People’s Democratic Republic of Algeria

Ministry of Higher Education and Scientific Research

Mohamed Seddik Benyahia University of Jijel

Faculty of Science and Technology

Electrical Engineering Department

Handout course

DESIGN OF ELECTRICAL SYSTEMS

Third-Year Bachelor's Students: Electrical engineering

University lecturer

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The engineer's goal is to create systems that are both functional and beautiful

Raymond Loewry

PREFACE

Electrical machines play an important role in countless applications, ranging from industrial machinery, aircraft, manufacturing processes, electrical networks and renewable energy generation. They are designed to convert electrical energy into mechanical energy and vice versa. Their operating success and efficiency are largely dependent on a successful design process. Studying electrical system design is crucial for students to understand machine limitations.

This course handout is intended for **third-year undergraduate students on the Electrical Engineering programme**; its aim is to provide the necessary foundations for the sizing of the main types of electrical machines, namely transformers, direct current machines, asynchronous machines and synchronous machines.

Each chapter begins with an overview of the fundamental elements of electrical machines, including magnetic circuits, windings, and insulation techniques, to facilitate students' comprehension of the function of each component in the machine's operation and to provide them a complete knowledge before introducing the related design method. The chapters conclude with an example that demonstrates the process for estimating the principal dimensions of the machine under consideration.

This document is a useful resource for anyone wishing to acquire fundamental knowledge in the field of electrical systems design.

D[r] DOUNIA SEDIRA

COURSE HANDOUT ORGANIZATION

The first chapter provides an overview of the materials used in the construction of electrical machines including magnetic, conductive, insulating and mechanical materials. Examples and characteristics are presented for each one of them. The chapter also cover the thermal classes.

In second chapter a detailed description of transformer construction is presented covering types of magnetic cores and windings, it also discussed their manufacture, selection criteria and different cooling methods. At the end, an example of a single-phase transformer design is given.

Chapter three is dedicated to the design of a DC machine, it presents the operating principle, the construction of the field system such as the frame, poles and field windings. The rotor construction is discussed focusing on armature core, armature slots, windings arrangement and commutator. Finally, main dimensions of a shunt motor are calculated.

In a similar manner, chapter four and chapter five are devoted to the design of asynchronous and synchronous machines, each chapter presents the construction of the stator which is the same for both. Material used in manufacture, assembly methods of magnetic core and type of windings are provided too. The rotor structure is given, with a focus on the features of squirrel cage and wound rotors in induction motors, as well as salient-pole and cylindrical rotors in synchronous machines. The characteristics, working principles, construction details, and materials employed for each rotor type are also covered. Both chapters provide the computation of the main dimensions of an asynchronous induction motor and a synchronous machine.

Semestre: 5
Unité d'enseignement: UED 3.1
Matière 2:Conception des systèmes électriques
VHS: 22h30 (Cours: 1h30)
Crédits: 1
Coefficient: 1

Objectifs de l'enseignement:

Etre capable de calculer et dimensionner une machine électrique en fonction des exigences d'un cahier des charges précis.

Connaissances préalables recommandées:

Eléments constitutifs et principes de fonctionnement des machines électriques.

Contenu de la matière:

Chapitre 1 –Rappels **(1 semaine)**
Rappel sur les matériaux pour les machines électriques : Isolants ; Conducteurs ; Magnétiques

Chapitre 2. Transformateurs **(3 Semaines)**
Rappel sur le principe de fonctionnement et leurs utilisations
Dimensionnement d'un transformateur monophasé, Choix du matériau actif (circuit magnétique, matériaux conducteurs et isolants, organes mécaniques).

Chapitre 3. Machines électriques à courant continu **(3 Semaines)**
Rappel sur le principe de fonctionnement et leurs utilisations
Dimensionnement de la machine, Choix du bobinage, plaques signalétiques.

Chapitre 4.Machines asynchrones **(3 Semaines)**
Rappel sur le principe de fonctionnement et leurs utilisations
Dimensionnement d'une machine asynchrone, Choix du bobinage, Choix et sélection des moteurs asynchrones.

Chapitre 5.Machines synchrones **(3 Semaines)**
Rappel sur le principe de fonctionnement et leurs utilisations
Dimensionnement d'une machine synchrone, Choix du bobinage.

Références bibliographiques:

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2. *Transformers desing, A. Dymkov, Mir Bublishers, Moscow, 1975*
3. *Calcul des machines électriques. Tome I et Tome II / M. Liwschitz Dunod / cop. 1967-1970*
4. *Conception des moteurs asynchrone triphasés, BOUCHARD & OLIVIER, Ecole ploytechnique de Montréal, 1997*
5. *Design of Rotating Electrical Machines, 2nd Edition, JuhaPyrhonen, TapaniJokinen, Valeria Hrabovcova, ISBN: 978-1-118-70165-2, Sep 2013, 616 pages*
6. *Théorie industrielle de l''électricité et des machines électriques, par A. Verdurand,...1919*
7. *La construction des machines électriques, Julien Dalemont, Librairie polytechnique, 1907 - 138 pages*

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Chapter IV: Asynchronous machines

Chapter V: Synchronous machines

Chapter I: Review

I.1 Introduction

Electrical transformers are widely used. They come in a wide variety of types, ranging from ringing transformers weighing a few hundred grams to large network connection transformers weighing several kilograms. This diversity is due to the many variables involved in the design of these devices: power, frequencies, number of phases, number of windings, coupling of these windings, voltage differences between the primary and secondary sides, cooling method, installation conditions, specific uses, etc. Despite this diversity, the calculation of these devices revolves around three fundamental points:

- The magnetic circuit.
- The winding (the electrical circuit).
- Insulation.

I.2 Classification of materials used in electrical machines

These materials can be divided into three categories:

- Construction materials
- Active materials (magnetic and electrically conductive)
- Insulating materials

I.2.1 Construction materials

Construction materials are used to manufacture machine parts and components that are primarily designed to transmit and receive mechanical loads and stresses and to give certain components the shapes required for the machine to function normally (e.g., transformer tanks and electrical machine frames). The following materials are used as construction materials:

- Ordinary, malleable, non-magnetic cast iron.
- Carbon steel and alloy steel to obtain high mechanical properties.
- Non-ferrous metals and their alloys
- Plastics

I.2.2 Magnetic materials

They are used to manufacture the magnetic circuits of electrical devices. The most interesting magnetic materials are ferromagnetic and ferrimagnetic materials. There are two classes: soft materials and hard materials.

- **Soft materials (high permeability):** This category includes:
  Steel sheets characterized by: Relatively low electrical resistivity, they are used in the form of sheets (lamination) to limit eddy current circulation and the resulting losses.
  Iron-nickel alloys: have very high magnetic permeability and very low magnetic excitation. They are found in magnetic shielding.
  Ferrites are electrical iron oxides whose high electrical resistivity limits eddy currents. They can be used at frequencies above 20MHz as coil or transformer cores.
- **Hard materials (permanent magnets):** This category includes: Alnico alloys, ferrites for permanent magnets, also known as ceramics and rare earth alloys which contain samarium and cobalt ($SmCo_5$ and Sm_2Co_{17}) or neodymium, iron, and boron (NdFeB).

I.2.3 Insulating materials

Insulating materials are used to electrically separate the conductive parts of a device from each other. They have high electrical resistance, which decreases as the temperature rises. The most important characteristic of an insulating material is its ability to withstand electrical stress without breaking down. This property is quantified by dielectric strength. Insulating materials include:

- Inorganic materials (ceramics and glass)
- Plastic films
- Resins and varnishes Adhesive tapes
- Mica products
- Textile insulation
- There is also gas insulation (SF6) and vacuum insulation.

Table I.1 shows the different thermal categories for insulation

Thermal category	Operating temperature (°C)
Y	90
A	105
E	120
B	130
F	155
H	180
200	200
220	220
250	250

Table I.1: Thermal class for transformer insulation

I.2.4 Conductive materials

The most commonly used conductor in electrical engineering is copper, which is generally used to make the windings of electrical machines. To obtain sufficiently lightweight transmission line cables, aluminum is used.

Depending on the application, a few percent of chromium, silver, or cadmium may be added to the copper. Table I.2 shows the resistivity of some conductive materials.

Conductive materials	Resistivity at 20° Celsius in ohm-meters, Ω·m
Silver	1.59^{-8}
Copper	1.72^{-8}
Gold	2.04^{-8}
Aluminum	2.63^{-8}
Magnesium	4.46^{-8}

Table I.2: Resistivity of conductive materials

Chapter II: Transformers

II.1 General information on transformers

II.1.1 Definition

A transformer is a static electromagnetic device designed to transform a primary alternating voltage (current) into a secondary alternating voltage (current) of the same frequency but generally at different amplitude in order to adapt it to different usage requirements.

There are two types of transformers: single-phase and three-phase. The transformer winding to which the alternating current energy is supplied is called the primary winding, and second winding from which the energy is drawn is called the secondary winding it feeds the load.

The winding connected to the higher voltage network is called the high voltage (HV) winding; the winding connected to the lower voltage network is called the low voltage (LV) winding. If the secondary voltage is lower than the primary voltage, the transformer is called a step-down transformer, and when this voltage is higher than the primary voltage, the transformer is called a step-up transformer.

II.1.2 Operating principle

When the primary is powered by an alternating source, an alternating flux also circulates in the magnetic circuit, the amplitude of which depends on the number of turns in the primary and the applied voltage. This flux induces a voltage in the secondary winding that is proportional to the number of turns in the secondary. Closing the secondary on a load causes secondary current to flow.

The magnetic core provides a path for channeling the magnetic flux (Figure II.1).

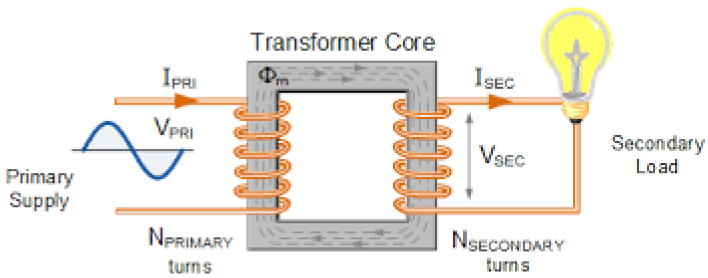


Figure II.1: Operating principle of a transformer

If we designate the number of turns in the primary winding as N1 and the number of turns in the secondary winding as N2, we obtain the theoretical transformation ratio "m" of the transformer.

$$m = \frac{N2}{N1}$$

II.1.3 Transformer symbols

Transformers are represented by the following symbols:

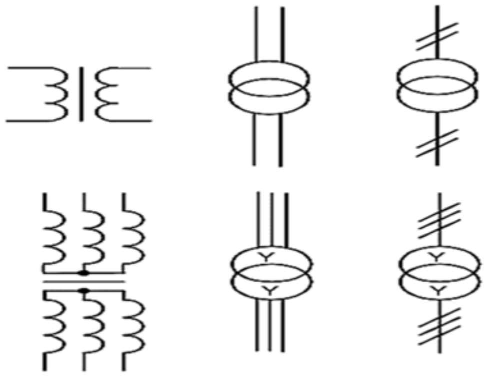


Figure II.2: Graphic symbols for transformers

II.1.4 Transformer rated values

The rated values of a transformer (power, voltages, currents, frequency, etc.) are indicated on the nameplate transformer, which must be visible (Figure II.3). These details are essential for safe installation, maintenance, and system integration. However, the term "rated" can also be applied to values that are not indicated on the nameplate but relate to the rated operating conditions as rated efficiency, rated cooling medium temperature conditions, type of coupling, …..etc. The key specifications on a transformer nameplate are:

- The rated power of a transformer is the apparent power delivered at the terminals of the secondary winding under rated conditions, expressed in VA or kVA.
- The rated primary voltage is the voltage applied to the primary winding under rated operating conditions.
- The no-load secondary voltage is the voltage across the secondary terminals when the rated primary voltage is applied and the secondary circuit is open.
- The rated primary and secondary currents of a transformer are those indicated on the nameplate. Since the efficiency of a transformer is very high, it is assumed that the rated powers of the two windings are equal.
- Rated frequency a frequency of 60 Hz is commonly used in North America, parts of South America, and some Asian countries, whereas a frequency of 50 Hz is used in Europe, most of Asia, Africa, and Australia.
- Number of phases indicates whether the transformer is 1-Ph (Single-Phase) or 3-Ph (Three-Phase).

- Temperature rise indicates the average winding temperature increase above ambint when the transformer operates at full load.
- Impedance (%Z) is the percentage of rated voltage required to circulate rated current when one winding of the transformer is short-circuited and the other is supplied at rated frequency.
- Connection type specifies the winding connection.
- Insulation class.
- Cooling method defines how heat is removed from the transformer (ONAN, ONAF, KNAN, KNAF……etc).
- Manufacture's name and serial number which is the unique identifier for the transformer.
- Year of manufacture.

Figure II.3: Nameplate of a power transformer

II.2 Construction

A transformer consists of a laminated magnetic circuit (made of steel sheets) on which two or more windings are wound. There are two active parts in the transformer: the magnetic circuit and the windings (Figure II.4).

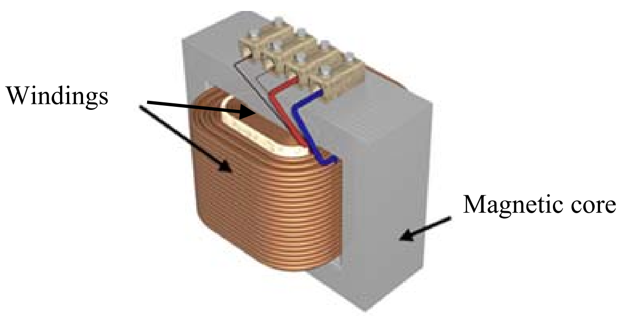


Figure II.4: Main parts of a transformer

II.2.1 Magnetic circuit

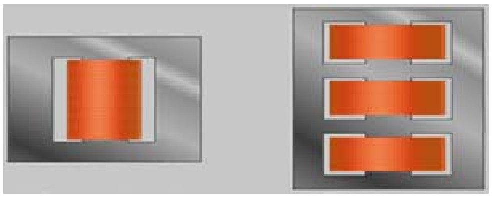
This is a closed assembly of high-permeability magnetic materials designed to provide a low-reluctance path for the magnetic flux that links the primary and secondary windings. (Figure II.5).

