# DESIGN OF A HYDRO GENERATOR

BY


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(2005 / 21979EE)

ELECTRICAL AND COMPUTER ENGINEERING

DEPARTMENT


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A PROJECT SUBMITTED TO THE

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# DEDICATION

This project work is dedicated to loving memories of my late brother Mal. Buhari Abdullahi Rabah who was also an ardent lover of teaching profession and always shows concern to me during the course of studies.

# DECLARATION

I Abubakar Abdullahi Rabah, declare that this work was done by me and has never been presented else where for the award of a degree. I also here by relinquish the copyright to the federal university of technology, minna.

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# ABSTRACT

This project involved the design of a 1MVA, 11KV, 500rpm, and 3 phase hydro-generator with at frequency of 50Hz. The project work involved only one stage viz design. During the design, an analysis was carried out to determine: The main dimensions, Armature Design, Rotor Design, Damper windings, Field winding and the Design of Yoke.

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# CHAPTER ONE

## 1.1 INTRODUCTION

An electric generator is a device for converting mechanical energy into electrical energy. The process is based on the relationship between magnetism and electricity. When a wire or any other electrically conductive material moves across a magnetic field, an electric current occurs in the wire. The large generators used by the electric utility industry have a stationary conductor. A magnet attached to the end of a rotating shaft is positioned inside a stationary conducting ring that is wrapped with a long, continuous piece of wire. When the magnet rotates, it induces a small electric current in each section of wire as it passes. Each section of wire constitutes a small, separate electric conductor. All the small currents of individual sections add up to one current of considerable size. This current is what is used for electric power

An electric utility power station uses either a turbine, engine, water wheel, or other similar machine to drive an electric generator or a device that converts mechanical or chemical energy to electricity. Steam turbines, internal-combustion engines, gas combustion turbines, water turbines, and wind turbines are the most common methods to generate electricity.

The concept used in this design is to generate electricity from water which has been around for a long time and there are many large hydro-electric facilities around the world. What is new to most people is the idea that this same concept will work on a smaller – and even individual – scale. With the rising costs of utility power and refinements to micro-hydro systems, it is now not only possible, but also very practical, to look at water as the source for your electricity.

systems, it is now not only possible, but also very practical, to look at water as the source for your electricity.

The capability to produce and deliver electricity for widespread consumption was one of the most important factors in the economic influence and wealth of any country. Hydroelectric power, among the first and simplest of the technologies that generated electricity, was initially developed using low dams of rock, timber, or granite block construction to collect water from rainfall and surface runoff into a reservoir. The water was funneled into a pipe (or pen-stock) and directed to a waterwheel (or turbine) where the force of the falling water on the turbine blades rotated the turbine and its main shaft. This shaft was connected to a generator, and the rotating generator produced electricity. One gallon (about 3.8 liters) of water falling 100 feet (about 30 meters) each second produced slightly more than 1,000 watts (or one kilowatt) of electricity, enough to power ten 100-watt light bulbs or a typical hairdryer.

There are now three types of hydroelectric installations: storage, run-of-river, and pumped-storage facilities. Storage facilities use a dam to capture water in a reservoir. This stored water is released from the reservoir through turbines at the rate required to meet changing electricity needs or other needs such as flood control, fish passage, irrigation, navigation, and recreation. Run-of-river facilities use only the natural flow of the river to operate the turbine. If the conditions are right, this type of project can be constructed without a dam or with a low diversion structure to direct water from the provide unique benefits not available with other electricity generating technologies. They do not contribute to air pollution, acid rain, or ozone depletion, and do not stream channel into a penstock. Pumped-storage facilities, an innovation of the 1950s, have specially designed turbines. These turbines have the ability to generate electricity the conventional way when water is delivered through penstocks to the turbines from a reservoir. They can also be reversed and used as pumps to lift water from the powerhouse back up into the reservoir where the water is stored for later use. During the daytime when electricity demand suddenly increases, the gates of the pumped-storage facility are opened and stored water is released from the reservoir to generate and quickly deliver electricity to meet the demand. At night when electricity demand is lowest and there is excess electricity available from coal or nuclear electricity generating facilities the turbines are reversed and pump water back into the reservoir. Operating in this manner, a pumped-storage facility improves the operating efficiency of all power plants within an electric system. Hydroelectric developments produce toxic wastes. As a part of normal operations many hydroelectric facilities also provide flood control, water supply for drinking and irrigation, and recreational opportunities such as fishing, swimming, water-skiing, picnicking, camping, rafting, boating, and sightseeing. [ 7]

## 1.2 A BRIEF HISTORY OF HYDROPOWER

The mechanical power of falling water is an age-old tool. It was used by the Greeks to turn water wheels for grinding wheat into flour more than 2,000 years ago. In the 1700's mechanical hydropower from water wheels was used extensively for milling and pumping. In 1826, The Frenchman Jean-Victor Poncolet proposed a machine involving a fully enclosed waterwheel, where water would flow into the wheel rather than along the wheel. Following this concept, the American Samuel Howd patented the first turbine in 1838. James Francis later perfected it by curving the blades. Known as the Francis turbine, this became the foremost water turbine in use. Turbines slowly replaced the waterwheel in driving sawmills and textile mills. The turn of the century in the US was a golden era for hydropower. Thousands of small-scale hydro sites were scattered about the countryside, with hundreds of turbine manufacturers in existence. By the early 1900's, a new use was found for the water program, hydropower's percentage has slowly declined and today provides about 10% of the electricity in the US. One by one, the micro hydro turbine builders went out of business, watermills went silent and turbines were abandoned as power lines raced across the country. However, today hydropower is being revived as a clean and renewable energy source. Modern hydro plants range in size from the “micro-hydro”turbines that power remote cabins or small homes, to the giant dam systems like the Hoover Dam, providing electricity to millions of people daily.[ 6 ]

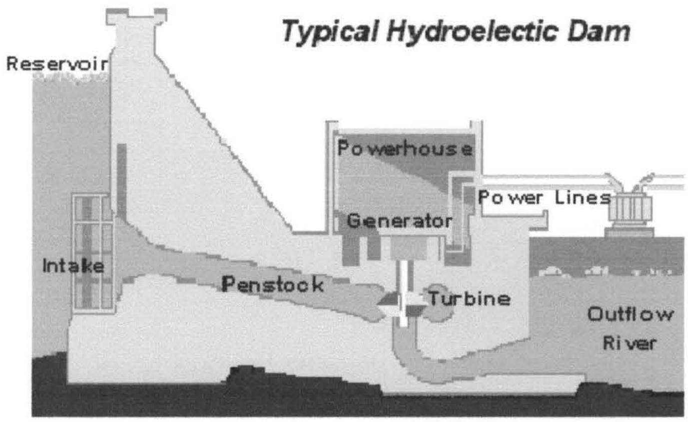



**Fig 1.1 A typical Hydro electric Dam**

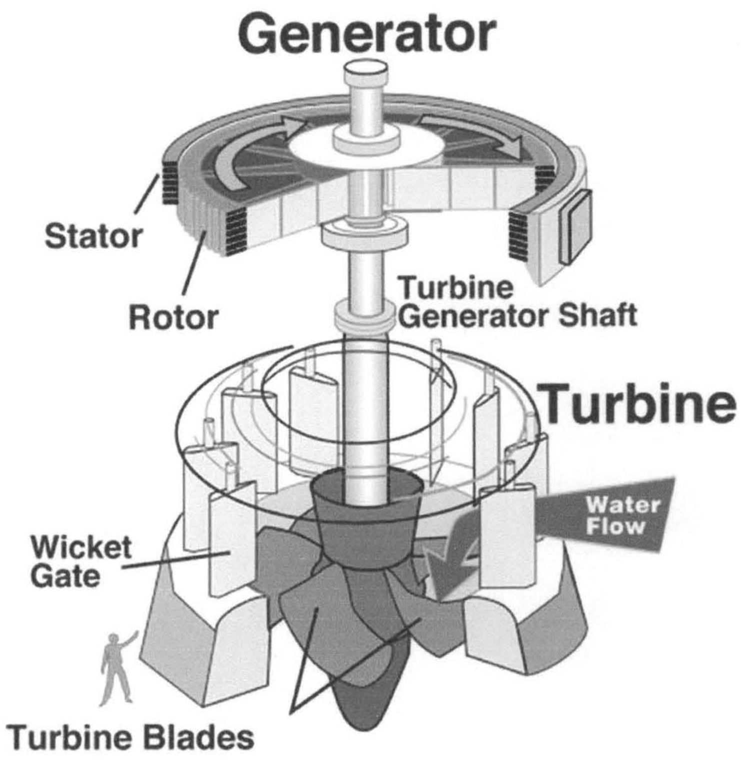



**Fig 1.2 A typical Hydrogenerator**

## 1.3 AIMS AND OBJECTIVES

This project is aimed at providing a full detail of information to the manufacturer in designing a hydrogenerator.

The objectives is to walk you through the steps in achieving a better design of a hydrogenerator according to the given specification,

## 1.4 SIGNIFICANCE OF THE STUDY

This project has a major role to play in eliminating the cost of fuel. The cost of operating is nearly immune to increases in the cost of fossil fuels such as oil, natural gas, or coal and no importance are needed.

Hydroelectric plants also tend to have longer economic lives than fuel-fired generation, with some plant now in services which were built 50 to 100 years ago. Operating labour cost is also usually low, as plants are automated and have few personnel on site during normal operation.

## 1.5 THE SCOPE OF THE STUDY

This project was written in 5 chapters. Chapter one contains the introduction, aims and objectives, and scope of work. In chapter two, the literature review (theoretical background) is discussed. Chapter three highlights the methodology which includes the relevant information about the design and the calculations carried out while chapter four contains information on the results obtained, and the discussions of those results. Finally, chapter five discusses the conclusions and recommendation

## 1.6 METHODOLOGY

In this research, the following are consulted,

[i] Textbooks

[ii] Internet

[iii]Various designer manuals

[iv] Consultations with learned individuals with vast experience and exposure.

# CHAPTER TWO

## 2.0 LITERATURE REVIEW

## 2.1 SYNCHRONOUS MACHINE

A synchronous machine is an ac rotating machine whose speed under steady state condition is proportional to the frequency of the current in its armature. 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.

