator core.

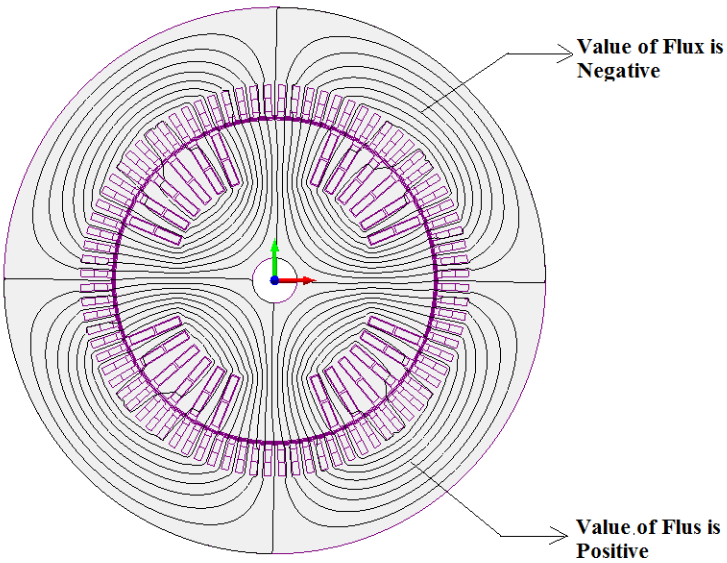


Figure 6.5: Flux Counter Plot(Physical Creation of Pole)

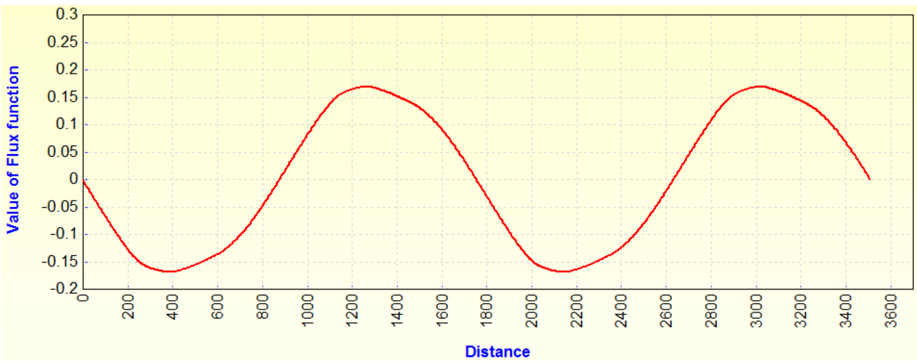


Figure 6.6: Graphical Representation of Pole and Value of Flux

The flux density at different part of the synchronous machine like stator core,stator teeth,rotor core,rotor teeth and air gap after the excitation of the rotor and stator winding is shown by the flux density plot in Fig. 6.7. The flux density at stator core, stator teeth, rotor core,rotor teeth and air gap are analyzed and is represented by

Fig.6.8, Fig.6.9, Fig.6.10, Fig.6.11 and Fig. 6.12 respectively .

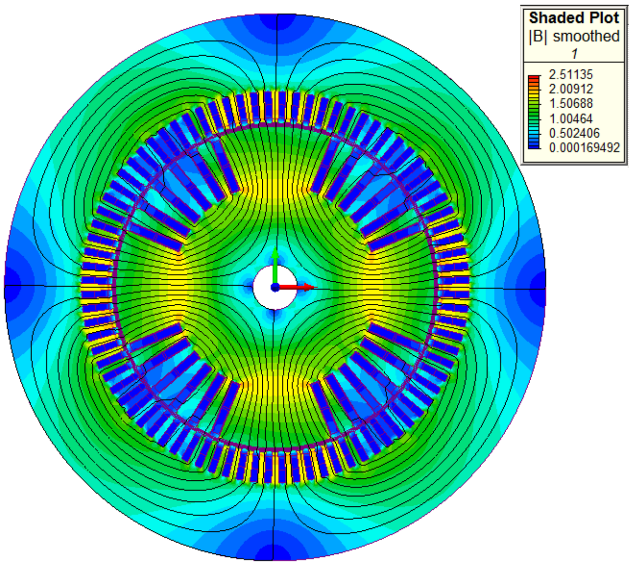


Figure 6.7: Flux Density Plot

Following Fig.6.8 represents the maximum flux density occur in the stator core at the center of the pole and reduces towards to the end of the pole. Maximum flux density is occur at stator and rotor teeth, is represented by Fig.6.9 and Fig.6.11 respectively. Fig6.12 shows the flux density at the air gap, in which maximum flux density occur at the center of the pole because of the more flux line passes through to the center of the pole and is value is suddenly rise and drop due the teeth and slot of stator and rotor. Fig6.10 shows the flux density at rotor core which shows the flux density is higher at the portion of the core which is near to the center of the rotor pole and reduce at both end of the poles.

By taking the average value of the each flux density plot, it is very near to the calculated value, which shown in Table.6.1.The values of these flux densities are matched with calculated value of the analytic design of the synchronous machine.