Figure II.5: Magnetic circuit of a power transformer

II.2.1.1 Common shapes of transformer cores

There are two types of magnetic circuits:

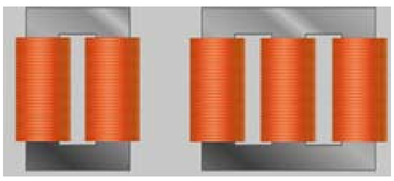
- **Shell- type:** The magnetic circuit completely surrounds the winding on both sides (Figure II.6).



a) Single-Phase **b)** Three-Phase

Figure II.6: Shell-Type transformer

- **Core-Type:** In this case, the windings surround the magnetic circuit (Figure II.7).



a) Single-Phase **b)** Three-Phase

Figure II.7: Core-Type transformer

Core- Type	Shell- Type
Ease of design and construction	Complexity of manufacturing
Low mechanical stress	High mechanical stresses
Repairability	Difficult to maintain and repair
Better heat dissipation from windings	Heat is not dissipated well from the windings because they are surrounded by the magnetic circuit
Used in high voltages	Not suitable for high voltage operation
Possibility of reducing leakage reactance	Possibility of reducing leakage reactance

Table II.1: Core-Type vs Shell-Type transformer comparison

II.2.1.2 Transformer limbs and yokes

The parts of the core on which the windings are placed are called limbs, and the parts that join the limbs and serve to close the magnetic circuit are called yokes. The spaces between the limbs and yokes, through which the windings pass, are called core windows (Figure II.8).

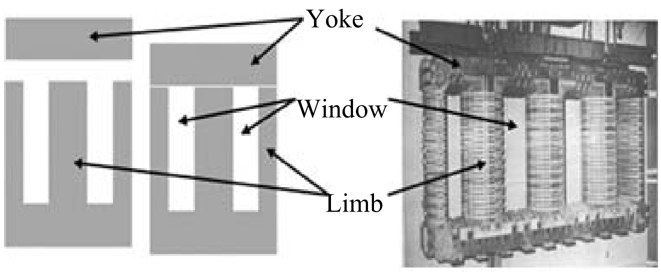


Figure II.8: Core, yoke, and window of a transformer

II.2.1.3 Cross sections of the limbs and yoke

- The cross-section of the limb is adapted as much as possible to the circular shape of the coils. In very small transformers a square shape is adopted. In small and medium transformers, the cross-section rectangular. A multi-stepped cross-section is used in power transformers (Figure II.9). Modern power transformers favors circular stepped cross-section which presents high electrical performance and improves space utilization.

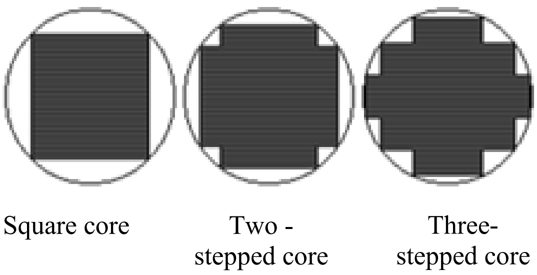


Figure II.9: Cross-sections of transformer limbs

- The cross-section of the yoke is almost always rectangular. Sometimes, in order to reduce reluctance and iron losses, it is made 15 to 30% larger than that of the limb.

II.2.1.4 Types of materials for magnetic circuits

Since an alternating magnetic field flows through the magnetic circuit of a transformer, the cores are usually made from laminated magnetic materials which presents high permeability, high resistivity and low losses, the most commonly used is silicon steel that have the following advantages:

- Reducing hysteresis losses.
- Reducing eddy current losses due to an increase in resistivity, which is 5 to 6 times that of iron.
- Eliminating the aging phenomenon.

The manufacturer provides two curves:

- Magnetic flux density curve (Tesla).
- Specific core loss curve (W/kg).

II.2.1.5 Construction of magnetic circuits

The limbs and yoke are made of sheets 0.35-0.5 mm thick. Thinner sheets are used when very low losses are required. In general , the cores of high-power transformers (over 100 kVA) are made of 0.5 mm steel sheets because assembling the core with 0.35 mm sheets is more difficult to achieve.

The main types of magnetic core joints include:

- **Butt joint core assembly:** The limbs and yokes are assembled separately and connected using fasteners. This core construction facilitates the installation of the windings on the limbs , as it only requires the removing of the upper yoke , figure (II.10).

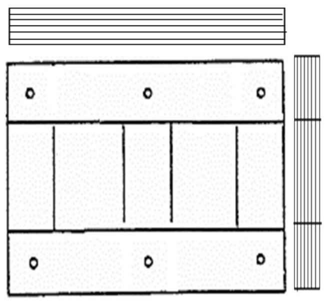
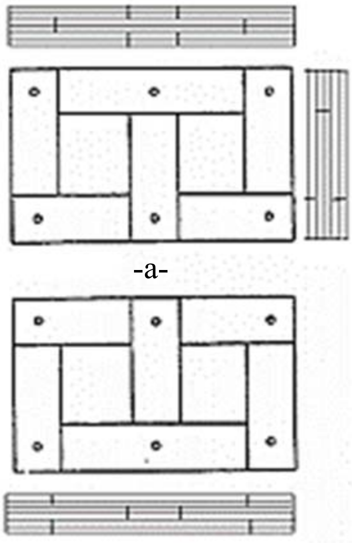


Figure II.10: Butt joint core assembly

- **Interlocking core assembly :** The core is assembled as a complete unit; therefore, when placing the winding on the limb, the upper yoke must be removed and then reinstalled, after the winding is positioned. In an interleaved core assembly, the two types of sheet metal layers are alternated layer by layer as shown in Figure (II.11).



-b-

Figure II.11: Interlocking core assembly

If the surface area of the core is insufficient to dissipate the heat, the laminated core is subdivided by cooling channels.

In medium- and high-power transformers, longitudinal cooling channels are used (Figure II.12-b). In very high-power transformers, transverse channels are added (Figure II.12-c).

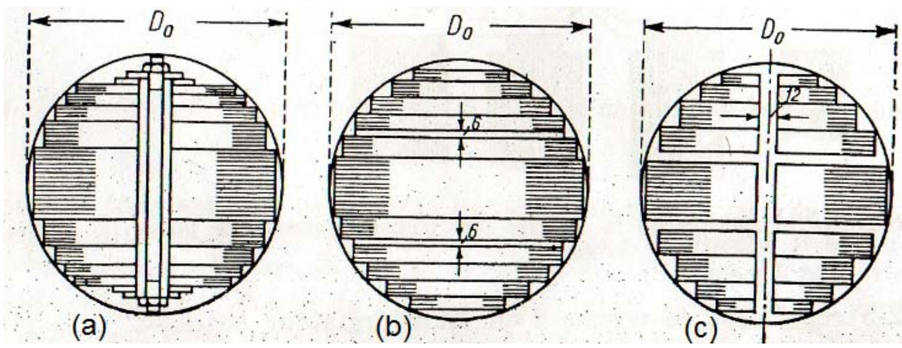


Figure II.12: Stepped shape of the single-column section: a- without channels; b- with longitudinal channels; c- with longitudinal and transverse channels.

II.2.1.6 Insulation of metal sheets

To reduce eddy current losses, laminations are insulated from each other. For very small transformers less than 5 KVA, the sheets are covered by a light layer of oxide. For higher power ratings, insulation is provided by thin paper 0.02 to 0.03 mm thick, which is glued to the surface of the sheet, resulting in an additional thickness of 0.03 to 0.04 mm.

Another more recent method involves enameling, the sheet metal is covered by a thin layer of enamel that is baked in a high-temperature oven. The enamel adds a thickness of around 0.015 mm. The mechanical strength and heat resistance are very good. Sheet metal can also be insulated by covering it with a layer of varnish, which is then air-dried.

Insulation between laminations reduces the core's effective or net area. The core's laminations and insulation, such as paper or varnish, result in a net core cross-sectional area that is approximately 10% smaller than the gross core area. The iron space factor (K_i) refers to the ratio of net to gross cross-sectional area.

$$K_i = \frac{A_i}{A_{gc}}$$

A_i: Iron's net cross-sectional area of the core.

A_{gc}: Gross cross-sectional area of the core.

II.2.2 Windings (coils)

Windings are generally made of copper, although aluminum is also used in low-power transformers for cost reasons. They are wound around the cross sections of the limbs (Figure II.13).

Figure II.13: Transformer winding of a three-phase transformer

The type of the transformer winding is mainly selected according to different factors like voltage and current level, mechanical and thermal stresses, frequency, cooling conditions and cost effectiveness.

II.2.2.1 Winding configuration

There are three main type of transformer windings:

- **Single concentric winding:** The LV winding is placed directly around the core section, while the HV winding is wound concentrically around the LV winding. Insulation is inserted between the core and the LV winding, and between the two windings to provide adequate electrical isolation. This configuration is common in core-type transformers (Figure II.14).

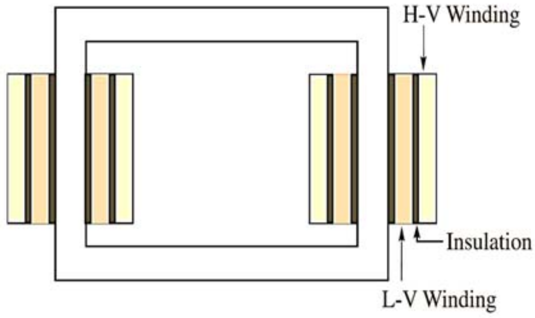


Figure II.14: Simple concentric winding

- **Double concentric winding:** In this case, the low-voltage winding is divided into two sections. The first section is wound onto the core and insulated. The high-voltage winding is then placed and insulated, and the remaining part of the LV winding is wound last (Figure II.15).

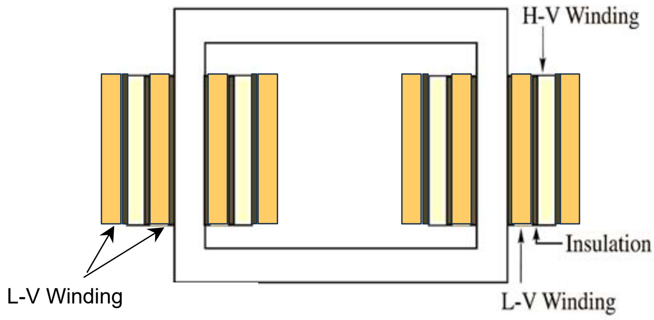


Figure II.15: Double concentric winding

- **Sandwich winding:** The HV and LV windings are made in layers and placed alternately along the core's leg. In this arrangement, the LV windings are positioned directly against the iron core to reduce leakage reactance. Sandwiched windings are almost used inshell type transformer. (Figure II.16).

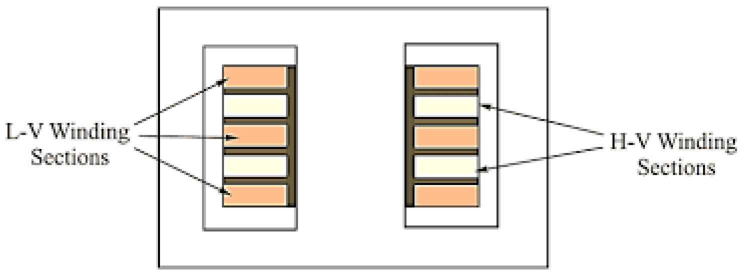


Figure II.16: Sandwich winding

II.2.2.2 Cross sectional shapes of transformer conductors

The most common cross-sections used for the transformer conductors are:

- **Circular cross-section (round wires):** Used in high-voltage, low-current applications and when the conductor cross-sections are less than or equal to 4 mm² (Figure II.17).

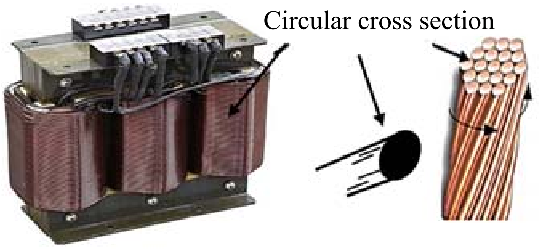


Figure II.17: Circular cross section

- **Rectangular cross-section:** Used in high-current windings and when the conductor cross-sections are greater than 4 mm² (Figure II.18). They allow better space utilization and maximize heat dissipation. However, compared to round wires, flat wires involve more complex manufacturing and higher costs.

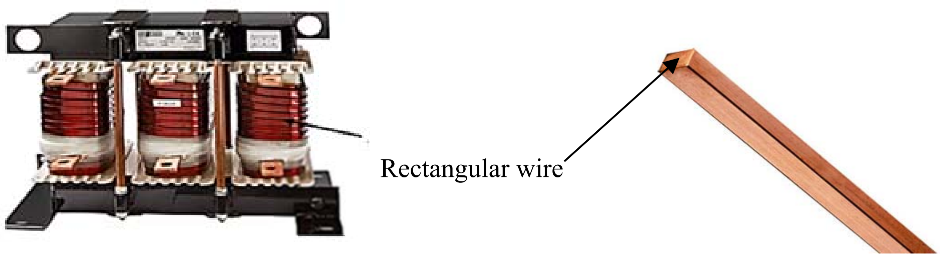


Figure II.18: Rectangular cross section wire

II.2.2.3 Winding insulation

A transformer would rapidly fail due to electrical breakdown, thermal deterioration, or moisture incursion in the absence of strong and well chosen insulating materials. Generally, insulation in a power transformer is provided:

- Between the turns and the layers of a winding.
- Between the different windings (high-voltage and low-voltage sections).
- Between each winding and the magnetic circuit.

The insulation system is used to electrically insulate the active parts of the transformer (windings, magnetic circuit, etc.) and to provide cooling. There are three main categories of transformer insulation: solid insulation, liquid insulation, and gas insulation:

- **Solid insulation:** The solid insulation system consists of paper and cardboard. Paper is used for turn and winding insulation, whereas cardboard provides insulation between the windings and between the windings and the core. Both materials are impregnated with a liquid dielectric (oil) to enhance their dielectric strength and reduce the likelihood of partial discharges.
- **Liquid insulation:** Serves a dual purpose: electrical insulation and cooling. The oil transfers the heat generated by losses in the windings, magnetic circuit, and insulating materials to the cooling devices (external radiators). Furthermore, it retards the oxidation and ageing of the solid insulation and provides electrical insulation for the components of the transformer's active part. Varnish is also employed as an insulating material for conductors.
- **Gas insulation:** Gas insulation is primarily used in specialized transformers, such as gas-insulated transformers (GITs). SF_6 is the most widely used it ensures quick arc extinction gas and exhibits high insulating strength under high voltage circumstances, Air can be used as a dielectric medium; its dielectric strength is significantly lower than SF_6. Air-insulated transformers are typically used in lower-voltage applications.