Synchronous machines are commonly used as generators especially for large power systems, such as turbine generators and hydroelectric generators in the grid power supply. Because the rotor speed is proportional to the frequency of excitation, synchronous motors can be used in situations where constant speed drive is required. Since the reactive power generated by a synchronous machine can be adjusted by controlling the magnitude of the rotor field current [ 8 ]

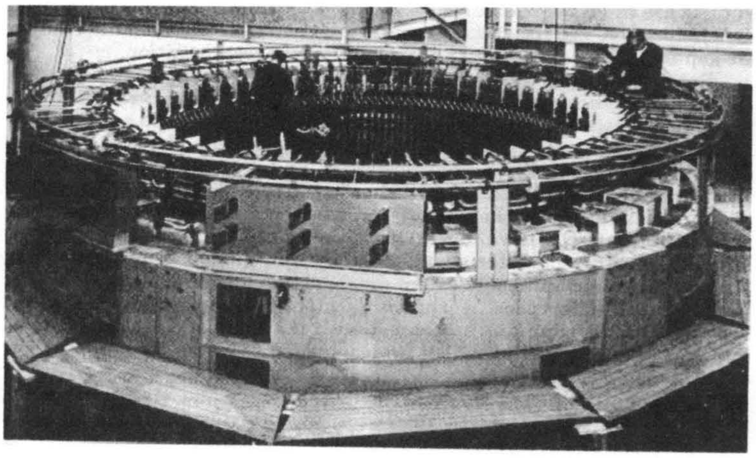


Fig 2.1 A stator of a hydrogenerator

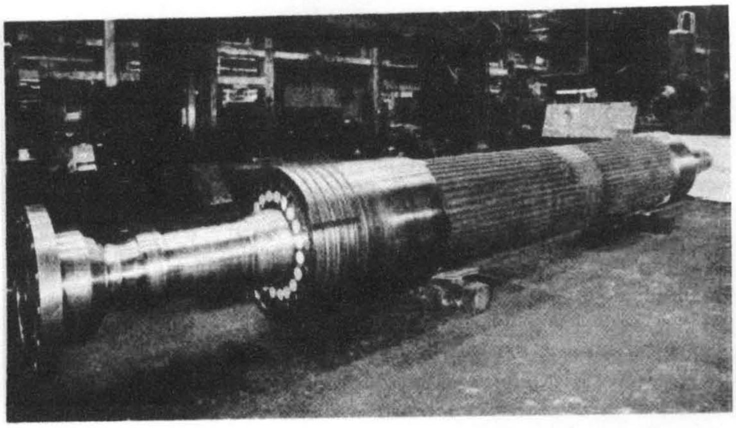


Fig 2.2 rotor of a hydrogenerator

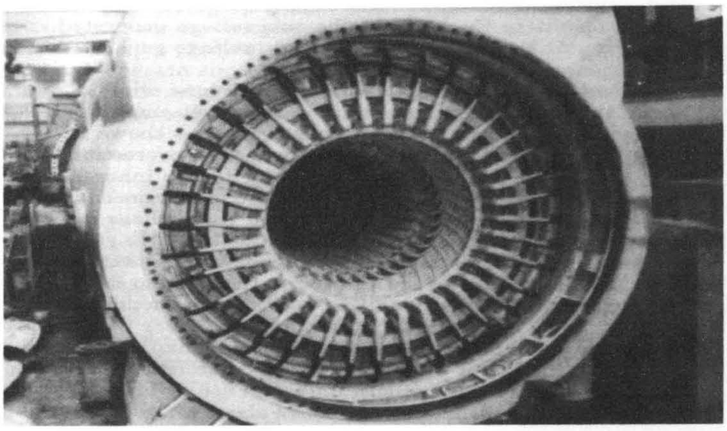


Fig 2.3 Stator of a hydro generator

## 2.2 STATOR WINDING

The magnitude of the voltage induced in the stator winding is a function of the magnetic field intensity, the rotating speed of the rotor, and the number of turns in the stator winding. An actual description of individual coil design and construction, as well as how the completed winding is distributed around the stator. The basic goal is to obtain three balanced and sinusoidal voltages having very little harmonic content (harmonic voltages and currents are detrimental to the machine and other equipment in a number of ways). To achieve a desired voltage and MVA rating, the designer may vary the number of slots, and the manner in which individual coils are connected, producing different winding patterns. The most common winding arrangement is the lap winding. A connection scheme that allows great freedom of choice in designing the windings to accommodate a given terminal voltage is one that allows connecting sections of the winding in parallel, series, and/or a combination of the two. Below is the typical winding arrangements for a four-pole generator. [9 ]

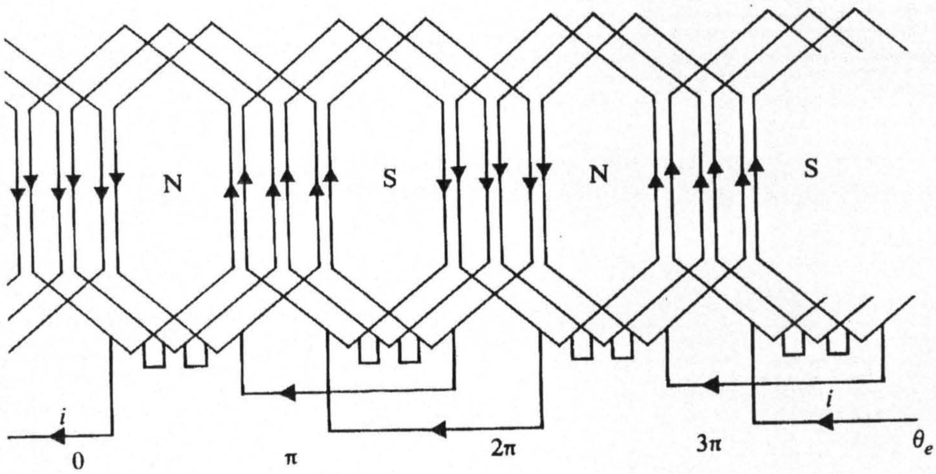



Fig 2.4 Single-phase,wole-coil distributed winding

### 2.2.1 STATOR CONSTRUCTION

Synchronous machines come in all sizes and shapes, from the miniature permanent magnet synchronous motor in wall-clocks, to the largest steam-turbine driven generators o

up to about 1500 MVA. Synchronous machines are one of two types: the stationary field or the rotating dc magnetic field. The stationary field synchronous machine has salient poles mounted on the stator—the stationary member. The poles are magnetized either by permanent magnets or by a dc current. The armature, normally containing a three-phase winding, is mounted on the shaft. The armature winding is fed through three sliprings (collectors) and a set of brushes sliding on them. This arrangement can be found in machines up to about 5 kVA in rating. For larger machines all the typical arrangement used is the rotating magnetic field. The stator core is made of insulated steel laminations. The thickness of the laminations and the type of steel are chosen to minimize eddy current and hysteresis losses, while maintaining required effective core length and minimizing costs. The core is mounted directly onto the frame or (in large two-pole machines) through spring bars. The core is slotted (normally open slots), and the coils making the winding are placed in the slots. There are several types of armature windings, such as concentric windings of several types, cranked coils, split windings of various types, wave windings, and lap windings of various types. Modern large machines typically are wound with double-layer lap windings [ 9 ]

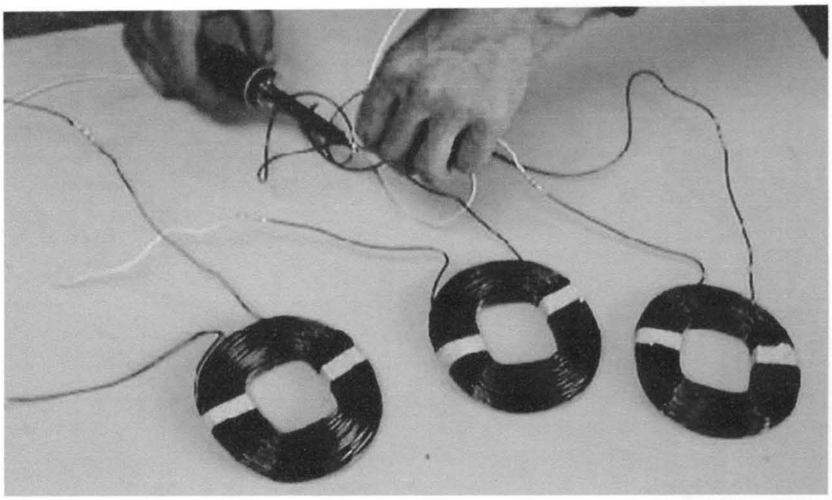
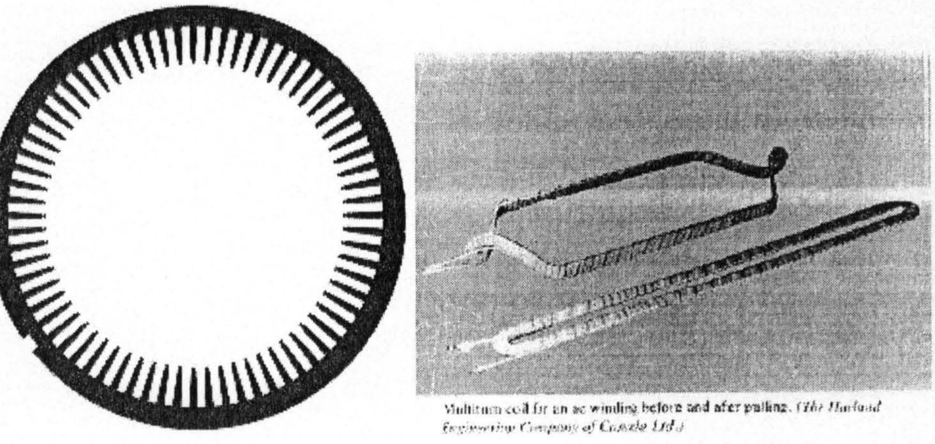


Fig 2.5 A typical double layer lap winding

### 2.2.2 STATOR PRINCIPLE OF OPERATION

When the stator winding of a three phase synchronous motor is supplied by a balanced three phase power supply of frequency *f*, the balanced three phase currents in the winding will generate a rotating magnetic field of speed $nf = 120f/P$. This rotating magnetic field will drag the magnetized rotor, which is essential a magnet, to rotate at the same speed $n=nf$. On the other hand, this rotating rotor will also generate balanced three phase *emf's* of frequency *f* in the stator winding, which would balance with the applied terminal voltage

The stator of a synchronous machine consists of a laminated electrical steel core and a three phase winding. Fig.(a) below shows a stator lamination of a synchronous machine that has a number of uniformly distributed slots. Coils are to be laid in these slots and connected in such a way that the current in each phase winding would produce a magnetic field in the air gap around the stator periphery as closely as possible the ideal sinusoidal distribution. Fig.(b) is a picture of a coil.