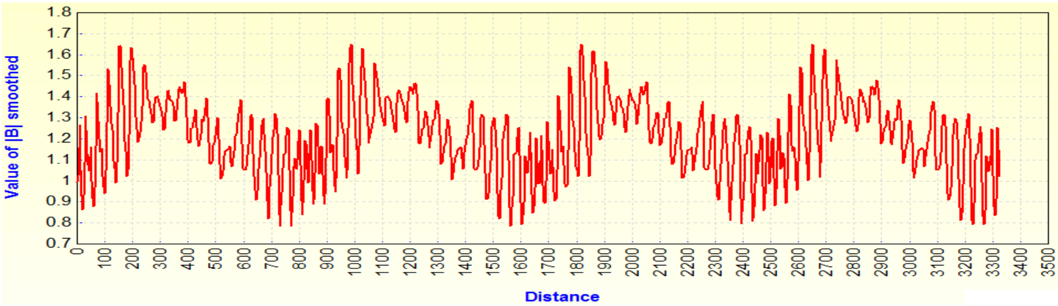


Figure 6.8: Graphical Representation of Flux Density at Stator Core

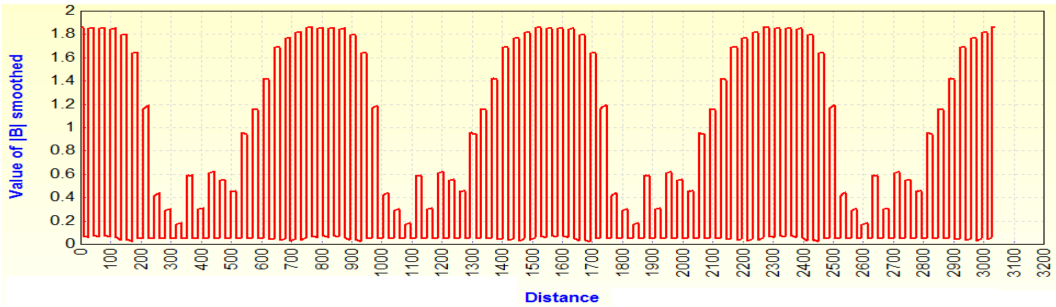


Figure 6.9: Graphical Representation of Flux Density at Stator Teeth

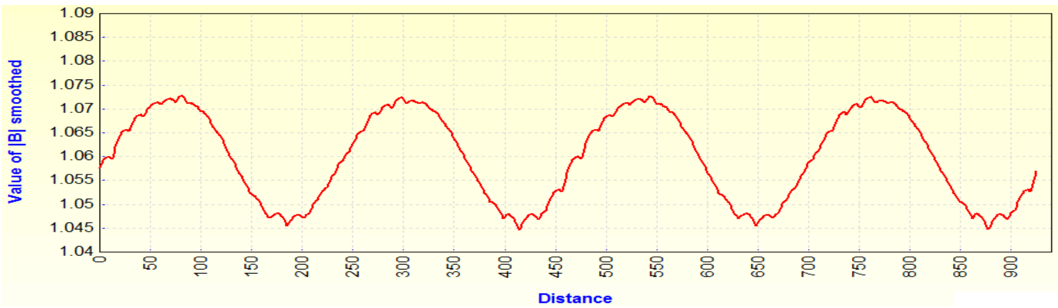


Figure 6.10: Graphical Representation of Flux Density at Rotor Core

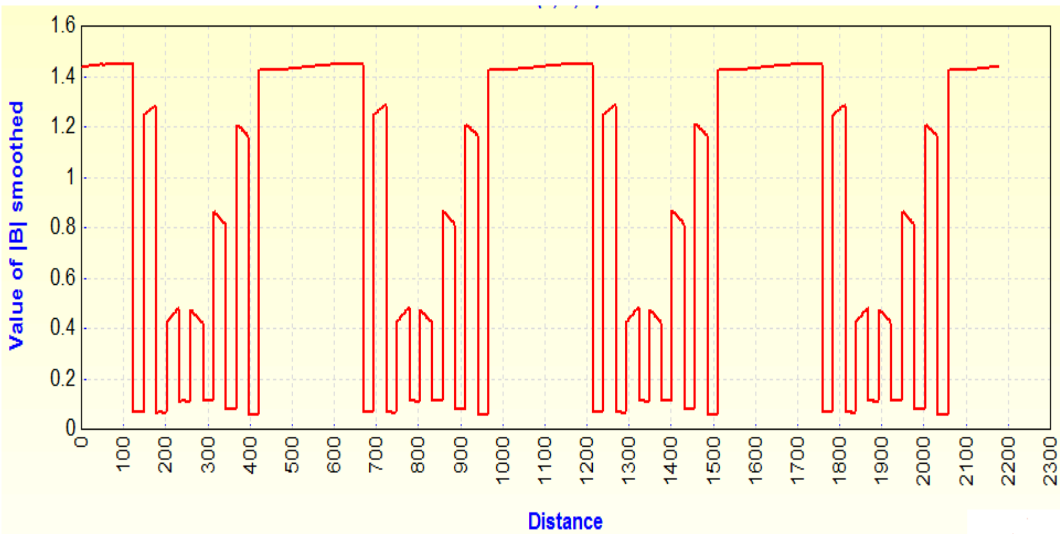


Figure 6.11: Graphical Representation of Flux Density at Rotor Teeth

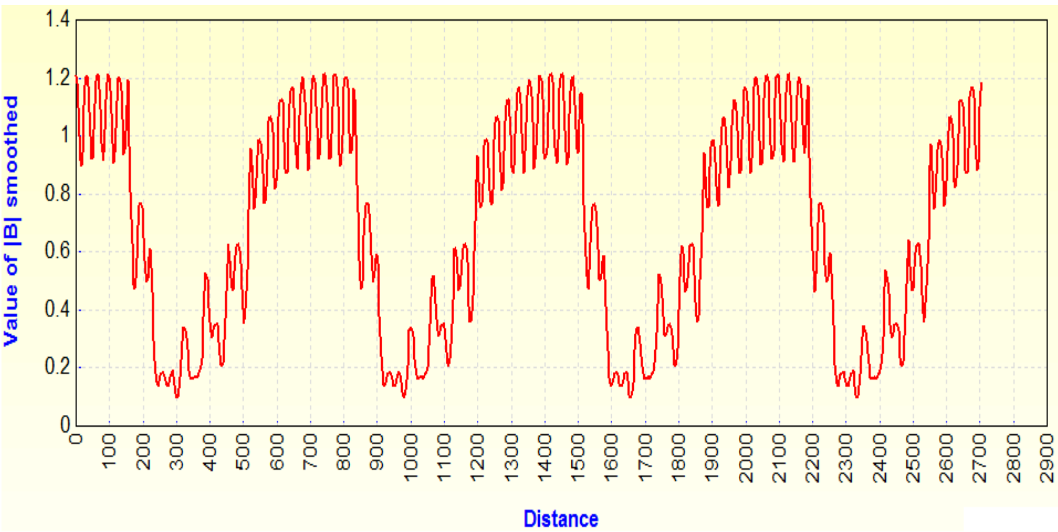


Figure 6.12: Graphical Representation of Flux Density at Air Gap

Table 6.1: Flux Density Plot

Flux Density (Wb/(mm^2)) At	Analytical Value	FEM Values
Stator Core	1.09	0.99
Stator Teeth	1.15	1.8
Rotor Core	0.9	1.05
Rotor Teeth	1.74	1.43
Air Gap	1.15	1.20

6.2.4 FEA Simulation Results of Time Harmonic Analysis

With help of this time harmonic simulation we can find the open circuit characteristic (OCC). In this analysis we have to excite the rotor(field) winding at various step of current. In analytical calculation OCC is plotted, so we get the idea about the various step of current.Here we are given the current in the step of 10 A, 20 A, 30 A, 40 A, 50 A, 60 A, 70 A, 80 A, 90 A, 100 A, 110 A, 120 A, 130 A, 140 A, 150 A. By applying this much current and run the solver for time harmonic analysis, we get no load terminal voltage for three phase for various step of current.By analyzing this characteristic we obtain phase value of the terminal voltage around 6134 V at 102 Amp. Here software gives phase value of voltage so multiplied by 1.732 to get line to line value of the voltage.