  Gas-based transformer insulation provides excellent insulation performance in limited spaces and reduces the risk of oil leakage or fire hazards.

II.3 Cooling system of transformers

When a transformer is operating, losses in the windings and core cause it to produce heat. Inadequate dissipation of this heat can accelerate material aging, deteriorate insulation, and eventually result in transformer failure. Maintaining the transformer's interior temperatures within safe bounds for a long service life is the fundamental goal of a cooling system. According to their cooling methods, transformers are classified into dry type transformers and oil immersed transformers. One of the benefits of oil natural cooling is that the windings are free from the effects of moisture and the ducts are not clogged.

II.3.1 Dry type transformers

II.3.1.1 Air Natural Cooling (AN): The natural air surrounding the transformer's core and winding cools small transformers with a few kVA rating. The winding is shielded from mechanical damage by a sheet metal enclosure.

II.3.1.2 Air blast: Natural air cooling is insufficient for transformers rated higher than 3 MVA. This technique uses blowers or fans to drive air onto the windings and core. To stop dust particles from accumulating up in ventilation ducts, the air supply needs to be filtered. Transformers up to 15 MVA can be utilized with this technique.

II.3.2 Oil immersed transformers

II.3.2.1 Oil Natural Air Natural (ONAN)

In this method, the assembly of the core and windings are placed in the oil-immersed tank, the heat generated in the core and winding is transferred to the oil by conduction. The oil becomes less dense and rises to the top of the tank, entering the radiators where it dissipated heat in the atmosphere due to the natural air flow around the transformer . As the oil cools, it becomes denser and falls back to the bottom of the transformer tank. This method can be used for transformers up to about 30 MVA.

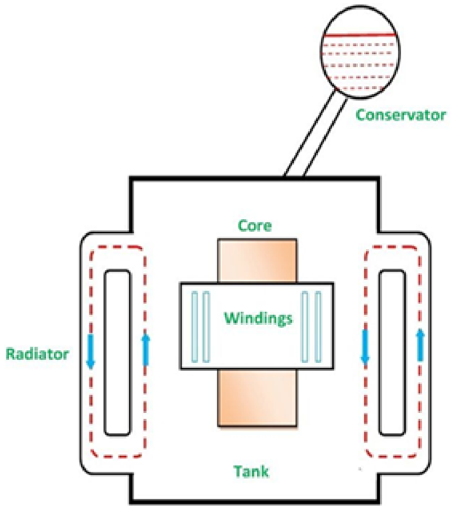


Figure II.19: Oil Natural Air Natural cooling method

II.3.2.2 Oil Natural Air Forced (ONAF)

To improve heat dissipation, ventilation systems are placed near the radiators. Forced air allows a faster heat dissipation than natural air circulation. This transformer cooling method is generally used for large transformers up to about 60 MVA.

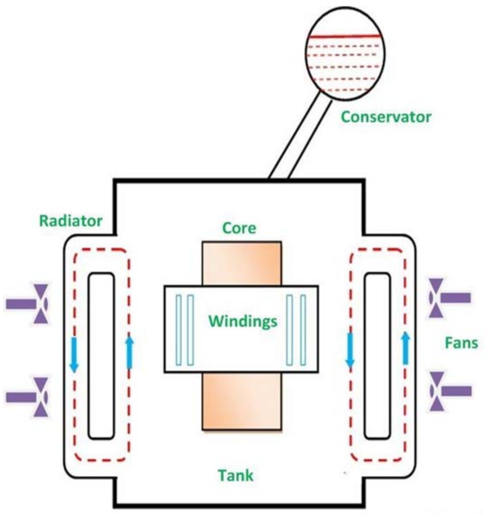


Figure II.20 : Oil Natural Air Forced cooling method

II.3.2.3 Oil Forced Air Forced (OFAF)

In this method, oil is circulated by a pump upward through the windings and then forced through the heat exchangers. Fans are then used to force compressed air onto the heat exchanger. This type of cooling is provided for higher rating transformers at substations or power stations.

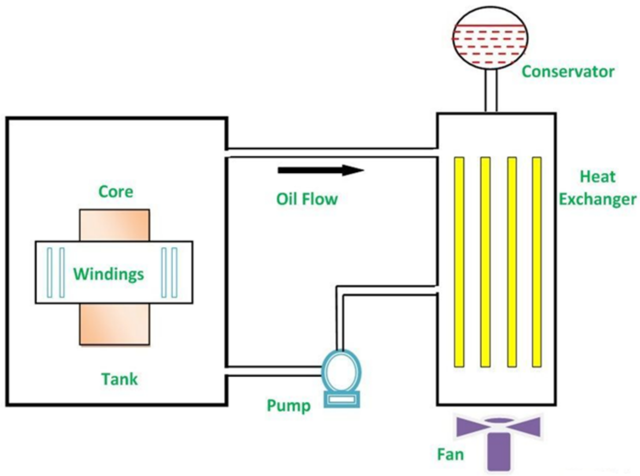


Figure II.21: Oil Forced Air Forced cooling method

II.3.2.4 Oil Forced Water Forced (OFWF)

Unlike the OFAF method, forced water circulation is used to remove heat from the heat exchangers through which the pumped oil passes. The heated water is in turn cooled in a spray pond or a cooling tower. This type of cooling is used in very large transformers having rating of several hundred MVA (Figure II.22) .

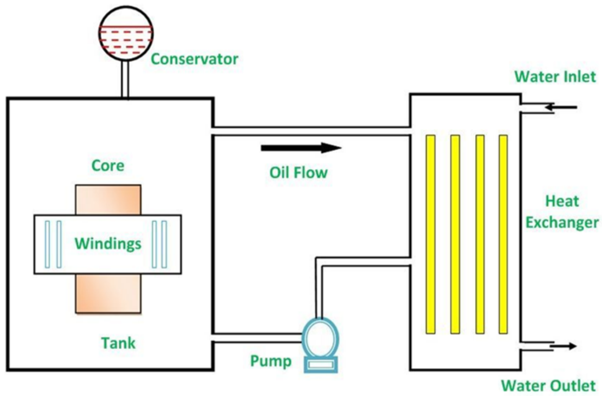


Figure II.22: Oil Forced Water Forced cooling method

II.4 Example design of small phase single phase transformer

Design of small single transformer can be divided in six steps as follows:

1. Define the parameters relating to design small single phase transformer.
2. Computation of required core size.
3. Computation of the number of turns required in primary and secondary windings.
4. Selection of wire size for primary and secondary windings.
5. Verification of winding accommodation in the magnetic core.
6. Efficiency evaluation after dimensioning.

II.4.1 Transformer specifications

The transformer under study is designed for operation at a rated frequency of 50 Hz, with a primary voltage of 220 V and a secondary voltage of 25 V supplying a load current of 2 A. The magnetic circuit is manufactured using electrical steel laminations with a thickness of 0.5 mm, The core material exhibits specific iron losses of 2.2 W·kg^{-1} at a maximum flux density of 1.2 T In the magnetic design, a lamination stacking coefficient K_i=1.1 is adopted to account for the effective cross-sectional area of the laminated core.

II.4.2 Computation of required core size and coil former dimensions

II.4.2.1 Determination of the magnetic core cross-sectional area

Since the apparent power is low, a shell type core is chosen, the concentric windings are positioned on the central column of the E-shaped lamination. The net magnetic core cross-sectional area is determined using the empirical relationship:

$$A_i = 1.2\sqrt{S}=1.2\sqrt{V_2 I_2} = 8.5\ cm^2$$

Where A_i is the iron net core cross-sectional area of the core (cm^2) and S is the apparent power (VA). Considering the iron space factor (K_i=1.1), the gross cross-sectional area of the core is:

$$A_{gc} = K_i \times A_i = 1.1 \times 8.5 = 9.35\ cm^2$$

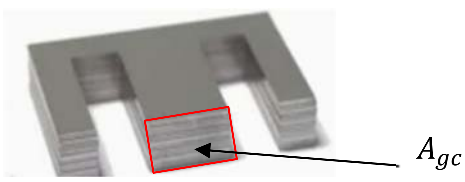


Figure II.23: Gross cross-sectional area of the central limb

The lamination stacking coefficient ($K_i = 1.1$) is only considered for the geometrical dimensioning of the laminated core. For the winding design, the net magnetic core cross-sectional area is taken.

II.4.2.2 Magnetic lamination dimensions

To calculate the dimension C, representing the width of the core (Figure II.24), the cross section of the central limb is considered to be initially square-shaped and then determined from the following relation:

$$C = \sqrt{A_{gc}} = \sqrt{9.35} \approx 3.07cm$$

In accordance to the value of C, the chosen magnetic core is constructed from laminated EI84 electrical steel sheets with the following dimensions:

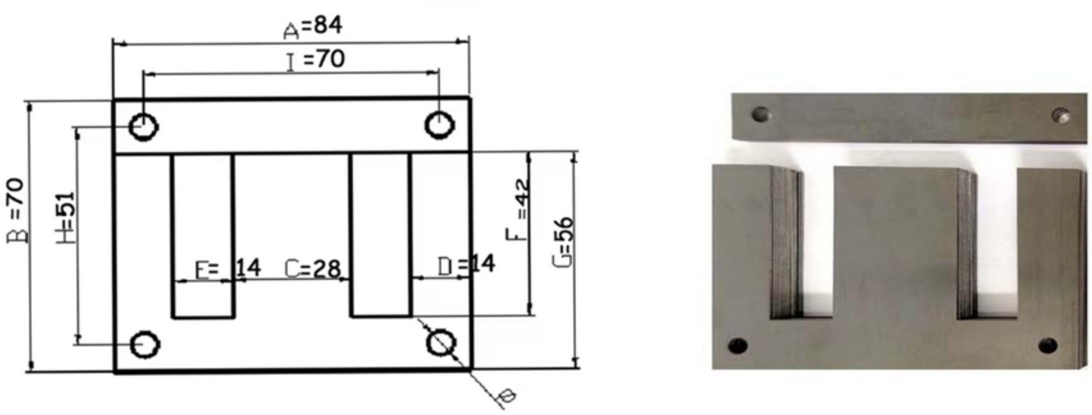


Figure II.24: Geometrical dimensions of Shell-Type transformer

II.4.2.3 Coil former dimensions

In a rectangular or square core, the cross-sectional area is expressed as:

$$S = C \times B$$

therefore:

$$B = S/C$$

$$B = 9.44/2.8 = 3{,}4\ mm$$

where:

- C is the **core width** (limb with).
- B is the **stacking depth (lamination depth)** represented in figure II.25.

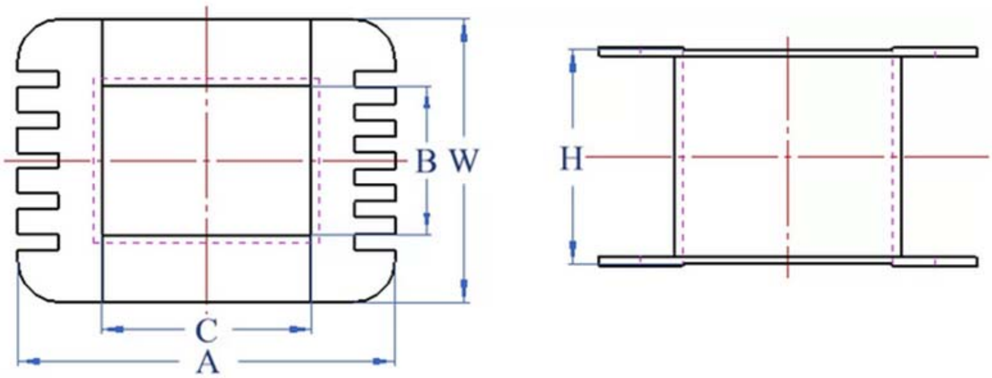


Figure II.25: Geometrical dimensions of coil former

A coil former with dimensions of 28 mm × 34 mm is selected to accommodate the transformer windings. The new gross core cross-sectional area is:

$$A_{gc} = 2.8 * 3.4 = 9.5\ cm^2$$

Therefore the net core cross-sectional area is given by:

$$A_i = 9.5/1.1 = 8.6\ cm^2$$

II.4.3 Calculation of winding turns and wire dimensions

II.4.3.1 Windings calculation

- **Primary winding turns calculation:** The number of primary turns is calculated using the transformer EMF equation:

$$N_1 = V_1\ /444f\ Bmax\ A_i$$

N_1= number of primary turns.

V_1 = primary voltage (V).

f = frequency (Hz).

$Bmax$=maximum flux density (Tesla).

A_i= net core cross-sectional area (m²)

$$N_1 = 220\ /4.44(50 *\ 1.2 *\ 8.6 * 10^{-4}) = 960\ turns$$

- **Secondary winding turns calculation:** Since the number of turns in a transformer is directly proportional to the voltage:

$$N_2/N_1 = V_{20}/V_1$$

So:

$$N_2 = N_1 * V_{20}/V_1$$

Since 25 V is the rated voltage under load. The no-load secondary voltage must be slightly higher in order to compensate for the voltage drop due to winding resistance and regulation.

The table II.2 below summarizes the percentage voltage regulation of the secondary winding for various transformer power ratings (VA).

Rated apparent power S(VA)	Up to 25 VA	Up to 100 VA	Up to 500VA
Secondary voltage regulation $\Delta V_2/V_2$(%)	15%	10%	5%

Table II.2: Regulation voltage

ΔV_2 = secondary voltage drop

V_2 = rated secondary voltage

In practice:

$$V_{20}=V_2*(1+\text{regulation})$$

In the parameter specification S= 50 VA so the regulation is 10%.

$$V_{20}=25*(1+0.1)=27.5\text{V}$$

The secondary winding turns are:

$$N_2 = 27.5 * \frac{960}{220} = 120 \text{ turns}$$

II.4.3.2 Wire dimensions

- **Secondary conductor cross-sectional area calculation**

$$A_s = I_2/J$$

A_s = Secondary conductor cross-sectional area (mm²)

I_2 = Secondary winding current (A)

J = current density (A/mm²)

The conductor diameter can be determined from its cross-sectional area using the following relationship:

$$D_2 = sqrt(4 * A_s/pi) = 1.13 * sqrt(I_2/J)$$

The current density is assumed to be 3.5 A/mm² for transformers with an apparent power rating of up to 100 VA, and 2.5 A/mm² for ratings above 100 VA. Therefore,

$$D_2 = 1.13 * sqrt(2/3.5) = 0.86mm$$

The standardized conductor diameter is selected as D_2=0.9.