(a) (b)

Fig 2.6 (a) stator lamination and (b) coil of a synchronous machine

As illustrated above, these coils are connected to form a three phase winding. Each phase is able to produce a specified number of magnetic poles . The windings of the three phase are arranged uniformly around the stator periphery and are labeled in the sequence that phase *a* is 120o (electrical) ahead of phase *b* and 240o (electrical) ahead of phase *c*. It is noted that in the diagrams above, two coil sides are laid in each slot. This type of winding is known as the double layer winding. In the case that there is only one coil side in each slot, the winding is known as the single layer winding. [ 9]

## 2.3.0 ROTOR WINDING

In self-excited generators, shaft-mounted exciter and rectifier (diodes) generate the required field current. The shaft-mounted exciter is itself excited from a stationary winding. The fact that unlike the stator, the rotor field is fed from a relatively low power, low voltage circuit has been the main reason why these machines have the field mounted on the rotating member and not the other way around. Moving high currents and high power through the collector rings and brushes (with a rotating armature) would represent a serious technical challenge, making the machine that much more complex and expensive. Older generators have field supplies of 125 volts dc. Later ones have supplies of 250 volts and higher. Excitation voltages of 500 volts or higher are common in newer machines. [10 ]

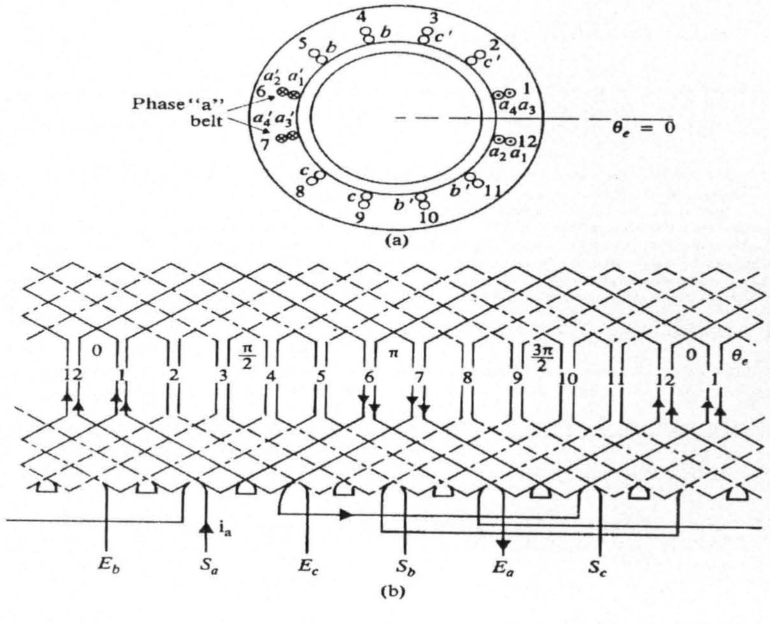



Fig 2.7 Two pole,three phase double- layer full-pitch winding

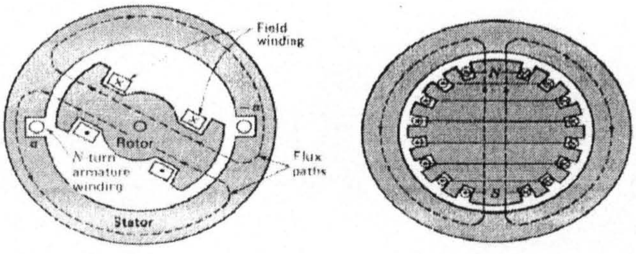
## 2.3.1 ROTOR CONSTRUCTION

The Rotor is a cylindrical structure made from solid forging of alloy steel must be homogeneous and flaw less. The surface is planed and milled to form the slots.Normally about two third of the surface have slots and the rest is left unslotted . Concentric multi-turn coils are used with slot-pitch so selected to avoid undesirable harmonics in the wave form of gap density .The end winding which are not being retained by slot wedges, must be contained [ 3 ]

The rotor field is either of salient-pole or non-salient-pole construction, also known as round rotor or cylindrical rotor. Non-salient-pole (cylindrical) rotors are utilized in two- or four-pole machines and in six-pole machines. These are typically driven by steam or combustion turbines. The vast majority of salient-pole machines have six or more poles. They include all synchronous hydro generators, almost every synchronous condenser, and the overwhelming majority of synchronous motors. The magnetic field distribution of a distributed phase winding can be obtained by adding the fields generated by all the coils of the winding.

When the field distributions of a number of distributed coils are combined, the resultant field distribution is close to a sine wave. The fundamental component of the resultant *mmf* can be obtained by adding the fundamental components of these individual coils.

In the case of a salient pole rotor, the rotor poles are shaped so that the resultant *mmf* and flux density would distribute sinusoidally in the air gap, and thus the induced *emf* in the stator windings linking this flux will also be sinusoidal




(a) (b)

(b)Fig 1.10 (a) round or cylindrical rotor and (b) salient rotor structures

## 2.3.2 ROTOR RINCIPLE OF OPERATION

The rotating magnetic field (also known as revolving-field) synchronous machine has the field-winding wound on the rotating member (the *rotor* ), and the *armature* wound on the stationary member (the *stator*). A dc current, creating a magnetic field that must be rotated at synchronous speed, energizes the rotating field-winding. The rotating field winding can be energized through a set of slip rings and brushes (external excitation), or from a diode-bridge mounted on the rotor (self-excited). The rectifier-bridge is fed from a shaft-mounted alternator, which is itself excited by the pilot exciter. In externally fed fields, the source can be a shaft-driven dc generator, a separately excited dc generator, or a solid-state rectifier. Several variations to these arrangements exist. [ 5 ]

## 2.4 EXCITER

The exciting current for the synchronous generator can be supplied by a small DC generator, known as the exciter, driven from the main shaft. The power absorbed by this DC generator amounts to 0.5% – 1.0% of the total generator power. Nowadays a static exciter usually replaces the DC generator, but there are still many rotating exciters in operation.

## 2.5. FACTORS AFFECTING THE SIZE OF THE MACHINE

### 2.5.1 SPECIFIC MAGNETIC LOADING ($B_{av}$)

This is defined as the average value of flux density over the whole surface of air gap in the machine

$$B_{av} = \frac{\text{Total flux in the air gap}}{\text{Area of flux path in the air gap}}$$

$$= {P\phi}/{\pi DL}$$

The following are the usually $B_{av}$ assumed.

| | |
|---|---|
| Cylindrical Rotor Machine | 0.55 to 0.65wb/m$^2$ |
| Salient Pole Machine | 0.50 to 0.65wb/m$^2$ |

Lower value for inner rating machines and higher value for higher rating machine

#### 2.5.2 Choice of Specific Magnetic Loading ($B_{av}$)

The following are some of the important factors influencing the choice of $B_{av}$.

1. **Iron Loss:** A higher value of $B_{av}$ means higher working flux density in teeth and core loading to increased are losses affecting the efficiency and temperature rise.
2. **Voltage:** A machine with high terminal voltage will require more slot space leaving reduce space for teeth. Therefore in such cases higher $B_{av}$ is not recommended.
3. **Short Circuit Current:** Synchronizing power which is directly responsible for the stability of the machine is inversely proportional to the synchronous reactance $X_s$. A high value of $B_{av}$ gives low value of $X_s$. Thus improving the stability.
4. **Satiability:** Synchronizing power which is directly responsible for the stability of the machine is inversely proportional to the synchronous reactance $X_S$. A high value of $B_{av}$ gives low value of $X_S$. Thus improving the stability.[ 3 ]

### 2.5.3 SPECIFIC ELECTRIC LOADING ($a_c$)

This is defined as the r.m.s. ampere conductors per meter of armature periphery at the air gap surface.

$$a_e = \frac{\text{Total armature ampere conductor}}{\text{Armature periphery at the air gap}}$$

Thus following are the usual value of $a_c$.

| | | |
|---|---|---|
| Turbo – machines | 50,000 to 100,000 | amp-cond/m |
| Salient pole machines | 20,000 to 60,000 | amp-cond/m |

### 2.5.4 CHOICE OF SPECIFIC ELECTRICAL LOADING ($a_c$)

The following are source of the important factors influencing the choice of $a_c$.

i. **Temperature Rise:** A high value of $a_c$ means increased amount of copper loss leading to high temperature rise sophisticated cooling methods must be employed to dissipate the heat, if not high $a_c$ can not be assumed.

ii. **Voltage:** For high voltage machine space required for insulation is more, thus less space for copper and therefore higher $a_c$ can not be assumed.

iii. **Synchronous Reactance:** A high value of $a_c$ means higher synchronous reactance leading to poor inherent voltage regulation lower short circuit current and small synchronizing power.

iv. **Stray Load Loss:** A high value of $a_c$ leads to higher stray load loss.

The output equation can be worked out in terms of peripheral speed since in many cases it is the limiting features.[ 3 ]

$Periheral\ speed\ v = \pi Dn\ m/sec$

i.e. $D = {}^{v}/_{\pi n}$

## 2.6 MAIN DIMENSIONS

The product $B_{av}$, $a_c$ determines the output per unit volume for a given speed. To increase the output per unit volume the loading constants $B_{av}$ and $a_c$ are increased.

## 2.7 SHORT CIRCUIT RATIO ON MACHINE PERFORMANCE

The ratio of field current required to produce rated voltage on open circuit to field current required to circulate current on short circuit is called as Short Circuit Ratio (SCR).

### 2.7.1 EFFECTS OF SCR ON MACHINE PERFORMANCE

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

ii. **Voltage Regulation:** A high value of SCR means that the synchronous reactance has a low value resulting into good inherent voltage regulation.

iii. **Short Circuit Current:** A small value of SCR means a large value of $X_d$ which will limit the short circuit current during fault conditions

iv. **Parallel Operation:** A machine with low value of SCR means a large value of $X_d$ giving a small value of synchronizing power. Such a machine will have difficulty during parallel running.

This a machine designed for high SCR is good from the point of view of stability, voltage regulation and parallel running but is costlier to build. So modern trend is to design the machine with a low value of SCR along with fast acting control and excitation system.[3]

## 2.8 AIR-GAP LENGTH

A machine with longer length of air gap means large value of reluctance to the flux produced by armature MMF decreasing synchronizing reactance and therefore higher SCR. The machine will characterize as having:

i. Higher stability

ii. Higher synchronizing power therefore easily tolerates load variation

iii. Inherently good voltage regulation

iv. Better cooling

v. Less percentage of unbalanced magnetic pull.[ 3 ]

## 2.9 ARMATURE DESIGN

Choice of number of slots, its dimension, conductor section, winding type, insulation and depth of stator core will fall under the design of armature.

i. **Choice of Number of Slots:** The following factor are considered for framing the guide lines for the choice of number of slots.

ii. **Balanced Winding:** The number of slots are selected that a balanced 3-ph winding obtained. The use of unbalanced winding will lead to generation of space harmonies and consequently over heating.

iii. **Hot Spot Temperature and Cost:** Choosing too small a number of slots will lead to crowding of conductor, hampering air circulation and consequently developing high internal temperature. However smaller number slots result in some saving in labour lessr coil to wind, insulate, place in to slots and connect.

iv. **Tooth Flux Density:** Choosing of too large number of slots will lead to narrower teeth resulting into increased tooth flux density beyond permissible limits.

v. **Leakage Current:** With lesser number of slots, the conductors are nearer loadings to increased leakage flux and there by increased leakage reactance..