Following Table.6.2 shows the phase value of terminal voltage at the various step of field current and Fig.6.13 represents OCC which obtain by the time harmonic analysis.The field current required to produce no load terminal voltage is near to the calculated value of the analytical design.

Table 6.2: Detail Parameter for OCC

Sr.No.	Field current (Amp)	Voltage (V) Phase value	Voltage (V) Line To Line Value
1	0	0	0
2	10	813.3633	1408.786
3	20	1626.727	2817.573
4	30	2440.062	4226.311
5	40	3523.3	5634.881
6	50	4065.425	7041.522
7	60	4829.725	8365.329
8	70	5369.435	9300.135
9	80	5701.619	9875.494
10	90	5934.042	10278.06
11	100	6104.347	10573.04
12	102	6134.353	10625.01
13	110	6244.458	10815.72
14	120	6364.543	11023.71
115	130	6469.718	11205.88
16	140	6564.629	11370.27
17	150	6651.61	11520.93

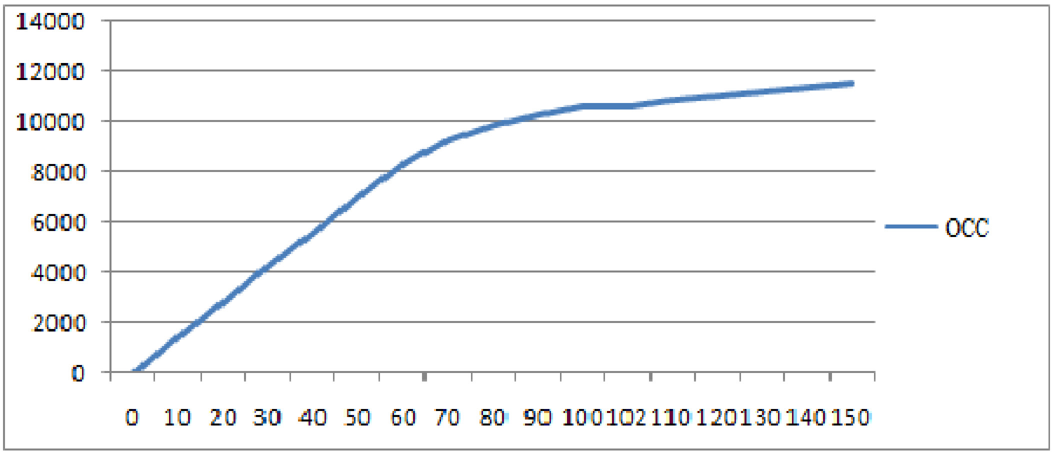


Figure 6.13: OCC Parameter

6.2.5 FEM Simulation Results of Transient with Motion

With the help of this transient simulation we can obtain the No-Load terminal voltage waveform.For this we have to define the start time, stop time and step for the solution. Here we are run the solver for start time at 0 ms and stop time is around 40 ms in step of 0.1 ms ,so we get the No-load terminal voltage up to approximately 2 cycles and its magnitude is also near to the 11kV under the No-load condition for particular No-load field current is shown in fig.6.14.Paricular No-load field current is getting by the time harmonic analysis.