- **Primary conductor cross-sectional area calculation**

  As the primary current Ip is initially unknown, it is determined from the efficiency at full load, the value of which is taken from Table II.3.

Output Apparent Power S (VA)	Up to 25VA	25 to 50 VA	50 to 100VA
Efficiency η (%)	75%	80%	85

Table II.3: Efficiency values

$$\eta = \frac{V_2 I_2}{V_1 I_1}$$

$$I_1 = \frac{V_2 I_2}{\eta V_1} = \frac{25*2}{0.85*220} = 0.27 \text{ A}$$

The diameter of the primary conductor is given by:

$$D_1 = sqrt(4 * A_p/pi) = 1.13 * sqrt(I_1/J)$$

A_p = Primary conductor cross-sectional area (mm²).

I_1 = Primary winding current (A).

Substituting the calculated values:

D_1=1.13*sqrt(0.27/3.5)=0.314mm

The standardized value selected for the primary conductor diameter is:

D_1=35/100 mm

The final transformer configuration obtained from the above design procedure is shown below:

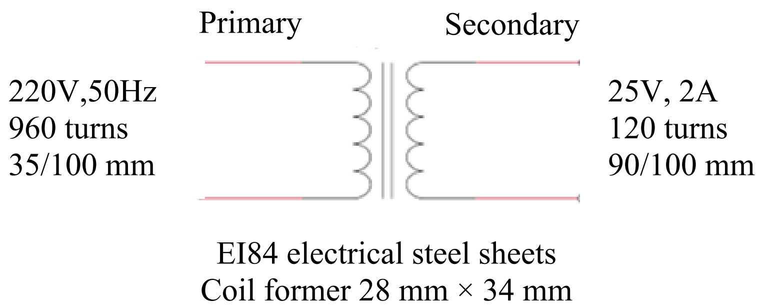


Figure II.26: Transformer design results

II.4.4 Design Verification

The transformer design calculations are now complete. However, two verifications are required:

1. Verification of the winding accommodation to ensure that the transformer can be assembled properly.
2. Verification of the validity of the assumed efficiency value.

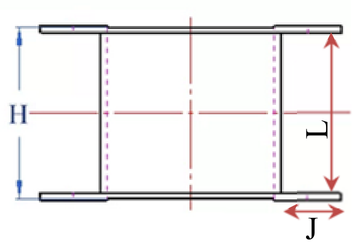
II.4.4.1 Winding accommodation

The feasibility of the winding arrangement must be verified to ensure that the windings fit within the selected bobbin.

J : Maximum winding thickness.

L : Winding length.

The values of J and L are:



$$J=11,5 \text{ mm} \quad , L=37,9 \text{ mm}$$

- **Winding Thickness Calculation**

  A winding factor of 0.8 is adopted.

  In the primary winding the standardized diameter of the primary conductor is:

$$D_1 = 35/100 \ mm$$

The number of turns per layer $= \frac{37,9}{0,35} \times 0,8 = 86$ turns/layer

The corresponding number of layers $= \frac{968}{86} = 12$ layers

In the secondary winding the standardized diameter of the primary conductor is:

$$D_2 = 90/100 \, mm$$

The number of turns per layer $= \frac{37,9}{0,9} \times 0,8 = 33$ turns/layer

The corresponding number of layers $= \frac{121}{33} \approx 4$ layers

Therefore, the total winding thickness is:

$$e = \frac{12 \times 0,35 + 4 \times 0,9}{0,8} \approx 9,8 \text{mm}$$

Since the calculated winding thickness e is smaller than the maximum allowable winding thickness J, the winding arrangement is considered feasible.

II.4.4.2 Efficiency value verification

The efficiency η of a transformer is given by:

$$\eta = \frac{P_{out}}{P_{out} + P_{fe} + P_{cu1} + P_{cu2}}$$

Where :

P_{out}: Power output.

P_{fe}: Core losses.

P_{cu1} and P_{cu2}: Copper losses in primary and secondary windings respectively.

- **Iron Loss Calculation**

The number of laminations $= \frac{B}{\mathrm{t}} = \frac{3{,}4}{0{,}5} = 68$ laminations

t is the thickness of one lamination.

Total weight of the magnetic core= Number of laminations × weight of a single lamination

$$= 68 \times 17{,}1 \times 10^{-3} = 1{,}6 \text{ Kg}$$

The total iron loss is given by:

$$P_{fe} = 2{,}2 \times 1{,}16 = 2{,}5 \text{ W}$$

- **Copper losses calculation**

Based on the dimensions A, B, and C of the coil former (Figure II.5), the mean length of one turn (MLT) is given by:

$$\text{MLT} = 2(A + \frac{C-A}{2} + B + \frac{C-A}{2}) = 2(\text{B+C})$$

$$= 2(\text{B+C})$$

$$\text{MLT} = 2(34+55)$$

$$\text{MLT} = 17{,}8 \text{ cm}$$

The total length of the primary winding is given by:

$$L_1 = MLT \times N_1$$

$$= 17{,}8 \times 10^{-2} \times 968$$

$$= 172\ m$$

The total length of the secondary winding is calculated as follows :

$$L_2 = MLT \times N_2$$

$$= 17{,}8 \times 10^{-3} \times 121$$

$$= 21{,}5\ m$$

The conductor D_1 with a diameter of 0.35 mm has a resistance of 0.2 Ω/m. Therefore, the resistance of the primary winding is:

$$R_1 = 172 \times 0{,}2 = 34.4\Omega$$

The corresponding primary copper losses are

$$P_{cu_1} = R_1 \times I_1^2 = 34{,}4 \times (0{,}27)^2$$

$$P_{cu_1} = 2{,}5 \text{ W}$$

The conductor D2 with a diameter of 0.90 mm has a resistance of 3×10⁻² Ω/m. Thus, the resistance of the secondary winding is:

$$R_2 = 3 \times 10^{-2} \times 21{,}5$$

$$R_2 = 0{,}65\ \Omega$$

The secondary copper losses are therefore:

$$P_{cu_2} = R_2 \times I_2^2 = 0{,}65 \times (2)^2$$

$$P_{cu_2} = 2{,}6 \text{ W}$$

Substituting the calculated values in the transformer efficiency expression:

$$\eta = \frac{50}{50+2{,}5+2{,}6+2{,}5} = 0.868$$

$$\eta = 86{,}8\%$$

The calculated efficiency is approximately 86.8%, which is close to the initially assumed value of 85%. Therefore, the transformer design carried out is valid.

Chapter III : Direct Current Electrical Machines

III.1 Introduction

Although practically all the electric energy produced commercially is generated and distributed in the form of alternating current, much energy is utilized in the form of direct current in industry.

A DC machine is an electro-mechanical energy conversion device. When it converts mechanical power into DC electrical power, it is known as a DC generator. On the other hand, when it converts DC electrical power into mechanical power it is known as a DC motor.

Direct- current motors are used in a wide variety of industrial drives that requires the control of speed and torque, such as robots, machine tools, pulp and oil drilling rigs. They are also used extensively in automotive systems and railroads.

Direct -current generators, however, once the mainstay of electric power for large and small industrial plants, are being increasingly replaced by solid-state devices that convert available AC to direct current for DC drive systems and other DC applications.

III.2 Construction of DC Machine

A direct current (DC) electrical machine consists of two fundamental assemblies:

- The stator, the stationary magnetic structure that provides the main magnetic field.
- The rotor (also referred to as the armature), the rotating electromagnetic assembly where electromechanical energy conversion takes place.

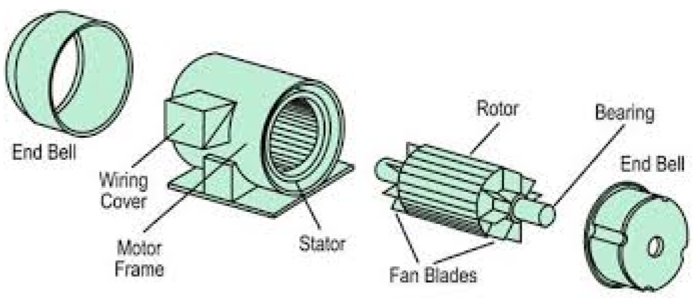


Figure III.1 : Construction of a direct current machine

III.2.1 Stator

The stator is composed of two main elements: the frame and poles.

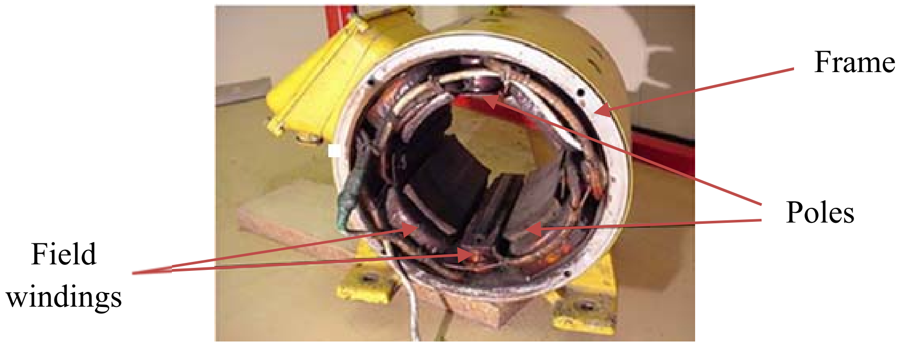


Figure III.2 : Stator structure

III.2.1.1 Frame (Yoke)

The frame, also referred to as the yoke, performs both mechanical and magnetic functions in a DC machine. It forms the outer casing of the machine, providing structural support for the poles and provides mechanical protection to the inner parts of the machine. From a magnetic standpoint, the yoke acts as the magnetic return path, carrying the magnetic flux generated by the main and auxiliary poles. It is typically made of cast iron for smaller machines and for larger machines, it is made of cast steel or fabricated rolled steel to provide both mechanical strength and a low-reluctance magnetic path. Additionally, end plates (end shields) are attached to the yoke, ensuring structural rigidity and supporting the bearings.

III.2.1.2 Poles

- **Main poles:** Main poles consist of a core terminating in a pole shoe and serve two essential purposes: They mechanically support the field windings (excitation coils) and they channel the magnetic flux lines of the main field toward the rotor, ensuring efficient magnetic coupling and electromechanical energy conversion. To reduce eddy current losses, the main poles are constructed from laminated steel sheets with a typical thickness ranging from 0.5 mm to 2 mm. They are securely mounted onto the yoke (frame) using bolted connections, ensuring robust mechanical support and precise magnetic alignment.

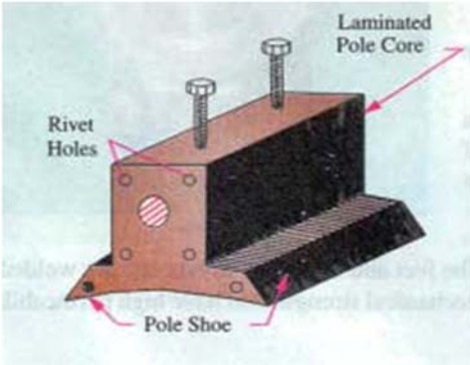
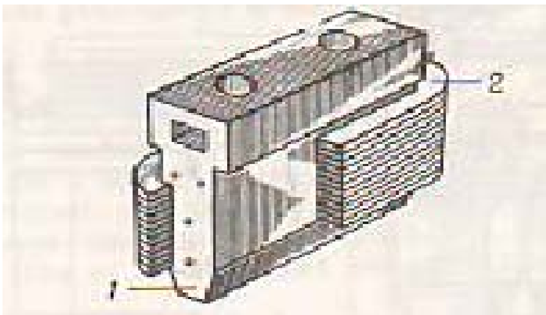


Figure III.3 : Main pole

- **Commutating poles (Interpoles):** The commutating poles, also known as interpoles, have the primary function of mechanically supporting the commutating windings. They are strategically positioned in the interpolar axis, i.e., midway between the main poles and are bolted to the yoke. Their main purpose is to induce a compensating electromotive force (EMF) in the armature conductors undergoing commutation, thereby improving commutation and reducing sparking at the brushes. The air gap in the region of the commutating poles is typically 1.5 to 2 times larger than that of the main poles, ensuring the desired magnetic characteristics. Additionally, auxiliary poles are narrower in width compared to the main poles.



1- Core 2- Coil

Figure III.4 : Commutating pole

III.2.1.3 Field windings

- **Main pole windings:** The main field windings (excitation windings) are supplied with direct current (DC) and are responsible for generating the primary magnetic field of the machine. This magnetic flux passes through the pole cores, the yoke, the armature, and the air gap, which typically ranges from 1.5 mm to 5 mm in low- and medium-power machines. The excitation of these windings can be configured as separately excited, shunt-excited, or series-excited: In separate or shunt excitation, the conductor cross-section is typically less than 7 mm^2 for round wires and greater than 7 mm^2 for rectangular (flat) conductors. In series excitation, the conductor cross-section usually exceeds 75 mm^2, and the windings are made of flat copper bars to handle the higher current.

As the rated power of the machine increases, the number of poles also increases to ensure adequate magnetic flux distribution and performance. In certain designs, particularly in small or specialized DC machines, the field windings and pole pieces may be replaced by permanent magnets, offering a compact and maintenance-free excitation system

- **Interpole windings:** When the output power of a DC machine exceeds a few kilowatts, the use of commutating windings becomes essential. Their function is to generate an auxiliary magnetic field that assists in the commutation process by inducing a compensating electromotive force (EMF) in the armature conductors undergoing commutation. These windings are connected in series with the armature circuit and therefore carry the armature current, which requires them to have a large conductor cross-section to handle the high current safely. Typically, commutating coils are constructed similarly to series field coils, i.e., they are made of rectangular (flat) copper bars, ensuring high mechanical strength and efficient current conduction.
- **Compensating Windings:** The compensating windings are designed to counteract the armature reaction that occurs in the polar arc region, thereby eliminating magnetic field distortion in this zone and improving commutation performance.