## 2.10 INSULATION

Class-B insulation is normally used. The modern practice is to employ class F insulation with temperature limits of class B to be used under normal running. High temperature is permitted with over loading for short duration if required. Employing class F insulation, makes optimum use of the active materials in the machine

## 2.11 CONDUCTOR AND COILS

Two types of coils are commonly used, either single turn bar or multi-turn depending upon conductor cross-section and number of turn. In large machines, owning to heavy current, the conductor section become large obviously rectangular conductors have to be used. Further a single conductor of large section can not be used but sub-divided into many part to reduce eddy current loss. These sub-divisions may be called as strands. Make the conductor more flexible and easy to form. The conductor sub-division is preferred by laying a number of insulated copper strips flat wise in the slot. The thickness of each strand is up to 3mm and width normally varies between 4 to 7mm. The numbers of size of strands are determined by eddy loss consideration and construction requirements.

## 2.12 THE DAM

It is a means of storage or a reservoir for large quantity of water for its effective use. It is usually built across a river where mankinds manage and utilized it for[ 5 ]

The generation of electricity. It is a zoned rock filled embankment dam located across the river Niger and which is extended to an impervious blanket of 450m long on the upstream side.

## 2.13 PENSTOCK

It is a channel through which water flows in from the dam and it I being stored then later conveyed for its effective use in the turbine system [ 5 ].

## 2.14 WICKET GATES

These are installed in the opening of the inner side of the scroll case of the spiral casing for the effective control of water from the dam into the turbine blade, which involves opening and closing of the gate by the servomotor.These gates are controlled hydraulically in such a way that their control keeps the system frequency stable by feeding the required quantity of water to the runner blades.[ 5 ]

## 2.15 TURBINE BLADE

It is a component that is being driven by the inflowing of the pressurized water system,which converts the turbine system into a kinetic energy.

## 2.16 BASIC PRINCIPLES OF OPERATION OF A HYDRO GENERATOR

In some generating power station, there are six (6) generator units of the same output. Each is made up of a rotating permanent magnet (which is the rotating part or the rotor) and a single-loop coil, which is on the fixed part called STATOR OF THE MACHINE. Each of the generators is then connected to a turbine with its shaft. When water flows in from the wicket gates into the turbine pit, which is open by the shaft ring. The pressure of the water tends to rotate the turbine blade (runner blade) whereby setting the turbine shaft into kinetic energy. The water used in the running of the blade in the turbine pit is transported through a conduit draft tube to the other side of the river dam. The running turbine shaft is connected to the permanent magnet of the rotor shaft in the generator, whereby producing an electrical energy from the kinetic energy produced by the turbine shaft.

The generator can not start operating until it is self-excited, with this process a battery bank is created so as to self ignite the generator (which is a direct current source type). The battery bank produces a direct current to a system called the field circuit. It is this system that self- excites the generator whereby allowing the generator to work for 10s before the field circuit breaker discharges itself from the generator system. It is at this point that the turbine running shaft takes up the running generator, allowing the generator to work as an alternating current. Each generator is connected to an electronic turbine regulator system, an electronic and hydraulic governing system in a unit to co-ordinate the operations and monitors the performance of the unit. A power transformer is attached to each units to step up the generated voltage from 16kv to 330kv is a national grid voltage [ 5 ]

# CHAPTER THREE

## 3.0 DESIGN ANALYSIS

Hydro-generator are designed to achieve the following information regarding its various parts, to supply those data to the manufacturer.

- Main dimensions of stator frame
- Complete details of the stator winding
- Details of the rotor and its winding.

In order to carry out the design for obtaining the above information, the designer needs the following:

- Detail specification of the hydro-generator.
- Design equations, based on which the design is initiated.
- Proper information for choosing justified vales of various design parameters.
- Limiting values of various performance parameters, such as iron losses,

## 3.1Specification

The starting point of any design is the specification to which the machine must be built. The

main specifications are:

KVA/MVA Capacity = 1MVA

Voltage rating = 11KVA

Speed = 500rpm

Number of Phases = 3 phase

Frequency = 50Hz

All these informations are necessary for the designer.

3.1.2 OUTPUT EQUATION

The output equation of a 3-phase synchronous machine is same as that of a 3-phase induction machine. We have to relate the output of the machine with its main dimensions. The following nomenclatures are use.[ 1 ]

$E_{ph}$ = Induce EMF per phase in volts (induced EMF per phase = applied voltage per phase)

$I_{ph}$ = Current per phase A

$T_{ph}$ = No of turns per phase

$\phi$ = flux per pole in the air gap

P = Number of poles

$K_w$ = winding factor

$B_{av}$ = Average value of flux density in the air gap

$A_c$ = Ampere conductor per meter of the armature periphery

D = Armature diameter or stator bore diameter in m

L = stator core length, in m

$n_s$ = synchronous speed in r.p.s.

η = Full load efficiency

Cos Φ = Full load power factor

T = pole pitch = $\pi D/p$

The MVA rating of a three phase by hydrogenerator is given by

$$MVA = 3 \times E_{ph} \times I_{ph} \times 10^{-3}$$

Or

$$MVA = 3 \times 4.44kw\ f\ \phi\ T_{ph} \times I_{ph} \times 10^{-3} \qquad 3.0$$

Two important quantities are o be considered at this stage

3.1.3 Specicific electric loading

$$a_c = \frac{\text{Total armature ampere conductor}}{\text{Armature periphery at the air gap}}$$

$$= \frac{3 \times 2 \times I_{ph}}{\pi D} \qquad 3.1$$

From the relation

$$f = {n_s p}/_{2} = {P_{NS}}/_{120} \qquad 3.2$$

From equation (3.1)

$$\phi = B_{av} \times {\pi DL}/_{P}$$

And from equation (3.1)

$$I_{ph} \times T_{PH} = {ac \times \pi D}/_{3 \times 2}$$

Rewriting equation (3.0) and inserting the above derived values

$$MVA = 3 \times 4.44 \times Kw \times n_s \times \frac{P}{2} \times B_{av} \times \frac{\pi DL}{P} \times \frac{ac \times \pi D}{3 \times 2} \times 10^{-3}$$

$$= (1.11\pi^2 Kw \times B_{av} \times ac \times 10^{-3}) \cdot D^2 L n_s \qquad 3.3$$

$$= C_o D^2 L n_s \qquad 3.4$$

Where

$$C_o = 1.11\pi^2 Kw B_{av} \cdot a_c \times 10^{-3} \qquad 3.5$$

Equation (3.3 or 3.4) is called the output equation of a hydrogenerator and $C_o$ is called as output coefficient.

The following are the usually $B_{av}$ assumed.

| | |
|---|---|
| Cylindrical Rotor Machine | 0.55 to 0.65wb/m$^2$ |
| Salient Pole Machine | 0.50 to 0.65wb/m$^2$ |

Lower value for lower rating machines and higher value for higher rating machine

$$Periheral\ speed\ v = \pi Dn\ m/sec \qquad 3.6$$

$$\text{i.e. } D = {v}/_{\pi n} \qquad 3.7$$

Inserting this in equation (3.7) we get

$$MVA = 1.11 K_w B_{av} a_c \times 10^{-3} \frac{v}{n} L \quad 3.8$$

Thus following are the usual value of $a_c$.

| | | |
|---|---|---|
| Turbo – machines | 50,000 to 100,000 | amp-cond/m |
| Salient pole machines | 20,000 to 60,000 | amp-cond/m |

## 3.2 DESIGN OF A SALIENT POLE MACHINE

`3.2.1 Main Dimension

Stator bore diameter ≃ Rotor outer diameter

The selection of D is influenced by the peripheral speed $v$ and the type of pole construction.

**TABLE 3.1**

| **Type of Pole Fixing** | **Allowance Peripheral Speed** |
|---|---|
| Bolted on Pole Construction | 50m/secs |
| Devetailed and T-head Construction | 80m/secs |

Given that

MVA Capacity = 1MVA

Voltage Rating = 11KV

Synchronous Speed = 500rpm = 8.33rps

Number of phases = 3 – ph (assumed)

Frequency = 50Hz

3.2.2 Determination of the Number of Poles

From the relationship

$$f = n_s \frac{P}{2} \quad 3.9$$

$$= \frac{P_{NS}}{120}$$

$\therefore 120f = P_{NS}$

$p = \frac{120 \times f}{N_s}$ 3.10

Where

P = Number of pole

F = frequency

$N_s$ = Synchronous speed in r.p.m OR

$n_s$ = Synchronous speed in r.p.s

$\therefore \quad P = \frac{120 \times 50}{500} = 12$

$P = 12\ poles$

By using the output equation refer to (3.3)

MVA = $1.11\pi^2 K_w B_{av} a_c \times 10^{-3} D^2 L n_s$

Where

$K_w$ = Winding factor

$B_{av}$ = Average value of flux density in the air gap

$a_c$ = Ampere conductor per meter of the armature periphery

D = Armature diameter or stator bore diameter

L = Stator core length in m

$N_s$ = Synchronous speed in r.p.s.

Assuming

$K_w$ = 0.955

$B_{av}$ = 0.65wb/m$^2$

$a_c$ = 40,000amp – cond/m

$1 \times 10^6 = 1.11\pi^2 \times 0.955 \times 0.65 \times 40{,}000 \times 10^{-3} D^2 L \times 8.333$

$D^2L = {1 \times 10^6}/{(1.11\pi^2 \times 0.955 \times 0.65 \times 40{,}000 \times 8.333)}$

$= {1 \times 10^6}/{2267.323251}$

$= 441.049m^3$

3.2.3 The limiting value of peripheral speed $v = \pi Dn = 60m/sec$

$D = {60}/{\pi n}$

3.11

$= {60}/{(\pi \times 8.333)}$

$= 2.292m$

3.2.4 The stator core length (L)

$L = {D^2L}/{D^2}$

3.12

$= {441.049}/{2.29} \times 2.20$

$= 84.104m$

3.2.5 calculation of flux per pole

$flux\ per\ pole\ \phi = B_{av} \times {\pi DL}/{P}$ 3.11

Where

$\phi$ = flux per pole

$B_{av}$ = Average value of flux density in the air gap

D = Armature diameter or stator bore diameter

L = Stator core length

P = Number of poles

$\therefore \quad \phi = {(0.65 \times 3.142 \times 2.29 \times 84.104)}/_{12}$

$= {393.343}/_{12}$

$= 32.777Wb$

$Maximum\ Value\ of\ flux = {\pi}/_{2}\,\phi$ 3.12

$= {\pi}/_{2} \times 32.777$

$= 51.493Wb$

3.2.6 calculation of turn per phase

$T_{ph}$ = Turn per phase

$E_{ph}$ = The voltage per phse (11KV)

$K_w$ = Winding factor (0.955)

f = frequency (50Hz)

$\phi$ = flux per pole

$$\therefore \quad T_{ph} = \frac{(11 \times 1000)/\sqrt{3}}{4.44 \times 0.955 \times 50 \times 32.777}$$

$$= \frac{6350.852961}{6949.05177} = 0.914$$

One conductor per slot is used

3.2.7 Total number of slot $= 3 \times 0.914$

$= 3.42 \approx 4$

**TABLE 3.2:** short circuit ratio on machine performance

| **Type** | **SCR** |
|---|---|
| Modern Turbo-generator | 0.5 to 0.6 |
| LC speed-generator | 1.0 to 1.5 |

## 3.3 ARMATURE DESIGN

Considering the given parameters as follows

Ampere per conductor = 40,000

Peripheral speed $v$ = 60m/sec

Winding factor $K_w$ = 0.955

Average gap density = $6A/min^2$ (assumed)

Number of poles = 12

$$n = \frac{500}{60} = 8.333\ r.p.s.$$

Using equation 3.8

$$MVA = 1.11 K_w B_{av} a_c \times 10^{-3} \times \frac{v}{n} L$$

Where

$B_{av}$ = Average value of flux density in the air gap

$a_c$ = Ampere conductor per meter of the armature

n = synchronous speed r.p.s.