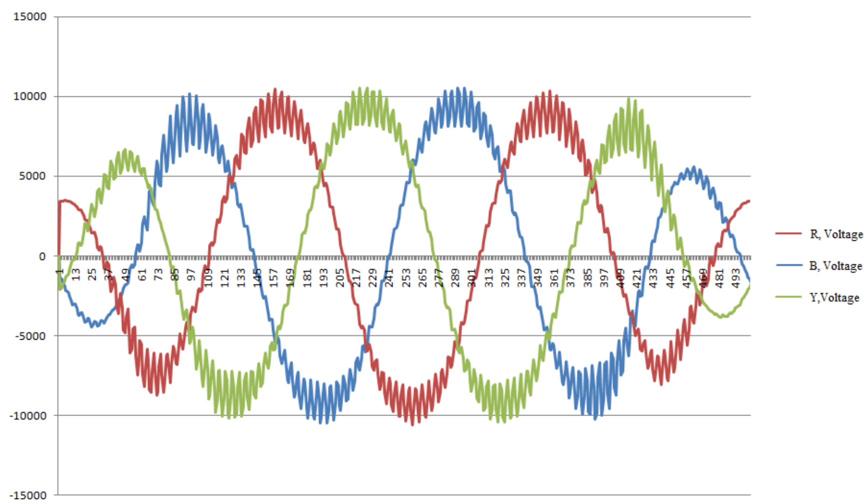


Figure 6.14: No-Load Terminal Voltage

6.3 Reactance Calculation

Reactance is parameter which greatly determine the performance of the synchronous generator in power network under normal condition and during short-circuit transients. This parameter are usually measured during manufacturing which do not correspondence to the operating condition of the generator.[8] The direct-axis synchronous reactance X_d is determine as a quotient of the excitation current corresponding to the rated voltage on the air gap line. This value of X_d corresponds to an unsaturated state of the machine.[11]

6.3.1 Unsaturated Steady-state Direct-axis Reactance

For computation of reactance "X_d", the finite element model is crated in which the phase R axis is aligned with the field winding axis i.e, angle between the field winding and phase R phase axis is zero. The field current is set to zero and the armature winding conductors are loaded to provide a space fundamental magnetomotive force waveform with its axis aligned with the field winding axis(d-axis). The linear magnetostatic simulation is used. The result can be seen in fig.6.15.

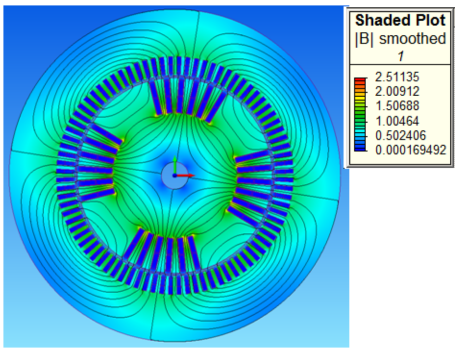


Figure 6.15: Direct-axis Armature Field in the Steady-state Obtained by using the Magnetostatic Simulation

Here we are exciting R phase with rated armature current, when it is aligned with the field winding as shown in fig.6.15. Total flux linkage with R phase coil is 57.200 Wb and current in that phase is 328.4 Amp.

So, Inductance is given By;

$$L = \Psi_d / I = 57.2/328.4 = 0.1744H \tag{6.1}$$

Reactance is given by;

$$X = 2 * \Pi * f * L = 2 * \Pi * 50 * 0.1744 = 54.7863 \tag{6.2}$$

Value of terminal voltage is 11kV(line to line) and phase voltage is 6350.853 kV, So Base Impedance is given By;

$$Z_{base} = V/I = 6350.853/328.4 = 19.362 \tag{6.3}$$

Direct-axis reactance is given by;

$$X_d\% = (X/Z_{base}) * 100 = (54.7863/19.362) * 100 = 282.953 \tag{6.4}$$

So, short Circuit Ratio in P.U is given by;

$$S.C.R._{P.U} = (1/X_d\%) * 100 = (1/282.953) = 0.35 \tag{6.5}$$

In analytical calculation the value of S.C.R. is 0.40, so it near to the value of S.C.R. which is getting by the FEM results.

6.3.2 Unsaturated Steady-state Quadrature-axis Reactance

The quadrature-axis synchronous reactance "X_q" can be obtained in a similar way, only in this case R phase axis and the armature winding MMF are aligned with the quadrature-axis. The field solution is shown in Fig.6.16
Here we are also exciting R phase with rated armature current and total flux linkage with this R phase coil is 54.800 Wb. Quadrature axis reactance can be calculated in similar way to the Direct-axis reactance. After making the calculation quadrature-axis reactance is 271.081 %. So, both direct-axis and quadrature-axis reactance are nearer to each other. This is because of the cylindrical rotor machine having a constant air gap length, so flux linkage in air gap will remain same in both position of the field

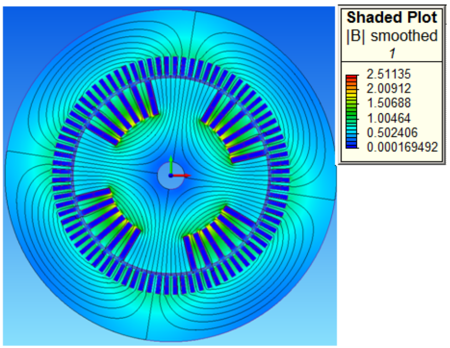


Figure 6.16: Quadrature-axis Armature Field in the Steady-state Obtained by using the Magnetostatic Simulation

winding.

6.3.3 Unsaturated Transient Direct-axis Reactance

The magnetic flux of the generator field during short circuit transient is mainly closed through the leakage paths. Science the magnetic resistance of the leakage path is much higher than the magnetic resistance of iron, the reactance of the armature winding in short circuit will be much lower then under a steady-state condition. At the instant immediately after the sub transient phenomenon in the rotor iron has subsided the currents induced in the short circuited field winding still do not allow the stator field to closer over rotor.
In the direct-axis the transient reactance X_d', which is significantly lower then X_d is distinguished, while in quadrature-axis the shorted circuited field winding theoretically does not affect the condition in the armature winding because there axis is then perpendicular.