These windings are embedded in slots located in the pole shoe extensions of the main poles and are connected in series with the armature circuit, meaning they carry the same current as the armature. Depending on the machine design, the slots housing the compensating windings can be open or semi-closed, ensuring proper mechanical retention and optimal magnetic compensation.

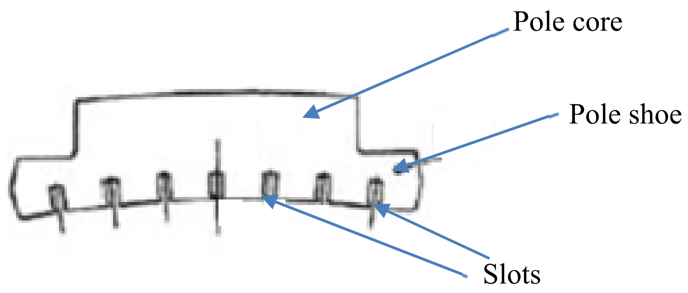


Figure III.5 : Compensating winding slots

III.2.2 Armature

The armature assembly consists of four main components: The magnetic core (armature core), the winding (armature winding), the commutator and the brushes.

III.2.2.1 Armature core

Armature core forms part of the magnetic circuit and provides a path for the magnetic flux. The magnetic circuit of the armature is constructed from a stack of laminated, toothed steel sheets of low loss silicon steel, as illustrated in figure III.6. they are usually 0.4 to 0.5 mm thick and are insulated with varnish. Laminations are used to reduce eddy current losses, and the teeth serve to hold the armature windings.

Ventilation ducts are integrated into the core to ensure effective cooling of both the laminations and the copper windings. The entire magnetic core is mounted on a shaft and rotates within the magnetic field generated by the field poles.

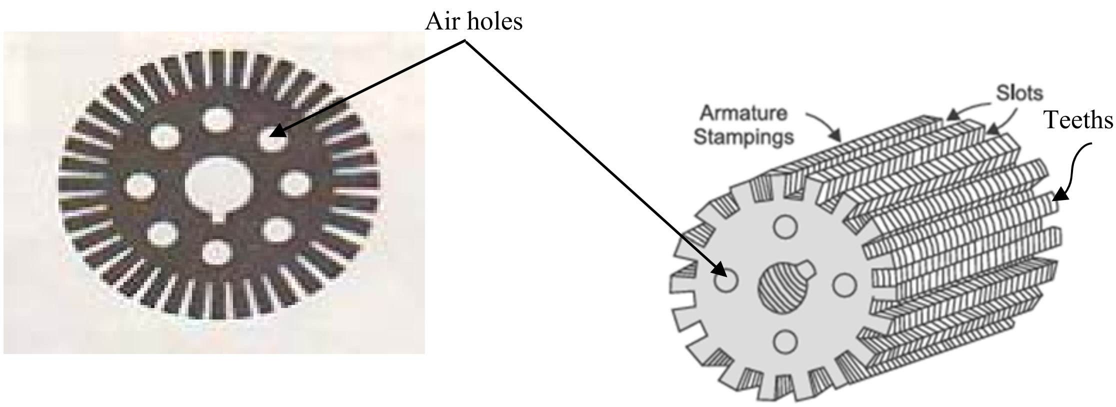


Figure III.6 : Armature steel laminations

Up to armature diameters of about one metre, the circular stampings are cut out in one piece (Figure III.6). Above this size these circles are difficult too handele. The circular laminations are cut in number of suitable sections or segments. A complete circular lamination is made up of four or six or even eight segmental laminations.

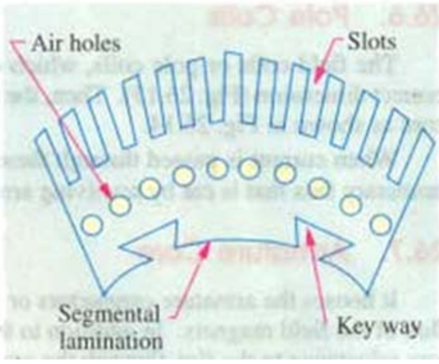
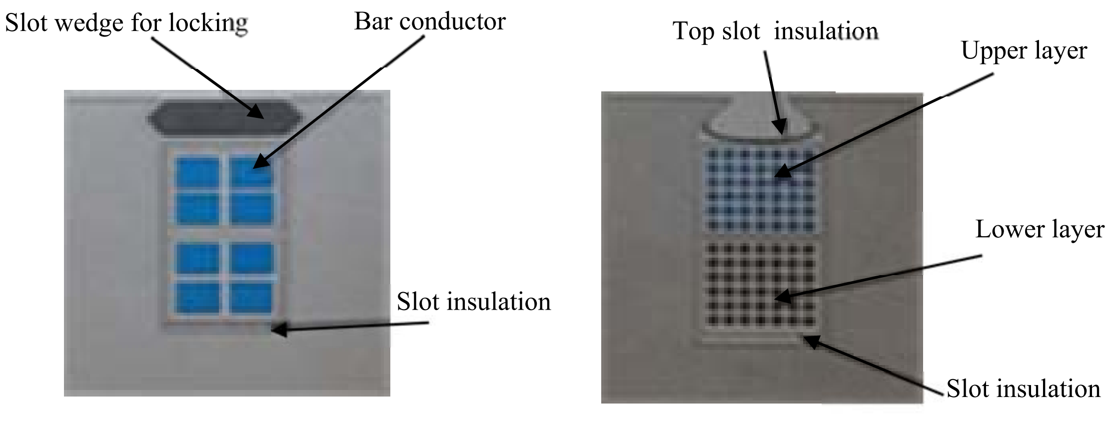


Figure III.7 : Segmental lamination

Two main types of slots are typically used to house the armature conductors:

- **Open slots**: Designed for bar conductors, commonly employed in large-capacity machines.
- **Closed slots**: Intended for round conductors; these slots can have a rounded or rectangular profile.



(a) Open slot **(b)** Closed slot

Figure III.8 : Armature slots

Figures III.9 illustrates the arrangement of the various windings in a DC machine relative to the armature structure.

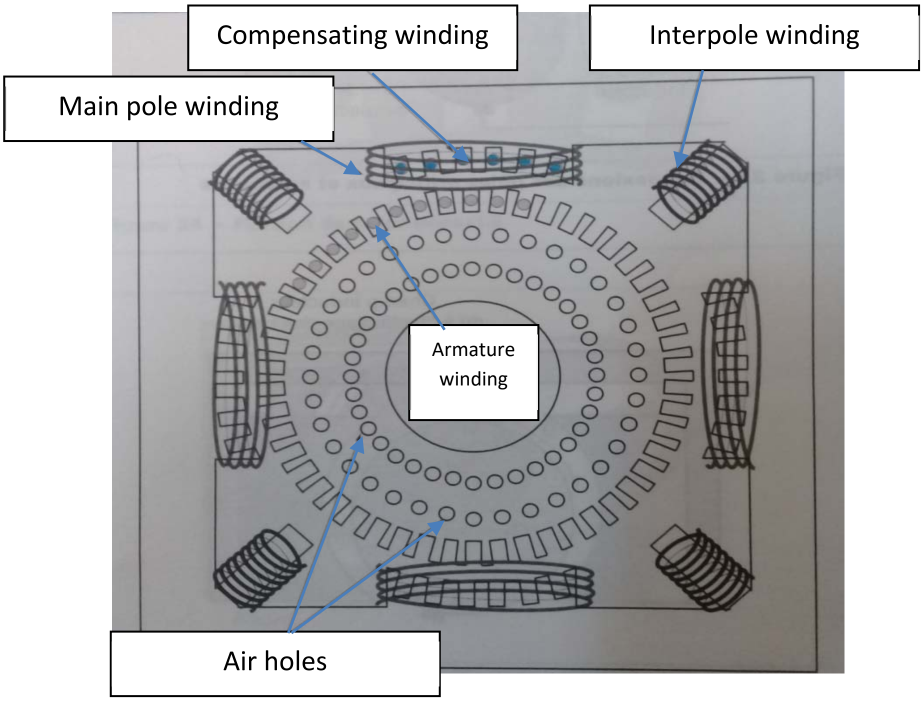


Figure III.9 Windings arrangement in a DC machine

III.2.2.2 Armature Winding

The armature winding is a very important element where the electromotive force (EMF) is induced and current is generated or supplied. Winding is mounted on the rotor it consists of one or more turns of wire grouped together namely coil**,** each coil has two sides that cuts the magnetic flux produced respectively by a north pole and a south pole of the field system. Each side of a section is placed in a slot

- A multi-turn coil can be represented by single line diagram.
- A front end connection is a wire that connects the end of a coil to a commutator segment. This wire is located at that part of the coil that is nearest the commutator.
- A back end connection is a wire or conductor that connects an inductoror one side of the coil to an inductor on the other side of the coil. It's on the end opposite to the commutator.

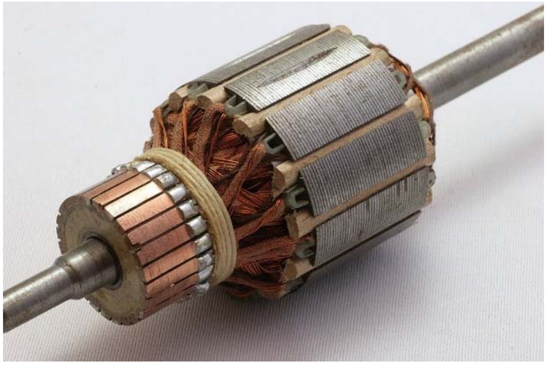


Figure III.10 : General structure of the armature

The conductors can be made of copper wire or copper bars:

- In small machines, the wires are directly wound onto the rotor.
- In larger machines, the conductors are assembled into coils or sections and inserted into the armature slots**.**

To prevent short-circuits, the conductors are insulated from each other by textile wrapping (lacing) in large machines or by an enamel coating.

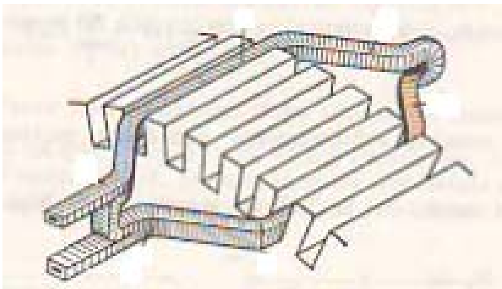


Figure III.11 : Armature winding

a) **Fundamental winding parameters:** The fundamental winding parameters are:

- **Coil pitch :** The distance measured in terms of armature slots between two sides of the same coil.
- **Back pitch (Y_B):** The distance in terms of number of armature conductors between first and last conductor of the same coil.
- **Front pitch (Y_F):** The distance in terms of number of armature conductors or number of slots between second conductor of one coil and the first conductor of the next coil which are connected to the same commutator segment on the front.

- **Commutator pitch (Y_C):** The distance measured in terms of commutator segments between the segments to which the two ends of a coil are connected.
- **Resultant pitch (Y_R):** The distance in terms of number of armature conductors or number of slots between the start of one coil and the start of the next coil to which it is connected.

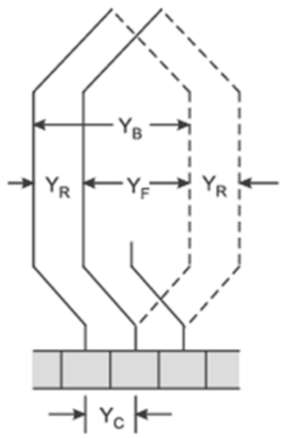


Figure III.12 : Winding parameters

b) Lap and wave windings: The armature windings in a DC machine are typically of two main types: Lap winding and wave winding.

- **Lap Winding:** In a lap winding, the first side of each coil is positioned adjacent to the first side of the preceding coil. All the coils are connected in series around the armature periphery, forming multiple parallel paths. This type of winding is particularly suitable for low-voltage, high-current applications.

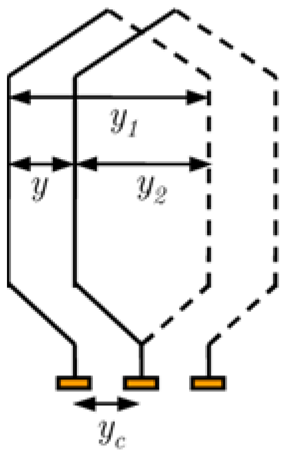


Figure III.13 : Lap winding

- **Wave Winding**

In a wave winding, the first side of each coil is positioned approximately two pole pitches away from the first side of the preceding coil. Unlike lap windings, a wave winding provides only two parallel current paths, regardless of the number of poles. Because of this configuration, the armature current is divided into only two paths, resulting in a higher voltage generated per path. Consequently, wave windings are typically used in high-voltage, low-current DC machines.

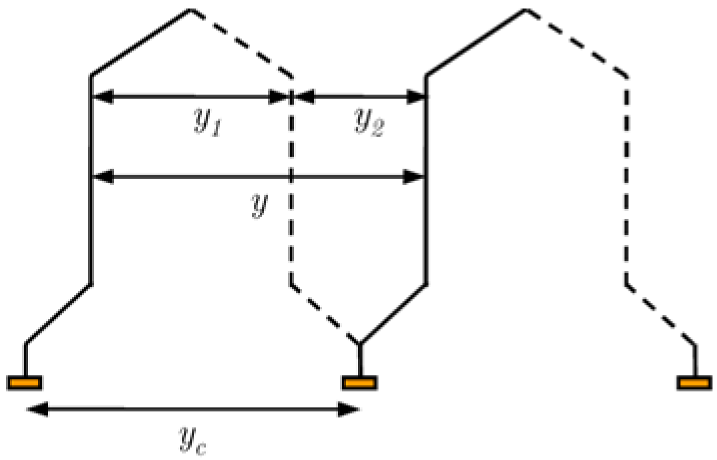


Figure III.14 : Wave winding

III.2.2.3 Commutator

The commutator converts alternating voltage to a direct voltage. The commutator is composed of multiple copper segments (commutator bars), each electrically insulated from the others by thin layers of insulating material (such as mica). These segments are mounted around the shaft and form a cylindrical surface. The ends of the armature windings are connected to the commutator segments either by spot welding or brazing.