$l$ = armature core length

Substituting we have

$$1 \times 10^6 = 1.11 \times 0.955 \times 0.05 \times 40{,}000 \times 10^{-3} \times {60^2}/{8.333}\, L$$

$$L = \frac{1 \times 10^6 \times 8.333}{1.11 \times 0.955 \times 0.05 \times 40{,}000 \times 10^{-3} \times 60 \times 60}$$

$$L = \frac{8333000}{99220680}$$

$$L = 0.084m$$

and

$$D = \frac{v}{\pi n} = \frac{60}{\pi \times 50} = 0.382\text{m}$$

3.3.1 The value of flux = $\pi D L B_{av}$

$= \pi \times 0.382 \times 0.084 \times 0.65$

$= 0.066Wb$

3.3.2 The flux per pole $= \phi = B_{av} \frac{\pi D}{P} L$

$= 0.68 \frac{\pi \times 0.382}{12} \times 0.084$

$= 0.006Wb$

3.3.3 Number of Turn per phase

$$T_{PH} = \frac{E_{ph}}{4.49k_W f \phi}$$

$$= \frac{11000/\sqrt{3}}{4.44 \times 0.955 \times 50 \times 0.055}$$

$$= \frac{6350.852961}{1.272060}$$

$= 4992.57$

$\approx 4992$turns

3.3.4 Current per phase $I_{ph} = \frac{MVA}{3 \times (11000/\sqrt{3})}$

$$= \frac{1 \times 10^6}{3 \times 6350.852961}$$

$$= \frac{1000000}{19052.559}$$

$= 52.486A$

3.3.5 Now the total ampere conductors $= \pi D a_c$ 3.13

$= \pi \times 0.382 \times 40{,}000$

$= 48009{,}76$

3.3.6 Total conductors $Z = \frac{48009.76}{52.486}$

$= 914.716$

$= 914$

3.3.7 Conductor section $a_s = \frac{I_{ph}}{3 \times P}$ 3.14

$$= \frac{52.486}{12 \times 3} = \frac{52.486}{36}$$

$$= 1.458mm^2$$

Using one conductor per slot, total slots = $52 \times 36 = 1872$

3.3.8 Slot-pitch $\tau_{ss} = \frac{\pi \times 0.382}{1872}$

$$= 0.0064m$$

$$= 6.4cm$$

Recall

Flux per pole $\phi = 0.006$

3.3.9 Flux density

$$B = \frac{\phi}{Effective\ area\ per\ pole}$$ 3.15

Assuming an effective area $a_e = 0.09$

$$\therefore B = \frac{0.006}{0.09}$$

$$= 0.067Wb/m^2$$

AT required for air gap $AT_g = 800{,}000Bl_g$ 3.16

Assuming; Air gap length at pole center = 20mm

Field current for full load short circuit current = 70A

Field turns per pole = 60

$$\therefore AT_g = 800{,}000 \times 0.067 \times 20 \times 10^{-3}$$

$$= 1072$$

3.3.10 Total A required = $SCR \times AT_g$ 3.17

$$= 1.2 \times 1072$$

$= 1286.4$

3.3.11 Field current require at no load = $\frac{1286.4}{60} = 21.44A$

3.3.12 Short circuit ratio SCR = $\frac{21.44}{70} = 0.306$

And

$X_d = \frac{1}{SCR} = 3.268$

$X_d = 3.268$

## 3.4 STATOR SLOT DIMENSION

To determine the minimum width $W_{t(min)}$ you can the equation

$$W_{t(min)} = \frac{\phi}{\psi \frac{Ss}{P} Li \times 1.8} \quad 3.18$$

Where

$\phi$ = flux per pole

$\psi$ = ratio $\frac{pole-are}{pole-pitch} = 0.65$

Ss = Number of stator slot

Li = Length of stator

$$W_{t(min)} = \frac{22.777}{0.65 \times \frac{4}{12} \times 84.104 \times 1.8}$$

= 0.00694m

$= 6.44 \times 10^{-3}$m

### 3.4.1 stator core depth

To find the stator core $d_c$ behind the slot use the relation in equation

$$d_c = \frac{\phi/_2}{Li \times B_c} \quad 3.19$$

Where

$\phi$ = flux per pole

Li = Length of stator

Assuming

$B_c$ = core flux density to be $1.2Wb/m^2$

$$\therefore \quad d_c = \frac{32.777/_2}{84.104 \times 1.2} = 0.162\text{m}$$

= 0.162m

**3.4.2 Stator Outer Diameter**

It has been stated that the outer the diameter of the stator is given by the relation in equation. Thus $D_o = D + 2(d_{ss} + dc)$ 3.20

Where

D = Stator internal diameter

$d_{ss}$ = Depth of stator slot

$d_c$ = Depth of stator core

But depth of stator slot is normally about 3 times the width. Therefore:

$$d_{ss} = W_{t(min)} \times 3 \qquad 3.21$$

$$d_{ss} = 0.00694 \times 3 = 0.021m$$

Substituting we have

$$D_o = 2.292 + 2(0.021 + 0.162) \qquad 3.22$$

$$= 2.650 \approx 3m$$

To determine the pole pitch τ

$$\tau_p = \frac{\pi D}{P} \qquad 3.23$$

Where

$\tau$ = pole pitch

D = Diameter

P = The number of poles

$\therefore \quad \tau_p = \frac{\pi \times 0.382}{12}$

= 0.100m

Assuming the ratio $\frac{pole-are}{pole-pitch}$ = 0.65

3.4.3 Pole arc = $\psi\ \tau$ 3.24

$= 0.65 \times 0.100 = 0.065m$

3.4.4 selection of number of slots

Taking slots per pole per phase g = 4

**NOTE**

For double layer winding number of conductors per slot must be an even integer.

3.4.5. Number of slots $S_s = 4 \times 12 \times 3$

$= 144$

3.4.6 Number of armature conductors $Z = P \times I_{ph}$ 3.25

Where

P = Number of poles

$T_{ph}$ = Tom per phase

$\therefore \quad Z = 12 \times 4992$

$= 59904$

Where

Z = Number of armature conductor

$S_s$ = Stator slot

$\therefore \quad Z_s = \frac{59904}{144} = 416s$

3.4.6 slot loading = $I_{ph} \times 4$ 3.26

$= 52.486 \times 4 = 209.944$

### 3.4.7 calculation of the air-gap length

The flux density distribution in the air-gap for a synchronous generator double layer full pitch coil is given by

$$B = B_1(Sin\alpha + 0.3\ Sin3\alpha + 0.1Sin5\alpha)wb/m^2\text{S} \qquad 3.27$$

From the trigonometric identities, it was deduced that voltage involved per turn

$$E_t = 4.44f\phi\sqrt{1+\left(\frac{Bm_3}{Bm_1}\right)^2+\left(\frac{Bm_5}{Bm_1}\right)^2} \qquad 3.28$$

Where

$f$ = frequency = 50Hz

$\phi$ = total flux per pole = 0.006Wb

$E_t = 4.44 \times 50 \times 0.006\sqrt{1+(0.3)^2+(0.1)^2}$

$= 1.332 \times 1.099$

$= 1.397v$

3.4.8 Voltage induce per phase

$E_{ph}$ = Number of coils in series × voltage per coil 3.29

$= 4992 \times 16.764$

$= 83{,}685.888v$

$= 83{,}685v$

3.4.9. The line voltage will be :

$E_{line} = \sqrt{3} \times E_{ph}$ 3.30

$= \sqrt{3} \times 83685$

= 144.946.6718SS

$= 144.996v$

## 3.5 CALCULATION OF ARMATURE RESISTANCE

3.5.1 The stator resistance per phase **(dc)** = $r_{dc} = \rho \frac{Lmt \cdot T_{ph}}{a_s}$ 3.31

Where

Lmt = Length of Mean turn = 823.48m

$T_{ph}$ = Number of turn per phase = 4992

$a_s$ = conductor section area = 1.458mm$^2$

$\rho$ = Resistivity of the conducting material

**TABLE 3.3**

| | Conducting material | Resistivity (ohm-m) at 20$^o$C x 10$^{-8}$ | Temperature coefficient of resistance in $^o$C at 20$^o$C x 10$^{-4}$ | Density Kg/m=3 | Melting Point |
|---|---|---|---|---|---|
| 1. | Silver | 1.6 | 40 | 10500 | 960 |
| 2. | Copper (annealed) | 1.7241 | 39.3 | 8890 | 1083 |
| 3. | Copper (hard drawn) | 1.777 | 39.3 | 8890 | 1083 |
| 4. | Aluminum (Annealed) | 2.8 | 40.3 | 2703 | 660 |
| 5. | Aluminum (Hard drawn) | 2.82 | 40.3 | 2703 | 660 |
| 6. | Tungsten | 5.50 | 50 | 18800 | 3300 |
| 7. | Brass | 7.0 | 15 to 20 | 8400 – 8700 | - |
| 8. | Nickel | 10.5 | 40 | 8850 | 1450 |
| 9. | Tin | 11.5 | 46 | 7300 | 232 |
| 10. | Lead | 21 | 41 | 11400 | 327 |

Taking $\rho = 1.7241$ from the table above

$$r_d = 1.7241 \times \frac{823.48 \times 4992}{1.458}$$

$$= 1.7241 \times \frac{4110612.16}{1.458}$$

$= 1.7241 \times 2819487.078$

$= 4{,}861{,}077.672$

Copper is choosing because it offers excellent electrical and mechanical properties.