For the computation of X_d' a time harmonic simulation at the frequency of 50Hz is used. The 2D time harmonic simulation is applicable only to the linear problems, because the flux density is assumed to vary sinusoidally in time, and the value of permeability must be valid for all values of flux density over the sine wave.The field winding is short circuited to allow the induction of currents and has a value of conductivity different from zero. The conductivity of the rotor iron set to zero. The result of the simulation is shown in fig6.17. It is apparent that very small number of flux line cross the rotor pole compare to saturated quadrature-axis position.This is case mainly in the area of rotor pole where there are no eddy currents induced in the transient state so the stator field can penetrate.

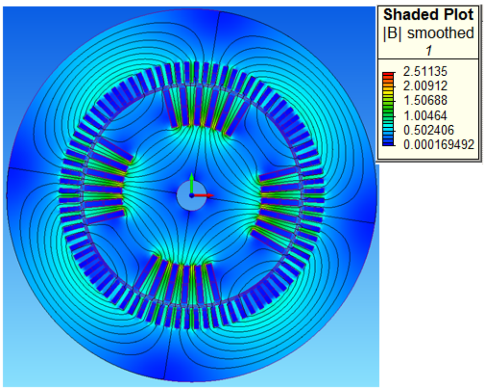


Figure 6.17: Direct-axis Armature Field in the Transient-state Obtained by using the Magnetostatic Simulation

The reactance X'_d is computed by using the same concept of the space phasor as in the case of steady-state reactance. The value of flux linkages of the phase and the value of unsaturated reactance are shown in Table.6.3

Table 6.3: Unsaturated Transient Reactance Computed by using the Time Harmonic Simulation

Flux linkages	4.56	Wb
Current	328.4	Amp
Inductance(L)	0.014	H
Reactance(X)	4.362	Ω
Voltage(L-L)	11000	V
Z_{base}	19.339	Ω
X'_d	0.226	P.U

6.3.4 Saturated Sub Transient Direct-axis Reactance

The saturated reactance X''_d is calculated by using the magnetostatic simulation. for the analysis of saturated condition we need to excite the field winding with such a high current so magnetic material of machine goes under saturation. Here we are also analyzing the value of sub transient direct-axis reactance for various frequency AND results are given for the 50 Hz frequency in Table.6.4. Here we are also exciting the R phase with rated armature current, but due to the saturation of magnetic material very less flux linkage with the R phase coil is shown in Fig.6.18.

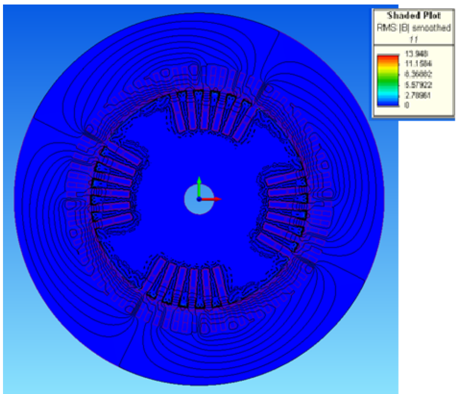


Figure 6.18: Direct-axis Armature Field in the Sub Transient-state Obtained by using the Magnetostatic Simulation for 50 Hz Frequency

Table 6.4: Saturated Direct-axis Armature Field in the Sub Transient-state Reactance Computed by using the Magnetostatic Simulation

Flux linkages	2.1760	Wb
Current	328.4	Amp
Inductance(L)	0.0066	H
Reactance(X)	2.0842	Ω
Voltage(L-L)	11000	V
Z_{base}	19.362	Ω
X''_d	0.1076	P.U

6.4 Summary

This chapter describe creation of the synchronous machine model in MAGNET software for the finite element analysis and with help of this software result we can verify our analytical design by comparing the analytical design and FEM results. Here also describe calculation of reactance under the various condition of machine with the help of results of the MAGNET software. Next chapter will give the conclusion and future scope for the project work.

Chapter 7

Conclusion And Future Scope

7.1 Conclusion

Main consideration for designing of synchronous generator rated as 5 MW, 1500 R.P.M., 11000 V, 0.8 power factor lagging with horizontal arrangement is selection of the proper value of magnetic loading and electric loading. Further, synchronous generator is designed with different number of stator slots like 72 slots, 84 slots, 96 slots.

Design of synchronous generator for all three considered cases are compared with the manufacturer design. According to the available size of the steel sheet and physical dimension of the machine modified the design parameter by selecting the proper value of loading of the machine.

Design with 84 No. of stator slots is quite near to the manufacturer design. So the design parameter with 84 stator slots are implemented in MAGNET software for the finite element analysis. In the FE analysis, design is verified by three different solvers; static analysis, time harmonic, analysis and transient analysis.

Design is verified by comparing the results of analytical calculation and FE analysis results. In static analysis, design is verified by comparing the value of flux density in the various part of the machine. In time harmonic analysis design is verified by comparing the OCC calculation. In transient analysis design is verified by comparing the terminal voltage under No load condition. Finally design is also verified by comparing the value of S.C.R. which is obtain from MAGNET(V 6.16) results and by analytical calculation as well.

7.2 Future Scope

For designing of synchronous machine with different rating and different specification iterative approach is required, so to get the all parameter by hand analytical calculation takes so much time. With the help of computer programming the software for the analytical calculation will be developed and get all the designed parameter in short time. Also all the analysis under loaded condition and short circuit condition will be make.