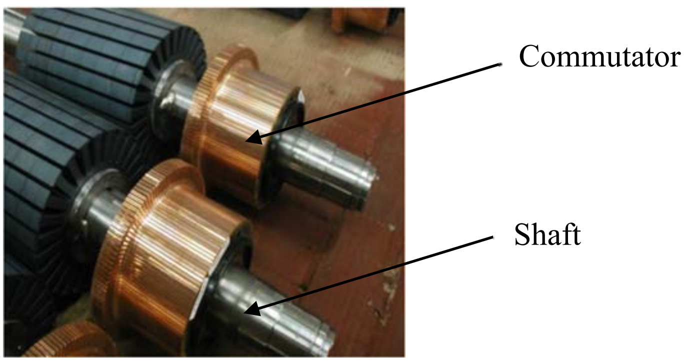


Figure III.15 : Commutator

III.2.2.4 Brushes

A DC machine is also equipped with brush holders fitted with carbon brushes, as shown in figure III.14. The primary function of the brushes is to ensure electrical contact between the stationary external circuit and the rotating commutator**.** By sliding on the commutator surface, the brushes transfer current to (in motor operation) or from (in generator operation) the armature winding, enabling continuous electrical energy conversion.

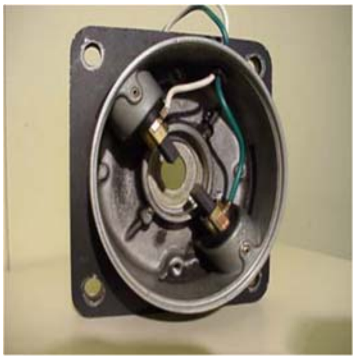


Figure III.16: Brushes and brush holder

III.3 Operating principle of a DC machine

III.3.1 Generator Operation

An electrical generator is a machine which converts mechanical energy into electrical energy. This energy conversion is based on the principle of the production of dynamically induced e.m.f. Whenever a conductor cuts magnetic flux, dynamically induced E.M.F is produced in according to Faraday’s law of electromagnetic induction. This e.m.f causes current to flow if the conductor circuit is closed.

The generated electomagnetic forec E depends on the magnetic flux per pole, the armature speed, and the number of armature conductors, it is expressed by:

$$E = \frac{P\emptyset ZN}{60a} \qquad \text{(III.1)}$$

Where:

P: Number of poles.

$\emptyset$: Magnetic flux per pole (W).

Z: Total number of armature conductors.

N: Rotational speed of armature (r.pm).

a: Number of parallel paths in armature.

The commutator and brushes converts alternating voltage induced in armature to a direct voltage.

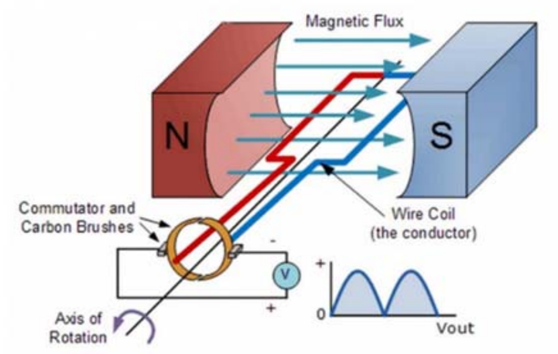


Figure III.15 : Operating principle of DC machine

III.3.2 Motor operation

A DC motor is a machine which converts electric energy into mechanical energy. The motor operation is based on the principle that when a current carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by left-hand rule.

The torque developed by the armature is given by the relation:

$$T_a = \frac{Z\emptyset I_a P}{2\pi a}$$

Where:

I_a: Armature current.

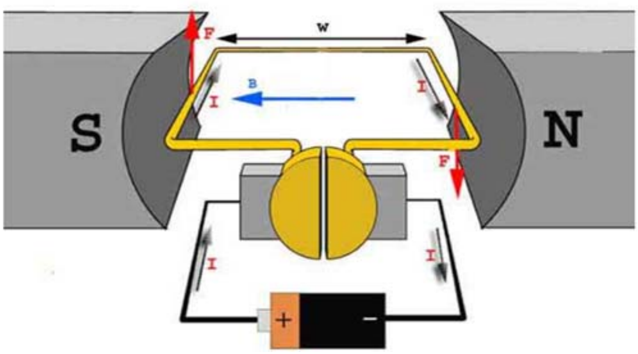


Figure III.16 : Torque generation in a DC motor

III.3 Types of excitation field in DC machines

III.3.1 Separately-Excited DC motor

In a separately excited DC motor, the field winding is supplied by an external DC source and the armature winding is independent of the field current. Separately excited motors offer more precise control of speed and torque.

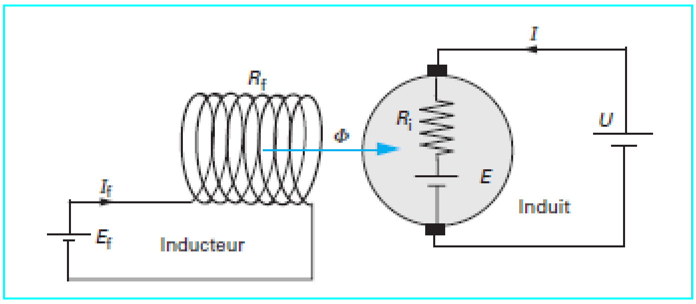


Figure III.17 : Principle of separate excitation

III.3.2 Series-Excited DC Motor

In a series-excited DC motor, the field winding is connected in series with the armature winding. Their speed varies significantly with load, and they must never be operated without load to avoid overspeed.

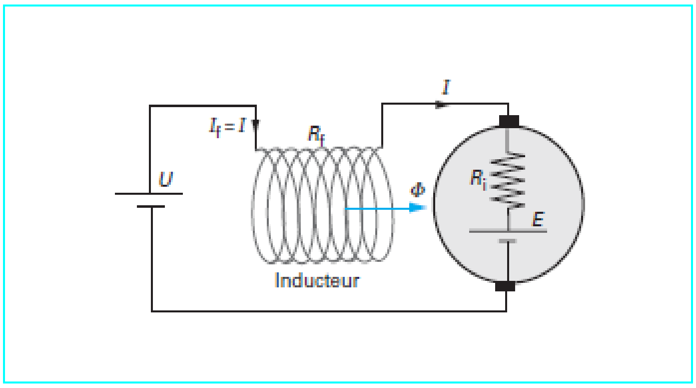


Figure III.18 : Principle of series excitation

III.3.3 Shunt-Excited DC Motor

In a shunt-excited DC motor, the armature winding and the field winding are connected in parallel and are therefore supplied with the same supply voltage**.** This configuration provides a nearly constant field flux, resulting in stable speed characteristics under varying load conditions.

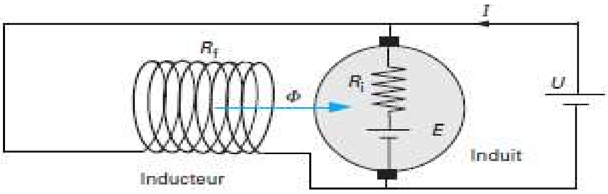


Figure III.19 : Principle of shunt excitation

III.3.4 Compound-Excited DC Motor

In a compound-excited DC motor, the field winding is divided into two separate windings**:** One part is connected in series with the armature winding, The other part is connected in parallel with it. This dual-excitation configuration combines the high starting torque characteristics of a series motor with the good speed regulation of a shunt motor.

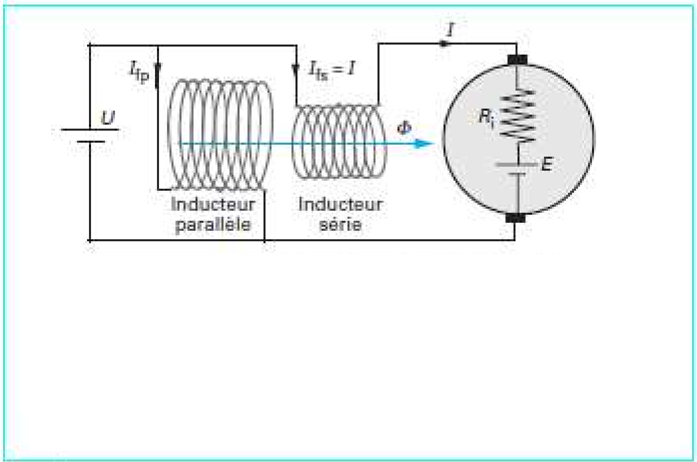


Figure III.20 : Principle of compound excitation

III.4 Example design of main dimension of DC machine

Find the main dimensions and the number of poles of a 37 kW, 230V, 1400 rpm shunt motor so that a square pole face is obtained. The average gap density B_{av} is 0.5 Wb/m^2 and the ampere conductors per metre ac are 22000. The ration of pole arc to pole pitch ψ is 0.7 and the full load efficiency η is 90 percent.

Given Data

Power output=37kW	Square pole face	$\psi = 0.7$
DC supply=230V	B_{av} = 0.5 Wb/m^2	η = 90 %
Speed n=1400 rpm	ac = 22000	

Solution:

If pole, p = 2, then $f = \frac{pN}{120} = \frac{2\times1400}{120} = 23.33Hz$

If pole, p = 4, then $f = \frac{pN}{120} = \frac{4\times1400}{120} = 46.67Hz$

Also, power input, $P_i = \frac{Power\ output}{Efficiency} = \frac{P}{\eta}$

Load current, $P_i = \frac{P}{\eta \times V \times 10^{-3}} = \frac{37}{0.9\times230\times10^{-3}} = 178.74\ A$

Let, armature current, $I_a \approx I = 178.74A$

The armature current is less than 200A. Hence then f 25 to 50Hz current per parallel path will not exceed the upper limit of 200A.When poles, p = 4, the frequency f = 46Hz, which lies in the range of 25 to 50Hz. Hence poles p = 4 is the best choice.

Output coefficient, $C_0 = \pi^2\ B_{av}\ ac \times 10^{-3}$

$$= \pi^2 \times 0.5 \times 22000 \times\ 10^{-3} = 108.57kW/m^3$$

Given that, power output, P = 37kW.

For dc motors power developed in armature, $P_a \approx P = 37\ kW$

Also, power developed in armature, $P_{a = C_e D^2 Ln}$

$$D^2L = \frac{P_a}{C_0 n} = \frac{37}{108.57 \times (1400/60)} = 0.0146\ m^3$$

Given that, $\frac{Pole\ arc}{Pole\ pitch} = 0.7$

For square pole face, lengh of armature is equal to pole arc

$$\frac{Pole\ arc}{Pole\ pitch} = \frac{Leng}{Pole\ pitch} = \frac{L}{\tau} = 0.7$$

Put, $L = 0.5498D$ in the equation for D^2L

$$D^2L = 0.0146$$

$$D^2(0.5498D) = 0.0146$$

$$D = \left(\frac{0.0146}{0.5498}\right)^{1/3} = 0.2983\ m \approx 0.3m$$

$$L = 0.5498D = 0.5498 \times 0.3 = 0.165m$$

Result

Number of poles,	P = 4
Diametter of armature,	D = 0.3 m
Lengh of armature,	L= à.165 m

Chapter IV: Asynchronous machines

IV.1 Introduction

Alternating-current machines are widely used in industry compared to direct-current machines because of their ease of implementation robustness, high reliability, low cost, compact size, and ease of maintenance. Within this category, there are two types of machines: asynchronous machines and synchronous machines. Three- phase induction motor is the most commonly used motor in industrial applications because of its simple design, simple maintenance and high efficiency.

IV.2 Definition

An asynchronous machine, or induction machine, is an electromechanical energy converter. It is primarily used as a motor or generator for power ratings below 1 MW. It is called asynchronous because the rotor's rotational speed differs from the synchronous speed, defined by:

$$N_s = \frac{120f}{p} \qquad \text{(IV. 1)}$$

Where N_s is the synchronous speed (r,p,m) , and p is the total number of poles.

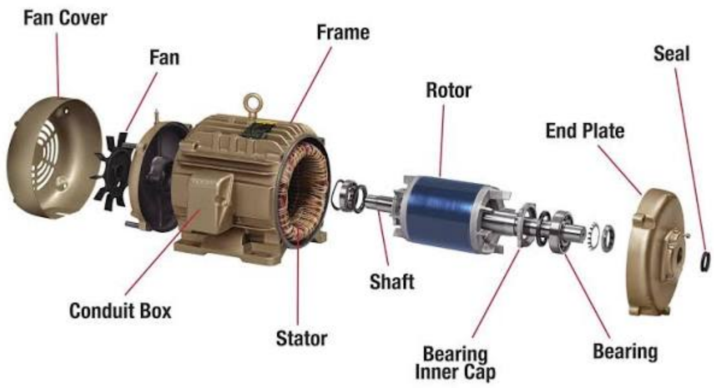


Figure IV.1: Component parts of an induction motor

IV.3. Constructional details

From a mechanical standpoint, asynchronous machines can be divided into two distinct parts: the stator and the rotor.

IV.3.1 Stator

Stator consists of a frame and a magnetic core in which the windings are placed.

IV.3.1.1 Frame

Frame houses the stator core, it is made of cast steel for small machines and of welded rolled steel plates for medium and large sized machines. A terminal box is mounted on the frame, where the stator windings leads are connected to the external power supply. The frame should be strong and rigid to avoid the irregular airgap around the machine.

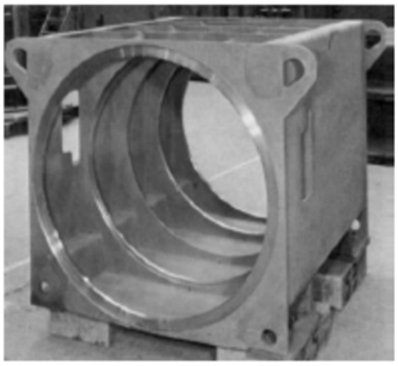


Figure IV.2: Frame of an asynchronous machine

IV.3.1.2 Magnetic core

The stator core consists of varnished laminated low loss electrical sheet-steel stampings, with thicknesses ranging from 0.35 to 0.6 mm. For small machines, the sheets are punched on single piece (Figure IV.3), whereas for large size machines, they are cut into segments and stacked with the staggered joints (Figure IV.4), segmented laminations help improve efficiency, reduce eddy currents, and enhance the overall performance of the motor. The laminations are provided with slots, which are either punched directly into the laminations or machined after the core has been assembled.

The laminations are assembled into stacks 35 to 50 mm thick and secured together with bolts. The elementary lamination stacks are separated by ventilation ducts 4 to 10 mm wide (Figure IV.5). The spacing between the sheet metal stacks is ensured by spacers welded to a steel plate called the master sheet.