## 3.6.ESTIMATION OF LENGTH OF AIR-GAP

The no load field per pole is related with the armature mmf per pole and short circuit ratio by a simple relation.

$$AT_{fo} = AT_a \times S.c.r \quad 3.32$$

Where

$AT_a$ = Armature mmf per pole

S.c.r = Short circuit ratio

But

$$AT_{fo} = 2.7\ \frac{I_{ph} \times T_{ph} \times K_w}{P} \quad 3.33$$

Where

$I_{ph}$ = Current per phase

$T_{ph}$ = Number turn per phase

$K_w$ = Winding factor

P = Number of poles

$$AT_{fo} = \frac{52.486 \times 4992 \times 0.955}{12}$$

$= 20851.638A$

3.6.1The no load field per pole 3.34

$$AT_{fo} = AT_a \times S.c.r$$

$= 20851.638 \times 1.2$

$= 25021.966A$

Now

$$B_g = {}^{B_{av}}/_{\psi} \qquad 3.35$$

Where

$B_{av}$ = Average value of flux density in the air gap

$\psi$ = ratio $\frac{pole-are}{pole-pitch} = 0.65$

$$B_g = {}^{0.65}/_{0.65} = 1.00Wb/m^2$$

Using the equation

$$l_g = \frac{0.8AT_{fo}}{800{,}000B_gK_g} \qquad 3.36$$

Where

$AT_{fo}$ = The armature mmf per pole

$K_g$ = gap extension

$B_g$ = Air gap density

Taking $K_g = 1.15$

$$\therefore \quad l_g = \frac{0.8 \times 25021.966}{800{,}000 \times 1.00 \times 1.15}$$

$= 21.8 \times 10^{-3}$m ⇒ Minimum gap length at the center of the pole

= 21.8mm

For the machine with open type slot

$${}^{l_g}/_{\tau_p} = {}^{0.00218}/_{0.10}$$

= 0.0218

Table value of $\boldsymbol{\delta_f}$

**TABLE 3.4**

| Type of Winding | $\boldsymbol{\delta_f}$ |
|---|---|

| | |
|---|---|
| Small round wires | 0.4 |
| Large round wires | 0.65 |
| Large rectangular conductors | 0.75 |
| Strip on edge winding | 0.8 |

**TABLE 3.5** Value of $d_f$

| **Pole Pitch** | $d_f$ |
|---|---|
| 0.1 | 0.025 |
| 0.2 | 0.035 |
| 0.4 | 0.045 |

## 3.7 ROTOR CALCULATION

The star connected salient pole alternator has the following design data. From the previous design.

Stator bore diameter = 2.292m

Stator core length = 0.084m

Slot per pole per phase = 4

Conductor per lot = 416

Winding factor = 0.955

power Rating= 1MVA

voltage Rating = 11KV

Speed = 500rpm

Number of phase = 3-phase

Number of poles = 12 poles

The total slot of a rotor is given by

3.7.1 Total slots = $3\frac{1}{2} \times p \times 3$ 3.37

$= 3\frac{1}{2} \times 12 \times 3$

$= 54$

3.7.2 Total conductors Z $=$ Total slots $\times$ slot per pole per phase 3.38

$= 54 \times 4 = 216$

There are two parallel path per phase

3.7.3 Number of turns in series per phase = ${}^{T_{ph}}/_{a}$ 3.39

$$= {}^{36}/_{2} = 18 turns$$

Where $T_{ph}$ = Turn per phase

a = Number of parallel path per phase

Now $E_{ph} = 4.44 f k_w \phi \frac{T_{ph}}{a}$ 3.40

Where

$f$ = frequency

$K_w$ = Winding factor

$\phi$ = flux per pole

a = Number of parallel 4path per phase

$T_{ph}$ = Turn per phase

$E_{ph} = 4.44 \times 50 \times 0.955 \times \phi \times 18$

Assuming a field winding dissipation = 1000

$$\Rightarrow \frac{1000}{\sqrt{3}} = 577.350 = 4.44 \times 50 \times 0.955 \times \phi \times 18$$

$$\phi = \frac{577.350}{4.44 \times 50 \times 0.955 \times 18}$$

$= 0.151 Wb$

This is the useful flux per pole

3.7.4 Total flux per pole $= \text{leakage factor} \times \text{useful flux}$ 3.41

$$= 1.2 \times 0.151 = 0.181Wb$$

Area of pole body $A_p = \frac{Total\ flux\ per\ pole}{Flux\ density\ in\ pole}$ 3.42

Considering

Flux density in pole = 1.5

$$A_p = \frac{0.181}{1.5} = 0.121m^2$$

$B_g$ taking the length of pole body $l_p$ = core length = 84.104m

3.7.5 The width of pole body $W_p = \sqrt{\frac{4}{\pi} A_p}$ 3.43

Where

$A_p$ = cross-section of a pole body

$$W_p = \sqrt{\frac{4}{\pi} \times 0.121} = 0.392m$$

3.5.6 Now current per phase $I_{ph} = \frac{1000000}{3 \times 577.350} = 262.042$

$$I_{ph} = 262.042A$$

3.5.7 Conductor current $I_z = {}^{I_{ph}}/_{2}$ 3.44

$$= \frac{262.042}{2} = 131.021A$$

3.5.8 Armature mmf per pole

$$AT_a = \frac{2.7 \times I_z \times T_{ph} \times K_w}{P}$$ 3.45

Where

$I_z$ = Conductor current

$T_{ph}$ = Turn per phase

$K_w$ = Winding factor

P = Number of poles

$$AT_a = \frac{2.7 \times 131.021 \times 4992 \times 0.955}{12}$$

= 52052.023AT

3.5.9 full load field mmf, $AT_{fL} = 2 \times AT_a$ 3.46

$$= 2 \times 52052.023$$

$$= 104{,}104.046A$$

3.5.10 Height of field winding $h_f = \frac{AT_{fL}}{10^4 \sqrt{P_\theta \cdot \delta_f \cdot d_f}}$ 3.47

Where $AT_{fL}$ = full load field mmf

$\delta_f$ = Copper space factor

$d_f$ = Depth of winding

$P_\theta$ = Permissible loss in w/m$^2$ = field winding dissipation

Taking from the table

$\delta_f = 0.8$

$d_f = 0.03$

$$\therefore h_f = \frac{104104.046}{10^4 \sqrt{1000 \times 0.8 \times 0.03}}$$

$h_f$ = 2.125m

= 212.5cm

By leaving 10cm for insulation

3.5.11 The Height of pole body $h_p$ = 212.5 + 10 = 222.5cm

Height taking by the flanges could taken equal to 10cm

3.5.12 Radial length of pole $h_{pl} = h_p + h_1$ 3.48

Height taking by the flanges

=222.5 + 10cm

$h_{pl}$=232.5cm

3.5.13 Total copper area of field winding = $\frac{AT_{fL}}{\delta_f}$ 3.49

Where

$AT_{fL}$ = full load field mmf

$\delta_f$ = current density in the field winding

Now Assuming $\delta_f$ = 3

Total copper area of field winding = $\frac{104104.046}{3}$ = 34701.349

Assuming suitably the space factor $\delta_f$ for the winding, total winding space factor could be estimated. Thus.

3.5.14 Total space required for field winding Total space required for winding = $\frac{\text{Total copper area of field winding}}{\delta_f}$ 3.50

Taking space factor $\delta_f$ = 0.8

= $\frac{34701.349}{0.8}$ = 43376.686

## 3.6 DESIGN OF DAMPER WINDING

Taking a case of a synchronous generator, the amplitude of fundamental mmf of one phase of a poly phase winding

$$AT_1 = \frac{4}{\pi} AT_m K_{w1} \qquad 3.51$$

*But*

$$AT_m\ gz_s \frac{I_z}{\sqrt{2}} = \sqrt{2} \frac{I_{ph} \cdot T_{ph}}{P} \qquad 3.52$$

$$\therefore \qquad AT_1 = \frac{A\sqrt{2} \cdot I_{ph} \cdot T_{ph} \cdot K_{w1}}{\pi p} \qquad 3.53$$

Where

$I_{ph}$ = current per phase

$T_{ph}$ = Turn per phase

$k_{w1}$ = Winding factor

p = Number of pole

3.6.1 Fundamental MMF of one phase $AT_1 = \frac{4\sqrt{2} \times 52.486 \times 4992}{\pi \times 12}$

$$= \frac{1482153.015}{\pi \times 12} = 39{,}310.233$$

$$AT_1 = 39{,}310.233$$

Thus the damper winding must develop an MMF equal to it.

3.6.2 MMF of damper winding $= \frac{4\sqrt{2} \cdot I_{ph} \cdot T_{ph} \cdot K_{w1}}{2\pi p}$ 3.54

$$= \frac{4\sqrt{2} \times 52.486 \times 4992}{2 \times 3.142 \times 12}$$

$$= \frac{1482153.015}{75408} = 19.655$$

3.6.3 Conductor per pole $= a_c \, {}^{\pi D}/_{p}$ 3.56

$$= a_c \tau_p$$

$$= {(6I_p \cdot T_{ph})}/_{p}$$

$$= \frac{4\sqrt{2}}{2\pi} \cdot \frac{a_c \tau_p k_w}{6} = 0.1425 a_c \tau_p$$

If $A_d$ be the total area of damper bars per pole and $\delta_d$ be the current density in the bars

$$A_d \cdot \delta_d = 0.1425 a_c \tau_p$$

$$A_d = \frac{0.1425 a_c \tau_p}{\delta_d}$$ 3.57

Where

$a_c$ = Ampere conductor per meter of the armature

$\tau_p$ = Pole-pitch

$\delta_d$ = Current density in the bar (normally take between 3 to 4 A/mm²).

Taking $\delta_d = 3$

$$A_d = \frac{0.1425 \times 40{,}000 \times 0.100}{3}$$

$= 190$

The total area $A_d$ of damper winding is distributed into several small sections depending upon

the number of bars used. The slot-pitch of the damper winding is about 0.8 times the slot pitch of the stator slots.

Let $N_d$ = Number of damper bars per pole;

$$N_d = \frac{\text{Pole-arc}}{0.8 \times \text{stator slot pitch}} \quad 3.58$$

Where

Pole arc = $\psi\tau$ = 0.065m

Stator slot pitch $\tau_{ss}$ = 6.4cm = 0.064m

$$N_d = \frac{0.065}{0.8 \times 0.064} = 1.269$$

Cross-section of each damper bar $a_d = {}^{A_d}/_{N_d}$ 3.59

Where $A_d$ = Total Area of damper bars

$N_d$ = Number of damper bars per pole

$\therefore\ a_d = {}^{190}/_{1.269} = 149.724$

$a_d = 149.724mm^2$

3.6.4 The length of each damper bar $L_d$ = s1.1L ⇒ In case of small machine

Considering = L + 0.1m for large machine

$\therefore\ L_d = L + 0.1$ (for large machines) 3.59

$\therefore\ L_d = L + 0.1$ (for large machines) 3.59

Where

L + length of stator core = 0.084m

$\therefore\ L_d = 0.084 + 0.1 = 84.204m$

$L_d = 0.1844m$

If circular bars are used having diameter $d_d$

$$d_d = \sqrt{4ad/_{\pi}} \quad 3.60$$

The bars are shorted by means of end rings provided on both ends. The cross-section area of each ring. $A_{(ring)} = (0.8 \text{ to } 7)_{Ad}$

Where

$a_d$ = Area of each bar

3.6.5 Diameter of each bar $d_d = \sqrt{\frac{4 \times 49.724}{\pi}} = 13.806$

**$d_d$** = 13.806mm

## 3.7 MMF FOR THE MAGNETIC CIRCUIT

MMF for air gap $AT_g$

For a salient machine with slot aid duct on one side and salient poles on the other.