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List of Publication

[1]Prashant K. Bhavsar, Santosh C. Vora, "Computational and FEM Based Analytical Aspects of Medium Capacity-Turbo Alternator Design" - Paper accepted in National Conference on Contemporary Control and Soft Computing in Electrical Engineering (ConCon-2012), May 30^{th}-31^{st} , 2012.

Appendix A

Design sheet

Here designed parameter with different number of stator slots are given:

1. Rating.
2. Stator Parameter.
3. Rotor Parameter.
4. Open Circuit Characteristic Calculation .
5. Weight,Losses And Efficiency Calculation.
6. Other Calculation.
7. Temperature Rise.

Table A.1: Machine Rating

Full load kVA	Q	6250
Full load power,kW	P	5000
Line voltage	V	11000
Phase voltage	E_{ph}	6350
Power factor	cosΦ	0.8 Lagging
Frequency	F	50Hz
speed	N_S	1500 R.P.M
Number of Poles	p	4

A.1 Designed Parameter with 84 Stator Slot

Table A.2: Design of Armature Parameters

No. of Stator Slot	S	84
Specific magnetic loading	B_{av}	0.55 Wb/m^2
Specific electric loading	ac	60000 a/m
Stator current per phase	Iph	328.4 Amp
Total core length	L	945.15 mm
Net Iron Length	Li	786.73 mm
Ventilating duct	L_S	9∗10 mm
Core outer diameter	Do	1450 mm
Core inner diameter	Di	874 mm
Pole pitch	pp	685.7 mm
Turns per phase	Tph	84
Slot pitch	sp	32.65 mm
Core depth	dc	206.24 mm
Core flux density	Bc	1.09 Wb/m^2
Bare conductor Height	Hc	1.4
Bare Conductor Width	Wc	10
No. of Conductor Height Wise		6
No. of Conductor Width Wise		1
Slot width	Ws	16.05 mm
Slot height	Hs	82 mm
Flux density at tooth tip	Bto	1.3 Wb/m^2
Conductor per slot	Zs	6
Flux/Pole	∅	0.3564 Wb
Current density	(cds)δ	3.90 Amp/mm^2
Mean turn length	Lmtr	4.30 m
Stator winding resistance per phase	Rph	0.09 Ω
Air gap length	Lg	10 mm
Armature reaction	ATa	17783
Leakage reactance	X_l	0.121 P.U
Chording Pitch		19/21
Winding		Double layer shorted pitch by 3 slot lap wound

Table A.3: Design of Field Parameters

Peripheral Speed	Va	67 m/sec
Rotor diameter	Dr	853 mm
Slot pitch	rsp	66.99 mm
Copper strip height	Hcr	8.5 mm
Copper strip width	Wcr	5 mm
No. of Conductor Height wise		10
No. of Conductor Width wise		4
Wound slot height	Hs2	98.7 mm
Slot width	Ws2	24.59 mm
Conductor per slot	Zs2	40
Area of conductor	Af	42.5 mm^2
Turns per pole	Tp2	60
Length of mean turn	Lmtr	3.70 m
Rotor winding resistance per pole	Rfp	0.1096 Ω
Winding		Double layer simplex lap wound

Table A.4: Details of Open Circuit Characteristic

E(L-L) P.U	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6
E(L-L) V	2200	4400	6600	8800	11000	13200	15400	17600
Stator Teeth (Wb/m^2)	0.23	0.46	0.69	0.92	1.15	1.38	1.61	1.84
Stator Teeth (AT/m)	78.85	106.02	129.5	180.2	341	949.6	3955	16750
Stator Teeth (AT)	6.465	8.693	10.619	14.77	27.96	77.86	324.31	1373.5
Stator Core (Wb/m^2)	0.21	0.436	0.65	0.87	1.09	1.30	1.52	1.74
Stator Core (AT/m)	48.95	76.15	105	136.95	172.5	376.5	875	3000
Stator Core (AT)	9.91	15.70	21.65	28.44	35.37	77.65	180.46	618.75
Rotor Teeth (Wb/m^2)	0.34	0.69	1.04	1.39	1.74	2.08	2.43	2.78
Rotor Teeth (AT/m)	90	129	245	1032.5	9500	42500	108050	185000
Rotor Teeth (AT)	8.88	12.73	24.18	101.90	937.65	4194	10664	18259
Rotor Core (Wb/m^2)	0.09	0.18	0.27	0.36	0.45	0.54	0.63	0.72
Rotor Core (AT/m)	25	41.05	57.5	66.95	70.25	88	98	109.5
Rotor Core (AT)	6.695	10.99	15.39	17.92	18.81	23.56	26.24	29.32
Air gap (AT)	1214.4	2428	3643	4857	6072	7286	8500	9715
TOTAL AT	1246	2466	3715	5021	7152	11660	19696	29996
If (Amp) OCC	20.77	41.98	61.91	83.67	119.194	194.337	328.271	499.93

Table A.5: Details of Weight, Losses and Efficiency

WEIGHT	*****	*****
Weight of stator core	Kgcore	4974 Kg
Weight of stator teeth	Kgteeth	836 Kg
Weight of rotor steel	Kgrtst	4598 Kg
Weight of stator copper	Kgstcu	811 Kg
Weight of rotor copper	Kgrtcu	167.93 Kg
Total weight	Kgtot	11284 Kg
Weight per kVA	Kg/KVA	1.80 Kg
LOSSES	*****	*****
Mechanical losses		75.42 kW
Stator copper losses		35.68 kW
Eddy current losses		43.22 kW
Iron losses		12.81 kW
Rotor copper losses		24.365 kW
Total losses		190.302 kW
EFFICIENCY		96.33 %

Table A.6: Details of Performance Related Parameters

Stator Temperature Rise	θ	29.022 C
Armature Reaction Field Current	Ifar	296.38 Amp
Field current on short circuit at rated armature current	Ifsc	298.50 Amp
Short circuit ratio	S.C.R.	0.40 P.U
No load field current	Ifo	118.20 Amp
Field current at rated load and rated power factor	Iffl	202.061 Amp
Voltage regulation	Vreg	25 %
Rotor current density	cds2	4.75 Amp/mm^2
Exciter Rating	Pex	67.56 kW

A.2 Designed Parameter with 72 Stator Slot

Table A.7: Design of Armature Parameters.