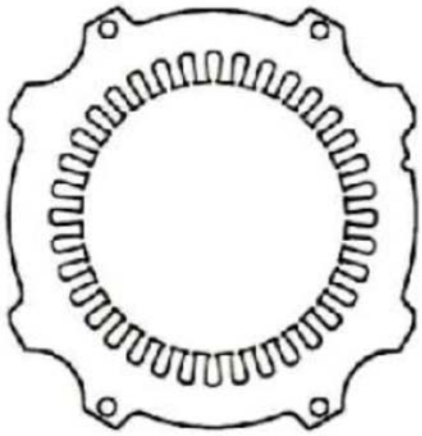
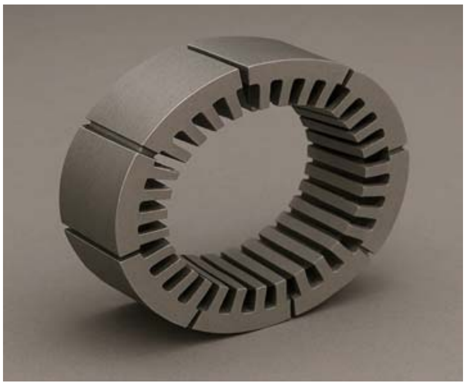
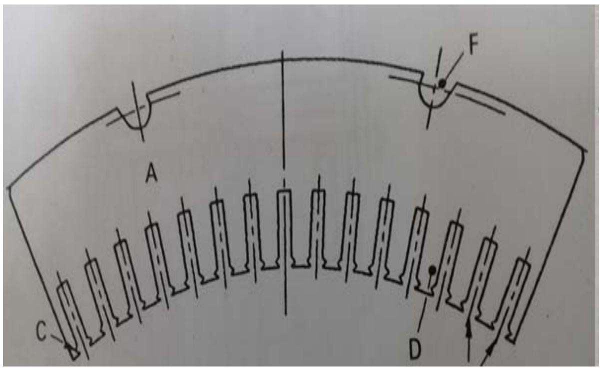


Figure IV.3: Stator laminations of a low-power asynchronous machine



(a) Segmented stator lamination stack



(a) Lamination segment

Figure IV.4: Stator of high-power asynchronous machine

(b) Stator lamination with vent ducts

(b): Vent spacer

Figure IV.5: Lamination stacks assembly in large size machines

Two types of stator slots are distinguished: open and semi-closed slots. Open slots are completely open to airgap, rectangular in shape and easy to insert winding, whereas semi-closed slots opening is narrow, presents better magnetic performance and commonly used in industrial motors.

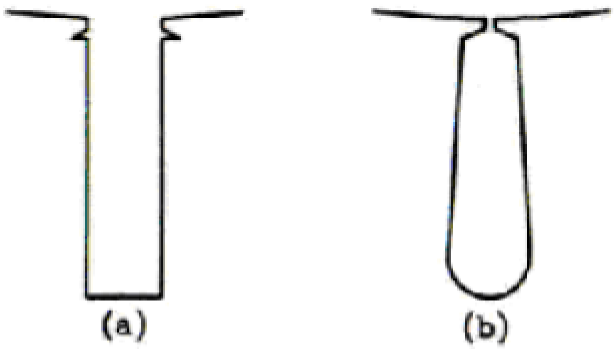


Figure IV.6: Stator slots of an asynchronous machine: a) open slot, b) semi-closed slot

IV.3.1.3 Windings

The fundamentals types of stator windings are distributed windings and concentrated windings. The distributed windings are the most widely used. The coil arrangements generally used in the latter are interleaved windings and concentric windings.

- **Interleaved winding**

  Three-phase distributed concentric windings consists of several coils which overlap one another, this arrangement gives more uniform airgap and reduce vibrations and acoustic noise. Ther are used in medium and high power AC machines.

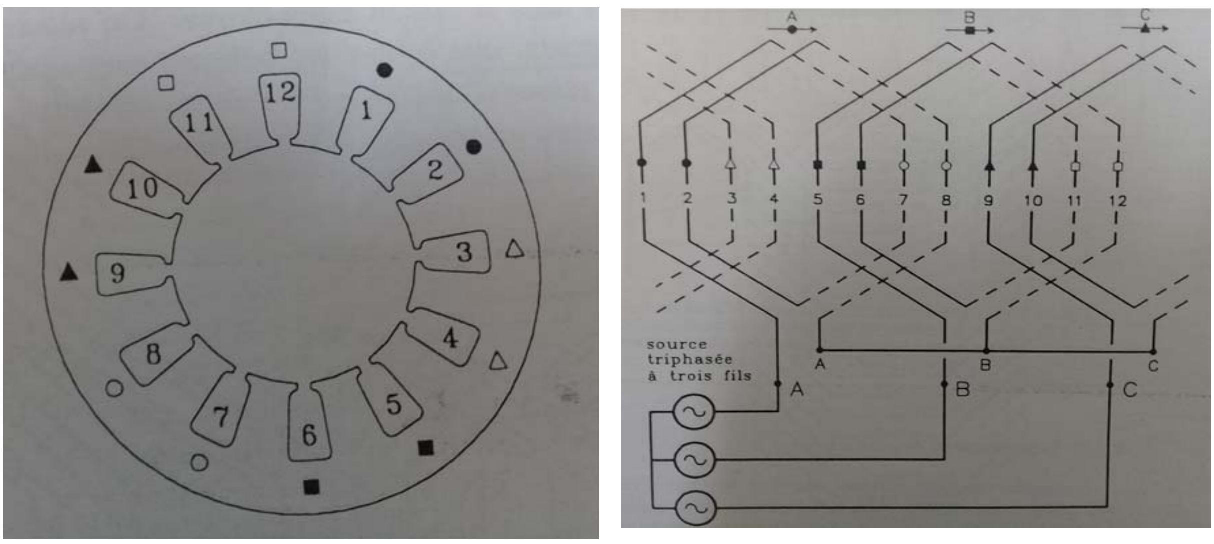


Figure IV.7: Three-phase distributed interleaved windings

- **Concentric Winding**

This type is commonly used in small induction motors. Figure IV.8 illustrates a three-phase distributed concentric windings , each coil occupies two slots. Within each phase, the coils have different diameters, and are arranged concentrically, with each coil nested inside the next.

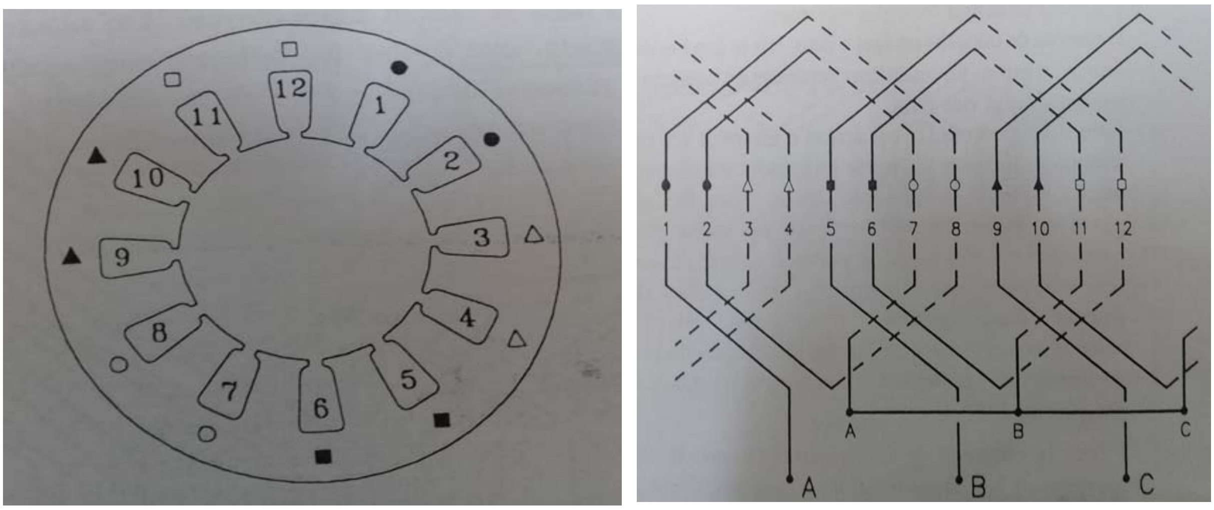


Figure IV.8: Three-phase distributed concentric windings

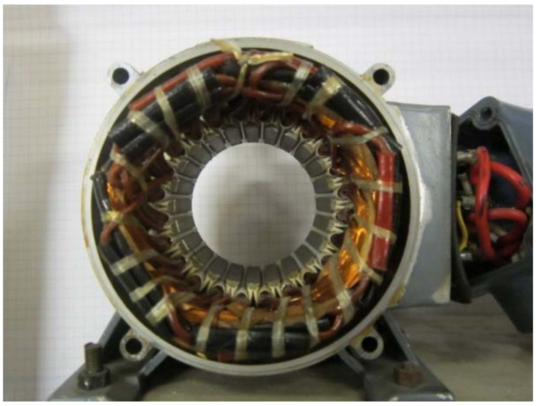


Figure IV.9: Winding location in a stator core

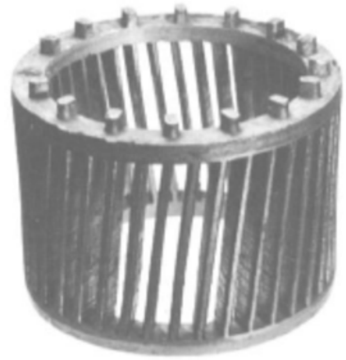
IV.3.2 Rotor

Rotor is mounted on a shaft and is free to rotate inside the stator. Like the stator, it consists of a stacked steel laminations forming a cylinder, to reduce noise and harmonics conductors are skewed relative to the motor axis. For small motors, the rotor laminations are punched as a single piece. In machines with larger diameters, the rotor laminations are manufactured in segments and then assembled and clamped together using bolts and nuts. There are two types of rotors: Squirrel-cage rotor and wound rotor.

IV.3.2.1 Squirrel-Cage rotor

Squirrel-cage rotor is made up of stamping which are keyed directly to the shaft. Slots are manufacturing into the magnetic circuit and contain embedded aluminum or copper conductor bars; at each end of the rotor, the bars are short-circuited by rings (Figure IV.10).

a: Location of the rotor bars



b: Squirrel-cage rotor

Figure IV.10: Short-circuited (squirrel-cage) rotor

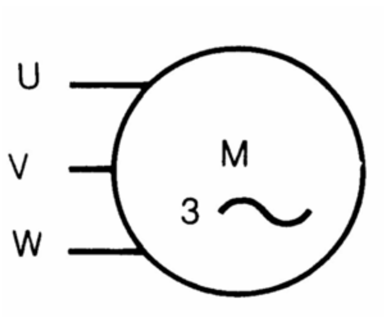


Figure IV.11: Symbol of squirrel-cage motor

Squirrel-cage rotors are classified into two main type: single cage rotors and double cage rotors.

A. **Single-cage rotor:** Conductive bars are placed in holes or slots arranged toward the outside of the cylinder and parallel to its axis. They are short-circuited to a metal rings at both ends . Single-cage rotor does not use brushes.

B. **Double-cage rotor:** This rotor consists of two concentric cages, an outer cage with relatively high resistance and an inner cage with lower resistance, the outer cage bars have a smaller cross-sectional area than the inner bars. During stating operation, the rotor frequency is high and the induced currents tend to oppose the penetration of the magnetic flux into the inner cage due to the skin effect. Thereby, providing significant torque while reducing starting current.

At the end of the starting period, the frequency in the rotor decreases; the magnetic flux penetrates more easily into the inner cage, and the motor behaves in a manner similar to that of a single cage rotor much as if it were constructed with a single cage with low resistance.

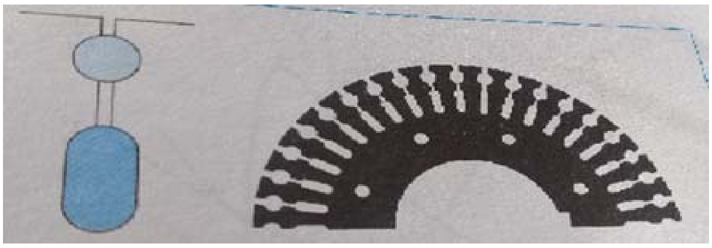


Figure IV.12: Stator laminations of a double-squirrel-cage rotor

IV.3.2.2 Types of slots in Squirrel-Cage rotor

The four rotor bar shapes according to the NEMA classification are shown in figure IV.13. Classes A and B have relatively low initial driving torque. In the case of class B, the maximum locked rotor torque is slightly lower than that of class A, and it is the most widely used for induction motors. In the case of the C class, it has a medium initial driving torque. Furthermore, the efficiency of class C is lower than that of classes A and B. Class D has the highest locked rotor torque.

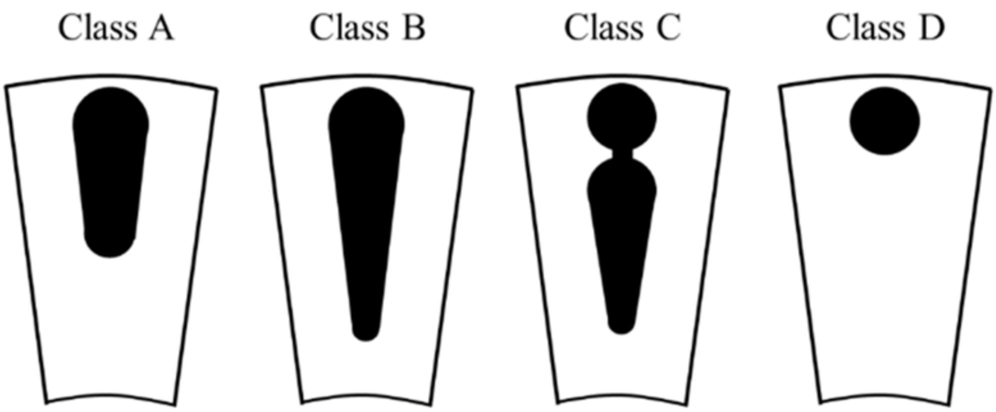


Figure IV.13: Rotor slot shape classification according to NEMA standard

IV.3.2.3 Wound rotor

Windings similar to those of the stator are housed in slots located in the magnetic core. The can be connected in star or delta and the three ends are connected to three slip rings which make contact with carbon brushes, allowing the rotor circuit to external circuits. The wound rotor is employed for induction rotors requiring speed control or extremely high values of starting torque.