3.7.1 MMF for air gap $AT_g = 800000\ \frac{B_{av}}{K_f} K_g \cdot K_{gd} \cdot l_g$ 3.61

Where

$K_g$ = Gap contraction factor for slot

$K_{gd}$ = Gap contraction factor for duct

$L_g$ = Minimum gap with at the center of the pole.

| Ratio $\frac{\text{Slot-opening}}{\text{Gap length}}$ | 1 | 2 | 3 | 3.5 | 4.0 |
|---|---|---|---|---|---|
| Carter's coefficient | 0.15 | 0.28 | 0.37 | 0.41 | 0.43 |

By considering the following parameters

Slot pitch = 6.4cm

Gross length of core = 0.084m = 8.4cm

Air gap length = 21.8 x $10^{-3}$m = 2.18cm

Pole arc = 65cm

Flux per pole = 0.006Wb

Assuming slot opening = 3.1cm

$$K_g = \frac{Y_S}{Y_S - K_c W_o} \qquad 3.62$$

Ratio $\frac{\text{Slot opening}}{\text{Gap length}} = \frac{3.1}{2.18} = 1.422$

This correspond to 1, carter's coefficient $K_c = 0.15$

$$\therefore K_g = \frac{Y_S}{Y_S - K_c W_o}$$

Where

$Y_s$ = slot-pitch

$K_c$ = Carter's coefficient

$W_o$ = Slot opening

$$\therefore K_g = \frac{6.4}{6.4 - (0.15 \times 2.1)} = 1.052$$

Gross core length = 8410.4cm

Ratio $\frac{\text{duct opening}}{\text{Gap length}}$

Assuming there are 8 ventilating duct each 5.2cm wide

Ratio = $\frac{5.2}{2.18} = 2.3$

Corresponding to 2.3, the carter's coefficient $K_d = 0.28$

3.7.2 Now Gap contraction for $duct_s = K_{gd}$

Where

$$K_{gd} \frac{L}{L - K_d A_d W_d} \quad 3.63$$

Where

L = length of core

$K_d$ = Carter's coefficient

$A_d$ = Number of ventilation duct

$W_d$ = Wide of ventilation duct

$$K_{gd} = \frac{8.4}{8.4 - (0.28 \times 8 \times 5.2)}$$

$$= \frac{8.4}{97.8432} = = 0.0859$$

$K_{gd} = 0.0859$

3.7.3 Gap density at the centre of pole

$$B_g = \frac{\text{Flux per pole}}{\text{Pole arc} \times \text{Core length}} \quad 3.64$$

$$= \frac{0.006}{6.5 \times 0.084}$$

$$\boldsymbol{B_g} = 0.01098 Wb/m^2$$

3.7.4 MMF for air gap

$$\boldsymbol{AT_g} = 8000{,}000\ B_g K_g K_{gd} l_g \quad 3.65$$

Where

$B_g$ = Density at the center of the pole

$K_g$ = Gap contraction factor for slot

$K_{gd}$ = Gap contraction factor for duct

$L_g$ = Minimum gap length at the center of the pole

$AT_g = 8000{,}000 \times 0.01098 \times 1.052 \times 0.0859 \times 21.8 \times 10^{-3}$

$= 0.0002017$

$= 2.017 \times 10^{-4} AT$

3.7.5 MMF for armature teeth $AT_t$

Where

h = the corresponding h, the at/m from the B – h curve characteristic of the material.

$L_t$ = length or height of tooth = depth of slot

**TABLE 3.7**

| at/cm | 50 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| B in Tesla | 1.7 | 1.84 | 1.96 | 2.04 | 2.09 | 2.13 | 2.16 | 2.18 | 2.20 | 2.22 | 2.23 |

By using the following information obtained

Slot pitch = 6.4cm

Slot width $W_s$ = 0.67cm

Stator core Length = 0.084m

The number of duct 8 each of 5.2cm wide

Assuming

- A space factor of 0.89
- Apparent density of 2.20

From

3.7.6 Stator gross lenth $L_i = 0.89\,(L - A_d W_d)$ 3.66

Where

L= Gross length

$n_d$ = Number of ventilation duct

$W_d$ = Wide of ventilation duct

$$\therefore\ L_i = 0.89\big(0.084 - (8 \times 5.2)\big)$$

$$= 0.890(0.084 - 41.0)$$

$$= 0.89 \times 42.504$$

$$= 37.829$$

3.7.7 Tooth width

$$W_t = Y_s - W_s \qquad 3.67$$

$$= 6.4 - 0.67$$

$$W_t = 5.73cm$$

3.7.8 Apparent tooth density

$$K_s = {}^{Y_{SL}}\!/_{W_t L_i} \qquad 3.68$$

$$= \frac{6.4 \times 84.104}{5.73 \times 37.829} = \frac{538.2656}{216.760}$$

$$= 2.48$$

By using the formula

$$B_{app} = B_{real} + 4\pi \times 10^{-7} h(K_s - 1) \qquad 3.69$$

$$\therefore\ B_{real} = B_{app} - 4\pi \times 10^{-7} h(K_s - 1)$$

$$= 2.20 - 4\pi \times 10^{-7} h(2.48 - 1)$$

$$= 2.20 - 4\pi \times 10^{-7} h \times 1.48$$

This is the equation of a straight line. The line can be drawn by heating two points are located as follows

When h = 0

$B_{real}$ = 2.23

The graph below is drawn corresponding to the given data

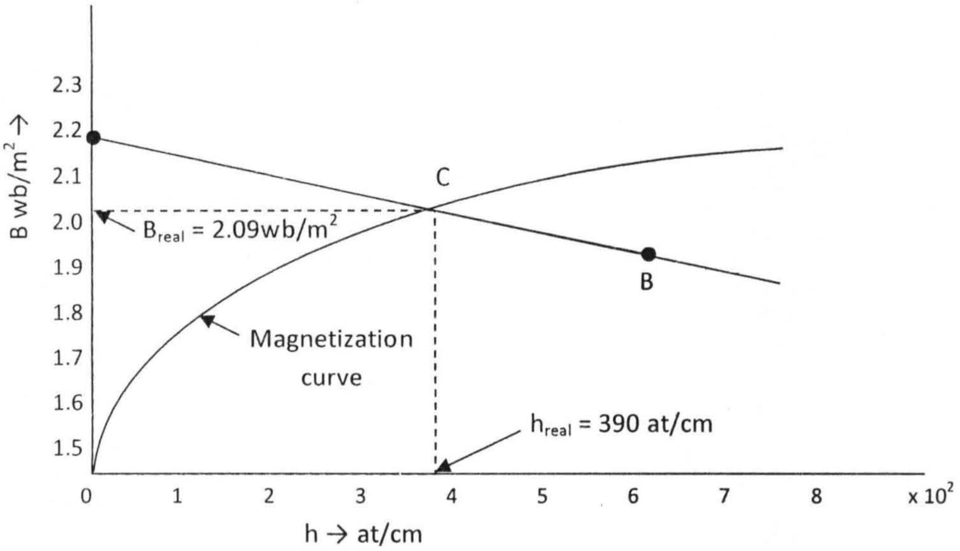
When

$H = \text{say } 600 \text{ at/cm} = 60{,}000\text{at/m}$

$B_{real} = 2.20 - 4\pi \times 10^{-7} \times 60{,}000 \times 1.48$

$= 2.088$

$\approx 2.09$




3.7.9 MMF for tooth $AT_t = h_{mean} \times l_t$ 3.70

$AT_t = 390 \times 10^2 \times \text{Depth of slot}$

$= 39000 \times d_{ss}$

Recall

$d_{ss} = 0.021m$

$\therefore AT_t = 39000 \times 0.021$

$= 319AT$

3.7.10 MMF for Armature Core

$AT_o = H_c \times l_c$ 3.71

$H_c$ = Corresponding ampere-turn per meter

$l_c$ = The length of flux path of the core

Fore core flux density $B_c$, we can find the corresponding value of ampere turn per meter $h_c$ from B – h curve of the core material. Thus from the graph above are can deduce that

$B_c = 2.01$

$H_c = 3900$

But $l_c$ is taken to be equal to half the pole-pitch at mean diameter.

i.e. $l_c = \frac{\pi(D+2d_{ss}+ d_c)}{2p}$ 3.72

where

D = Internal diameter

$d_{ss}$ = Depth of stator slot

$d_c$ = Depth of stator core

p = Number of poles

$\therefore\ l_c = \frac{\pi(2.292 +2 \times 0.021+0.162)}{2 \times 12}$ = 0.327m = 32.7cm

$AT_c = 39000 \times 32.7 = 1275.300AT$

3.7.11 MMF for Poles $AT_p$

The minimum flux in the poles $\phi_{c(min)} = \phi + \phi_{sl}$ and 3.73

Maximum flux in the poles $\phi_{p(max)} = \phi + \phi_{sl} + \phi_{pl}$ 3.74

The value of leakage flux $\phi_{sl}$ and $\phi_{pl}$ can be determine

Let $F_g$ = Gap MMF; $F_t$ = armature tooth MMF; $F_c$ = arc core MMF

$\therefore$ MMF across fluxes $\phi_{l1}$ and $\phi_{l2} = F = (F_g + F_t + F_c)$ 3.75

But

$\therefore F = 2\ (20.017 \times 10^{-4} + 819 + 1275.300)$

$= 4188.604$

The average MMF is $\frac{F}{2} = \frac{4118.604}{2}$

$= 2094.302$

But

Leakage flux between pole shoes per pole is about $20F \times 10^{-8}$, while leakage flux between pole core per pole is about $80F \times 10^{-8}$. Thus at the back of the pole is the main flux $\phi_m + 20F \times 10^{-8}$, the flux at the root of the pole is the main flux $\phi_m + 20F \times 10^{-8} + 80F \times 10^{-8}$

$\phi_{sl} = 20F \times 10^{-8}$

$= 51.493 + 20 \times 4188.604 \times 10^{-8}$

$= 51.494$

and

$\phi_{p(max)} = \phi_m + 20F \times 10^{-8} + 80F \times 10^{-8}$

$= 51.493 + 20 \times 4188.604 \times 10^{-8} + 10 \times 4188.604 \times 10^{-8}$

$= 51.493 + 8.377 \times 10^{-4} + 3.351 \times 10^{-3}$

$= 51.497$

3.7.12 Maximum flux density in the pole body

$$B_{p(max)} = \phi_{p(max)} / A_p \qquad 3.76$$

Where $\phi_{p(max)}$ = Maximum flux in the pole

$A_p$ = Area of pole body

$$B_{p(max)} = \frac{51.497}{0.121} = 425.595$$

Now corresponding to these values of densities the ampere-turn per meter $h_{p(max)}$ and $h_{p(min)}$ can be obtained from the B-h curve of the pole material.