No. of Stator Slot	S	72
Specific magnetic loading	B_{av}	0.60 Wb/m^2
Specific electric loading	ac	51000 a/m
Stator current per phase	Iph	328.4 Amp
Total core length	L	999.18 mm
Net Iron Length	Li	827.24 mm
Ventilating duct	L_S	10∗10 mm
Core outer diameter	Do	1495 mm
Core inner diameter	Di	882.24 mm
Pole pitch	pp	692.56 mm
Turns per phase	Tph	72
Slot pitch	sp	38.47 mm
Core depth	dc	228.37 mm
Core flux density	Bc	1.09 Wb/m^2
Bare conductor Height	Hc	1.3
Bare Conductor Width	Wc	11
No. of Conductor Height Wise		6
No. of Conductor Width Wise		1
Slot width	Ws	17.02 mm
Slot height	Hs	78 mm
Flux density at tooth tip	Bto	1.3 Wb/m^2
Conductor per slot	Zs	6
Flux/Pole	∅	0.4151 Wb
Current density	(cds)δ	3.82 Amp/mm^2
Mean turn length	Lmtr	4.42 m
Stator winding resistance per phase	Rph	0.07 Ω
Air gap length	Lg	8 mm
Armature reaction	ATa	15243
Leakage reactance	X_l	0.093 P.U
Chording Pitch		16/18
Winding		Double layer shorted pitch by 3 slot lap wound

Table A.8: Design of Field Parameters

Peripheral Speed	Va	68 m/sec
Rotor diameter	Dr	866 mm
Slot pitch	rsp	68.03 mm
Copper strip height	Hcr	5.5 mm
Copper strip width	Wcr	7.0 mm
No. of Conductor Height wise		19
No. of Conductor Width wise		2
Wound slot height	Hs2	123.04 mm
Slot width	Ws2	17.53 mm
Conductor per slot	Zs2	38
Area of conductor	Af	38.5 mm^2
Turns per pole	Tp2	56
Length of mean turn	Lmtr	3.82 m
Rotor winding resistance per pole	Rfp	0.1166 Ω
Winding		Double layer simplex lap wound

Table A.9: Details of Open Circuit Characteristic

E(L-L) P.U	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6
E(L-L) V	2200	4400	6600	8800	11000	13200	15400	17600
Stator Teeth (Wb/m^2)	0.23	0.46	0.70	0.936	1.17	1.40	1.63	1.87
Stator Teeth (AT/m)	78.85	105	130.9	180	375	1185	4450	18250
Stator Teeth (AT)	6.15	8.19	10.21	14.04	29.25	92.43	347.14	1423.5
Stator Core (Wb/m^2)	0.21	0.436	0.65	0.87	1.09	1.30	1.52	1.74
Stator Core (AT/m)	48.95	76.15	105	136.95	172.5	376.5	875	3000
Stator Core (AT)	10.97	17.39	23.97	31.27	39.39	85.98	199.82	685.11
Rotor Teeth (Wb/m^2)	0.26	0.52	0.78	1.04	1.31	1.57	1.83	2.09
Rotor Teeth (AT/m)	80	113.05	145	242.5	618	3000	17950	38050
Rotor Teeth (AT)	9.84	13.90	17.84	29.83	76.03	369.12	2208	4681
Rotor Core (Wb/m^2)	0.10	0.21	0.32	0.43	0.54	0.64	0.75	0.86
Rotor Core (AT/m)	28	48.75	62.05	75	87.75	98.95	112.25	133.05
Rotor Core (AT)	7	12.18	15.50	18.74	21.92	24.72	28.05	33.24
Air gap (AT)	1059	2119	3179	4239	5300	6359	7418	8478
TOTAL AT	1093	2171	3247	4333	5467	6931	10201	15301
If (Amp) OCC	19.51	38.76	57.97	77.37	97.61	123.77	182.16	273.22

Table A.10: Details of Weight, Losses and Efficiency

WEIGHT	*****	*****
Weight of stator core	Kgcore	5898 Kg
Weight of stator teeth	Kgteeth	906 Kg
Weight of rotor steel	Kgrtst	4989 Kg
Weight of stator copper	Kgstcu	731 Kg
Weight of rotor copper	Kgrtcu	147 Kg
Total weight	Kgtot	12798 Kg
Weight per kVA	Kg/KVA	2.04 Kg
LOSSES	*****	*****
Mechanical losses		78.72 kW
Stator copper losses		30.81 kW
Eddy current losses		32.65 kW
Iron losses		15.07 kW
Rotor copper losses		19.051 kW
Total losses		176.301 kW
EFFICIENCY		96.59 %

Table A.11: Details of Performance Related Parameters

Stator Temperature Rise	θ	24.73 C
Armature Reaction Field Current	Ifar	272.196 Amp
Field current on short circuit at rated armature current	Ifsc	280.99 Amp
Short circuit ratio	S.C.R.	0.34 P.U
No load field current	Ifo	97.625 Amp
Field current at rated load and rated power factor	Iffl	179.09 Amp
Voltage regulation	Vreg	37 %
Rotor current density	cds2	4.65 Amp/mm^2
Exciter Rating	Pex	53 kW

A.3 Designed Parameter with 96 Stator Slot

Table A.12: Design of Armature Parameters

No. of Stator Slot	S	96
Specific magnetic loading	B_{av}	0.58 Wb/m^2
Specific electric loading	ac	71000 a/m
Stator current per phase	Iph	328.4 Amp
Total core length	L	799.82 mm
Net Iron Length	Li	671.43 mm
Ventilating duct	L_S	7*10 mm
Core outer diameter	Do	1496 mm
Core inner diameter	Di	850.02 mm
Pole pitch	pp	667.27 mm
Turns per phase	Tph	96
Slot pitch	sp	27.80 mm
Core depth	dc	209.98 mm
Core flux density	Bc	1.09 Wb/m^2
Bare conductor Height	Hc	2.2
Bare Conductor Width	Wc	7
No. of Conductor Height Wise		6
No. of Conductor Width Wise		1
Slot width	Ws	13.02 mm
Slot height	Hs	113 mm
Flux density at tooth tip	Bto	1.3 Wb/m^2
Conductor per slot	Zs	6
Flux/Pole	∅	0.3095 Wb
Current density	(cds)δ	3.55 Amp/mm^2
Mean turn length	Lmtr	3.96 m
Stator winding resistance per phase	Rph	0.08 Ω
Air gap length	Lg	11 mm
Armature reaction	ATa	20324
Leakage reactance	X_l	0.167 P.U
Chording Pitch		22/24
Winding		Double layer shorted pitch by 3 slot lap wound

Table A.13: Design of Field Parameters

Peripheral Speed	Va	65 m/sec
Rotor diameter	Dr	828 mm
Slot pitch	rsp	65.032 mm
Copper strip height	Hcr	6.0 mm
Copper strip width	Wcr	7.5 mm
No. of Conductor Height wise		11
No. of Conductor Width wise		4
Wound slot height	Hs2	80.3 mm
Slot width	Ws2	34.59 mm
Conductor per slot	Zs2	44
Area of conductor	Af	45 mm^2
Turns per pole	Tp2	64
Length of mean turn	Lmtr	3.37 m
Rotor winding resistance per pole	Rfp	0.1006 Ω
Winding		Double layer simplex lap wound

Table A.14: Details of Open Circuit Characteristic

E(L-L) P.U	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6
E(L-L) V	2200	4400	6600	8800	11000	13200	15400	17600
Stator Teeth (Wb/m^2)	0.22	0.44	0.66	0.88	1.11	1.33	1.55	1.77
Stator Teeth (AT/m)	77.25	102.05	127.1	179.5	300	700	2705	11100
Stator Teeth (AT)	8.72	11.53	14.36	20.28	33.9	79.1	305.66	1254.3
Stator Core (Wb/m^2)	0.21	0.43	0.65	0.87	1.09	1.30	1.52	1.74
Stator Core (AT/m)	48.95	76.15	105	136.95	172.5	376.5	875	3000
Stator Core (AT)	10.09	15.99	22.04	28.75	36.22	79.06	183.74	629.97
Rotor Teeth (Wb/m^2)	0.44	0.89	1.33	1.78	2.23	2.67	3.12	3.56
Rotor Teeth (AT/m)	122.5	178.5	712.5	11250	67950	70224	72515	75840
Rotor Teeth (AT)	9.8	14.33	57.21	903	5456	5639	5823	6090
Rotor Core (Wb/m^2)	0.09	0.19	0.28	0.38	0.47	0.57	0.66	0.76
Rotor Core (AT/m)	25	44.5	58	69.05	79.5	90	99.75	115
Rotor Core (AT)	6.84	12.17	15.87	18.89	21.75	24.63	27.30	31.47
Air gap (AT)	1408	2817	4226	5634	7043	8452	9860	11269
TOTAL AT	1443	2871	4335	6605	12591	14274	16200	19275
If (Amp) OCC	22.53	44.85	67.74	103.20	196.73	223.027	253.12	301.16

Table A.15: Details of Weight, Losses and Efficiency

WEIGHT	*****	*****
Weight of stator core	Kgcore	4469 Kg
Weight of stator teeth	Kgteeth	1056 Kg
Weight of rotor steel	Kgrtst	3719 Kg
Weight of stator copper	Kgstcu	940 Kg
Weight of rotor copper	Kgrtcu	173 Kg
Total weight	Kgtot	10461 Kg
Weight per kVA	Kg/KVA	1.67 Kg
LOSSES	*****	*****
Mechanical losses		67.32 kW
Stator copper losses		34.17 kW
Eddy current losses		51.93 kW
Iron losses		12.05 kW
Rotor copper losses		38.06 kW
Total losses		203.536 kW
EFFICIENCY		96.09 %

Table A.16: Details of Performance Related Parameters

Stator Temperature Rise	θ	33.69 C
Armature Reaction Field Current	Ifar	317.56 Amp
Field current on short circuit at rated armature current	Ifsc	335.94 Amp
Short circuit ratio	S.C.R.	0.58 P.U
No load field current	Ifo	196.74 Amp
Field current at rated load and rated power factor	Iffl	252.56 Amp
Voltage regulation	Vreg	40%
Rotor current density	cds2	5.61 Amp/mm^2
Exciter Rating	Pex	105.49 kW

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