Thus

$$AT_p = h_{p(max)} \frac{h_{pl}}{3} + h_{p(min)} \frac{wh_{pl}}{3} \qquad 3.77$$

$$= 60{,}000 \cdot \frac{2.09}{3} + 3900 \cdot \frac{2(2.09)}{3}$$

$$= 41800 + 10868$$

$$AT_p = 52668M$$

## 3.8 DESIGN OF THE YOKE

The yoke is normally made of cast steel with a flux density of 1.1 to 1.2Wb/m$^2$. Now the flux in yoke = Half the value of total flux per pole. Thus

3.8.1 MMF for Yoke $AT_y$

Flux in the yoke, $\phi_y = \dfrac{\phi + \phi_{sl} + \phi_{pl}}{2}$ 3.78

$$= \frac{51.493 + 20F \times 10^{-8} + 20F \times 80F \times 10^{-8}}{2}$$

$$= \frac{51.493 + 8.377\times 10^{-4} + 8.337 \times 10^{-4}}{2}$$

= 25.749AT

Sectional area of yoke $A_g = \dfrac{\text{Flux in the yoke}}{\text{Yoke flux density}}$ 3.79

Taking flux density 1.2wb/m$^2$

$$Ay = 21.458m^2$$

The formula for yoke flux density is given as

$$B_y = \frac{\phi_y}{L \times d_y}$$ 3.80

$$A_y = L_y \times d_y$$ 3.81

Taking the length of the yoke $L_y$ equal to that of the pole, the depth of the yoke $d_y$ can be calculated.

$$d_y = A_y - L_y$$ 3.82

$$= 21.458 - 0.392$$

$$= 2.1m$$

**MMF for yoke $AT_y$** = $h_y$ x $l_y$ 3.82

$$l_y = \frac{\pi(Dr - 2h_{pl} - d_y)}{2p}$$

$$= \frac{\pi(0.382 - 2 \times 222.5 - 21)}{2 \times 12}$$

$$= 60.957m$$

Assuming a suitable yoke height $h_y$ = 5m

$$AT_y = 5 \times 60.957m$$

$$= 304.785m$$

3.8.2 Thus total field MMF at no load.

$$AT_{fo} = AT_g + AT_t + AT_c + AT_p + AT_y \qquad 3.83$$

$$= 2.017 \times 10^{-4} + 819 + 1275.300 + 52668 + 304.785$$

$$= 65067.08521AT$$

## 3.9 DESIGN OF FIELD WINDING

3.9.1 Length of mean turn of the winding = **$L_{mtf}$**

$$L_{mtf} = 2L_m + \pi(W_p + 0.01d_f) \qquad 3.84$$

$$= 2 \times 0.39 + \pi(0.392 + 0.01 \times 0.03)$$

$$= 0.78 + 1.233$$

$$= 2.013m$$

3.9.2 Voltage across each field coil $E_f = \frac{(0.8\ to\ 0.85)}{p} v_{ex}$ 3.85

Where $V_{ex}$ = Exiter Voltage

Assuming

$V_{ex}$ = 250v for large machine

$$E_f = \frac{0.85 \times 250}{12} = 17.708v$$

Resistance of each field coil at 75°C is $R_f$

$$R_f = \frac{\rho T_f \cdot L_{mtf}}{a_f}$$ 3.86

Where

P = Resistivity of the wire

$AT_{fl}$ = full load field MMF

$A_f$ = area of field winding

But

$$a_f = \frac{AT_{fl}\, \rho L_{mtf}}{E_f}$$ 3.88

$$\therefore a_f = \frac{104104.046 \times 1.7241 \times 2.013}{17.708} = 20403.4836$$

$$a_f = 20403.4836$$

Assuming a suitable value of current density $\delta_f$ $of\ 3A/mm^2$

$$I_f = a_f \cdot \delta_f$$

$$= 20403.4836 \times 3$$

$$= 61210.451$$

And also

$$T_f = \frac{AT_{fl}}{I_f} = \frac{104104.046}{61210.451} = 1.7008$$

$$\therefore R_f = \frac{1.7241 \times 2.013 \times 1.7008}{20403.4836} \text{SS}$$

$$= 0.000289 = 2.89 \times 10^{-4}\Omega$$

3.9.3 Copper loss in each field coil $W_f$

$$W_f = \frac{I_f^2\, \rho T_f\, L_{mtf}}{a_f}$$ 3.89

$$= \frac{(61210.451) \times 1.7241 \times 1.7008 \times 2.013}{20403.4836}$$

$$= 1083{,}942.66289$$

Cooling surface

$$s\delta = 2L_{mtf}\left(h_f + d_f\right) \quad 3.90$$

$$ss\delta = 2 \times 2.013(212.5 + 0.03)$$

$$= 885.645$$

Approximate temperature rise of the coil

$$\theta = \frac{(Copper\ loss\ in\ W) \times C_f}{S} \quad 3.91$$

Where $C_f$ = Cooling coefficient for coil

$$\theta = \frac{(0.14\ to\ 0.16)}{1+0.1Va}$$

$V_a$ = Peripheral speed of armature in m/

$$C_f = \frac{0.16}{1+0.1 \times 60} \quad = 0.002285$$

# CHAPTER FOUR

## 4.0 RESULTS

### 4.1 RESULT FOR STATOR

| | |
|---|---|
| Number of pole p | = 12 |
| Limiting value of peripheral speed v | = 60m/sec |
| The stator core length l | = 0.084m |
| Flux per pole $\phi$ | = 32.777wb |
| Stator bore diameter D | = 2.292m |
| Number turn per phase $T_{ph}$ | = 0.914 |
| Number of conductor per slot | = 1 |
| Total Number of slots | = 4 |
| The length of pole l | = 0.084m |
| Number of flux per pole $\phi$ | = 0.006wb |
| No. turn per phase $T_{ph}$ | = 4992 turns |
| Current per phase $I_{ph}$ | = 52.486A |
| Conductor section area $a_S$ S | = 1.458mm$^2$ |
| Table slots | = 1872 |
| Stator slot pitch $\tau_{ss}$ | = 6.4cm |
| Field current required at no load | = 21.44A |
| Short circuit ratio s.c.r. | = 0.306 |
| Minimum width $W_{t(mm)}$ | = 0.00694m |
| Flux density B | = 0.067wb/m$^2$ |
| Field current required at no load | = 21.44A |
| Depth of the stator core $d_c$ | = 0.162m |
| Stator outer diameter $D_o$ | = 3m |

Depth of the stator slot $d_{ss}$ = 0.021m

Pole pitch $\tau_p$ = 0.100m

Pole arc = 0.065m

Slot per pole per phase g = 4

Number of slit $S_s$ = 144

Number of armature conductor Z = 699.4

Conductor per slot $Z_s$ = 416

Slot loading = 209.944

Voltage induced per turn $E_t$ = 1.397v

Voltage induced per phase $E_{ph}$ = 83685v

Limit voltage $E_{line}$ = 144946

Static resistance per phase $r_{dc}$ = 4861077

Armature mmf per pole $AT_a$ = 20851.638AT

The no load field per pole $AT_{fo}$ = 25021.966A

**4.2 RESULT FOR ROTOR**

Total slot = 54

Total conductor Z = 216

Useful flux per pole $\phi$ = 0.151Wb

The diameter of rotor D = 0.382mm

Stator bore diameter ≏ Rotor outer diameter $D_o$ = 2.292m

Total flux per pole = 0.181wb

Area of pole body $A_p$ = 0.121m$^2$

Current per phase $I_{ph}$ = 262.042A

Conductor current $I_z$ = 131.021A

Total flux per pole = 0.181wb

Area of pole body $A_p$ = $0.121m^2$

Current per phase $I_{ph}$ = 262.042A

Conductor current $I_z$ = 131.021A

Stator gross length $W_p$ = 0.392m

Armature mmf per pole $AT_a$ = $52052.023A_t$

Full load field mmf $At_{ph}$ = 104104.046A

Height of field winding $h_f$ = 212.5cm

Height of pole body $h_p$ = 222.5cm

Radial length of pole body $h_{pl}$ =232.5cm

Total copper area of field winding = 34701.349

Total space required for winding = 43376.686

**4.3 RESULT FOR DAMPER WINDING**

Fundamental MMF of one phase $AT_1$ = 39310.233

MMF of damper winding = 19.665

Total area of damper bars per pole $A_d$ = 190 $mm^2$

Number of damper bars per pole $N_d$ = 1.269

Cross-section of each damper bar $a_d$ = $149.724mm^2$

Length of each bar $L_d$ = 84.204m

Diameter of each bar $d_d$ = 13.806mm

MMF for air gap $AT_g$ = $2.017 \times 10^{-4}$ AT

MMF for armature teeth $AT_t$ = 819AT

MMF for armature core $AT_c$ = 1275.300AT

MMF for pole $AT_p$ = 52668AT

## 4.4 RESULT FOR YOKE

| | |
|---|---|
| Flux in the yoke $\phi_y$ | = 25.749AT |
| Sectional area of yoke $A_g$ | = 21.458m$^2$ |
| Yoke height $h_y$ | = 5m |
| MMF for yoke $AT_y$ | = 304.785m |
| Total field MMF at no load $AT_{fo}$ | = 55067.08521AT |

## 4.5 RESULT FOR FIELD WINDING

| | |
|---|---|
| Length of mean turn of the winding $L_{mtf}$ | = 2.013m |
| Voltage across each field coil $E_f$ | = 17.708v |
| Resistance of each field coil $R_f$ | = 2.89 x $10^{-4}\Omega$/ohm |
| Copper loss in each field coil $W_f$ | = 1083942.662 |
| Cooling surface S | = 855.645 |
| Cooling surface for coil $C_f$ | = 0.002285 |

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATIONS

## 5.1 CONCLUSION

The designs was successfully carried out to provide a required data for the design of a hydrogenerator to the manufacturer. A design process is not merely engineering calculations, but involves careful consideration.

The designer's work lies in suitably allocating the space to frame, core, air gap, winding insulation and cooling medium in the machine. More over economy in manufacturing cost, operating and running costst of the machine is also kept in view.

The machines are salient-pole machines with low speeds, decided by the type of turbine and water head, having large number of poles. The diameter thus becomes very large to accommodate large number of poles. With several hundred tonnes of load it is just not possible to transport the machine as a single unit .Therefore the machine is designed to be transported to site in section.

Limitation are imposed on the design because:

- Saturation of magnetic parts, increased core losses and excitation at higher flux density.
- Insulation breakdown due to high voltage gradient causes temperature raise and mechanical damage.

## 5.2 RECOMMENDATION

It is recommended that more design should be carried out with different design specification in order to achieve both the design and construction of a micro hydrogenerators as a source of power for domestic applications

It is recommended that a research work should be carried out by the mechanical expert on how to design, the mechanical part of the machine.

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