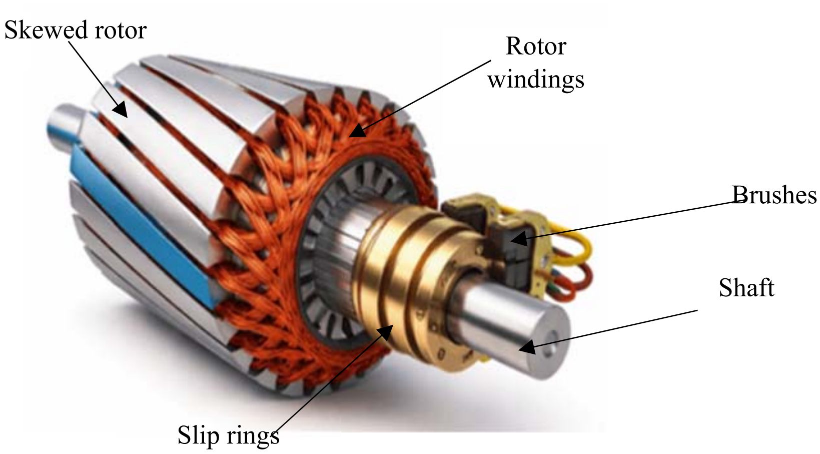


Figure IV.14: Wound rotor

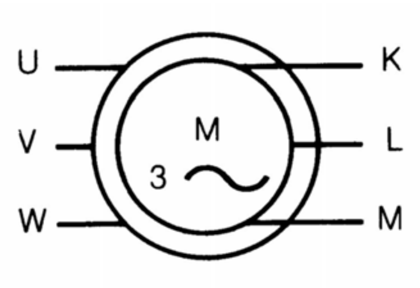


Figure IV.15: Symbol of a wound-rotor machine

IV.4 Operating Principle

When the three stator windings are supplied with a three-phase alternating AC voltage, a rotating magnetic field with the same frequency as the supply frequency is produced around the stator axis . Since the rotor conductors are short-circuited, induced currents are developped in them. The interaction between the induced rotor currents and the rotating magnetic field produces an electromagnetic torque, causing the rotor to rotate at an angular velocityΩ slightly lower than the synchronous angular velocity Ωs.

The difference between the synchronous speed and the rotor speed is expressed by the slip and is defined by:

$$s = \frac{\Omega - \Omega s}{\Omega s} \qquad (IV.2)$$

IV.5 Example design of main dimensions of induction machine

Estimate the main dimensions, air-gap length, stator slots stator turns per phase and cross sectional area of stator and rotor conductors for a 3-phase, 15HP,400V, 6 pole, 50 HZ, 975 rpm, induction motor. The motor is suitable for star delta starting. B_{av} = 0.45Wb/ m^2 , ac = 20000 amp.cond/m, L/τ = 0.85, η = 0.9, pf = 0.85.

Given Data:

3 – phase	400 V	Bav = 0.45Wb/ m2
15 HP	L/τ = 0.85	ac = 20000 amp.cond/m
50 Hz	6 pole	η= 0.9
pf = 0.85	975 rpm	star-delta starting

Where

C_0 is the output coefficient and is given by:

$$C_0 = 11B_{av}\ ac\ K_{ws}10^{-3}$$

D: Diameter of stator core (m).

L : Length of stator core (m).

n_s: Synchronous speed (rps).

B_{av} : Specific magnetic loading (W/m^2).

ac: Specific electric loading (W/m^2).

K_{ws}: Stator winding factor.

pf: Power factor.

Solution :

KVA input, Q = $\frac{HP\times 0.746}{\text{n}\times pf} = \frac{15\times 0.746}{09\times 0.85} = 14.63KVA$

Output coefficient, $C_0 = 11B_{av}ac\ K_{ws} \times\ 10^{-3}$

$$= 11 \times 0.45 \times 20000 \times 0.955 \times 10^{-3}$$

$$= 94.545\frac{KVA}{m^3}\ rps$$

Synchronous speed, $n_s = \frac{2f}{p} = \frac{2\times50}{6} = 16.667\ rps$

Q is also given by : $Q = C_0\, D^2\, Ln_s$

$D^2\, L = \frac{14.63}{94.545\ \times16.667} = 9.284 \times\ 10^{-3}$

$\frac{L}{\tau} = 0.85$

$L = 0.85\tau$

$L = 0.85\ \frac{\pi D}{P}$

$L = \frac{0.85\ \times \pi}{6}\ D$

Put, L = 0.445 D in the equation for $D^2\, L$

$D^2(0.445D) = 9.284\ \times 10^{-3}$

$D = \left(\frac{9.284 \times 10^{-3}}{0.445}\right)^{\frac{1}{3}} = 0.2753m\ \approx 0.275m$

$L = 0.445D = 0.445 \times 1.275 = 0.1224 \approx 0.12m$

$\emptyset_m = \frac{B_{av}\, \pi DL}{P} = \frac{0.45 \times \pi \times 0.275 \times 0.12}{6} \approx 7.775 \times 10^{-3}\ Wb$

For star delta starting, the motor should be designed for delta connection. In delta *connection, phase voltage is equal to line voltage.*

$T_s = \frac{E_s}{4.44f\emptyset_m\, K_{ws}} = \frac{400}{4.44 \times 50 \times 7.775 \times 10^{-3} \times 0.955} = 242.66 \approx 242$

Total conductors = 6 T_s = 6× 242 = 1452 *conductors*

Slot pitch y_{ss} lies between 15 mm to 25mm.

When $y_{ss} = 15mm$

$S_s = \frac{\pi D}{y_{ss}} = \frac{\pi\times0.275}{15\times10^{-3}} = 58$

When $y_{ss} = 25mm$

$S_s = \frac{\pi D}{y_{ss}} = \frac{\pi\times0.275}{25\times10^{-3}} = 34$

The number of slots lies between 34 and 58.

The stator slots should be multiple of q, where q is slots per pole per ohase.

Stator slots, S_s = Number of phases × poles × q

When q = 2, $S_s = 3 \times 6\ \times 2 = 36$

When q = 3, $S_s = 3 \times 6\ \times= 54$

When q = 4, $S_s = 3 \times 6\ \times 4 = 72$

Let $S_s = 36$

$Z_{SS} = \frac{6T_s}{S_s} = \frac{1452}{36}\ \approx 40$

Total stator conductors = $S_s\ \times\ Z_{ss} = 36 \times 40 = 1440$ conductors

New value of turns per phase, $T_s = \frac{Z_{ss} \times S_s}{6} = \frac{40 \times 36}{6} = 240$

KVA input, $Q = \sqrt{3}\, V_L \times I_L \times 10^{-3} = 3E_{ph}I_{ph}10^{-3}$

$$I_{ph} = \frac{Q \times 10^{-3}}{3E_{ph}} = \frac{14.62 \times 10^{-3}}{3 \times 400} = 12.183A$$

Let, $\delta = 3A/mm^2$

Area of cross-section of stator conductor a_s

$$a_s = \frac{I_{PH}}{\delta} = \frac{12.183}{3} = 4.061\, mm^2$$

$$a_s = 4.061mm^2$$

Length of air gap, $I_g = 0.2 + 2\sqrt{DL} = 0.2 + 2\sqrt{0.275 \times 0.12} = 0.5633mm$

Let, $I_g = 0.6mm$

Rotor slots:

Let, S_r = Number of rotor slots ; S_s = Number of stattors slots

We know that, $(S_s - S_r)$ *cannot be*, $0, \pm p, \pm 2p, \pm 3p, \pm 5p, \pm 1, \pm 2, \pm(p \pm 1), \pm(p \pm 2)$

Here, p=6

$$(S_s - S_r)\ cannot\ be, 0, \pm 6, \pm 12, \pm 18, \pm 30, \pm 1, \pm 2, \pm 5, \pm 7, \pm 8, \pm 4$$

Here, $(S_s - S_r)$ *can be*, $\pm 3, \pm 9, \pm 10, \pm 11, etc$ ...

Let, $(S_s - S_r) =, \pm 3$ $\quad S_{r\,=}\ S_s + 3 \quad or \quad S_r = S_s - 3$

Let, $S_{r\,=}\ S_s - 3 = 36 - 3 = 33$

Rotor bar current, $I_b = 0.85 \frac{6T_sI_s}{S_r} = \frac{0.85 \times 6 \times 240 \times 12 \times 12.183}{33} = 451.88\ A$

Let, $\delta_b = 4A/mm^2$

Area of cross section of rotor $a_b = \frac{I_b}{\delta_b} = \frac{451.88}{4} = 112.96 = 113mm^2$

End ring current, rotor $I_e = \frac{S_rI_b}{\pi p} = \frac{33 \times 451.88}{\pi \times 6} = 791.1amps$

Let, $\delta_e = 4\ A/mm^2$

Area of cross section of end ring, $a_e = \frac{I_e}{\delta_e} = \frac{791.1}{4} = 197.775mm^2$

Let, $a_e = 200\ mm^2$

Chapter V: Synchronous machines

V.1. Introduction

Synchronous machines are classified into generators and motors. Synchronous motors converts electrical energy into mechanical energy, while synchronous generators converts mechanical energy into electrical energy.

Synchronous motors are used principally in large power applications because of their high operating efficiency, reliability, controllable power factor and relatively low sensitivity to voltage dips. This motor runs at constant speed and it does not depend on the torque acting on it. Synchronous generators also called alternators or AC generators are the principal sources of electrical powers in the world. Synchronous machine runs at synchronous speed:

$$N_s = \frac{120f}{p} \qquad (V.1)$$

N_s is the synchronous speed in rpm, f is the supply frequency and p the number of poles of the machine

V.2 Synchronous machine

V.2.1. Principle

Synchronous machine operates on the principle of magnetic interlocking between a rotating magnetic field in the stator and a magnetic field on the rotor. The machine consists of a stator with a three-phase winding, called the armature, it is identical to that of a three-phase induction motor, and a rotor with a dc winding or permanent magnets.

In motor operation the armature, energized from a three-phase supply, develops a synchronous rotating field , which interacts with the constant magnetic field of the rotor, locks the rotor and causes it to rotate at synchronous speed.

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

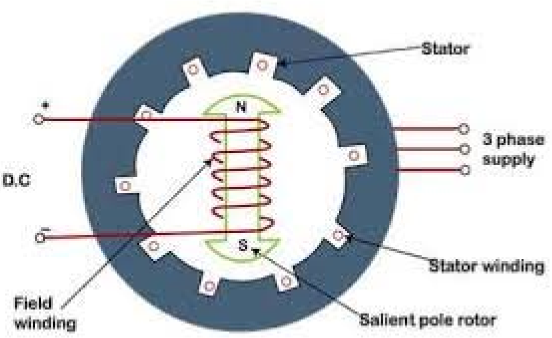


Figure V.1 : Operating principle of a synchronous machine

V.2.2 Main parts of synchronous machine

The construction of synchronous generators is essentially the same as for synchronous motor. A synchronous machine, consists of two main parts, namely the stator and the rotor. The stator, as indicated by its designation, constitutes the stationary component of the electrical machine and accommodates the armature winding. Conversely, the rotor represents the rotating element responsible for the machine's electromechanical energy conversion. (Figure 1.2).

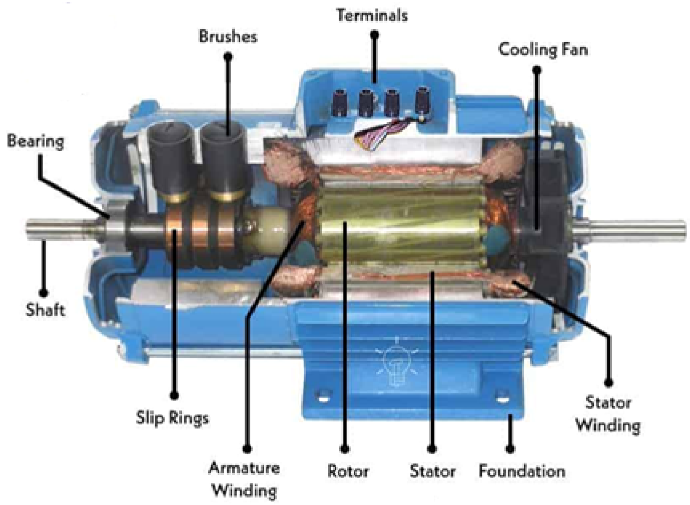


Figure V.2 : Main parts of synchronous machine

V.2.2.1 Stator : The stators in synchronous and asynchronous machines are identical**.** It consists of the following parts.

- **Stator frame:** The frame is the machine's outer component, supporting the stator core and protecting the inner parts of the machine from mechanical and environmental damage. It is built of cast iron or welded steel.
- **Stator core:** Stator core is built with sheet steel laminations having slots on its inner periphery. Its main role is to provide an easy path for magnetic lines and to hold a three phase winding placed on the slots. Different shapes of the armature slots are shown in figure I.3.

Figure V.3 : Stator parts of synchronous machine

- **Stator windings:** The phase windings, which can be single-phase or three-phase, are divided into several slots, hollowed out on the inner edge of the stator core. The material used is enameled copper. The spatial distribution of the produced electromotive force (EMF) is essentially sinusoidal. The construction of stator windings is largely similar to that of the asynchronous machine.

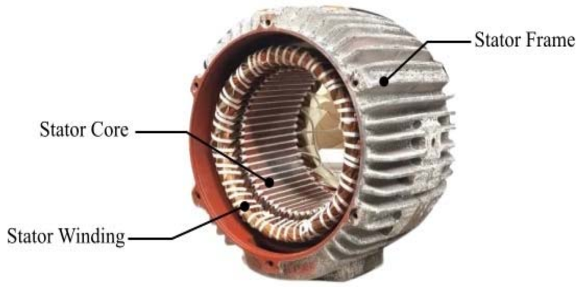


Figure V.4 : Stator parts of synchronous machine

V.2.2.2 Rotor: There are two different type of rotors, namely cylindrical (non-salient) rotors and salient rotors.

- **Salient pole rotor**

Salient pole rotor is distinguished by the presence of projecting poles extending from the rotor core surface, which inherently produces a non-uniform air gap distribution between the stator and rotor. Therefore, its reactance varies with the rotor position.

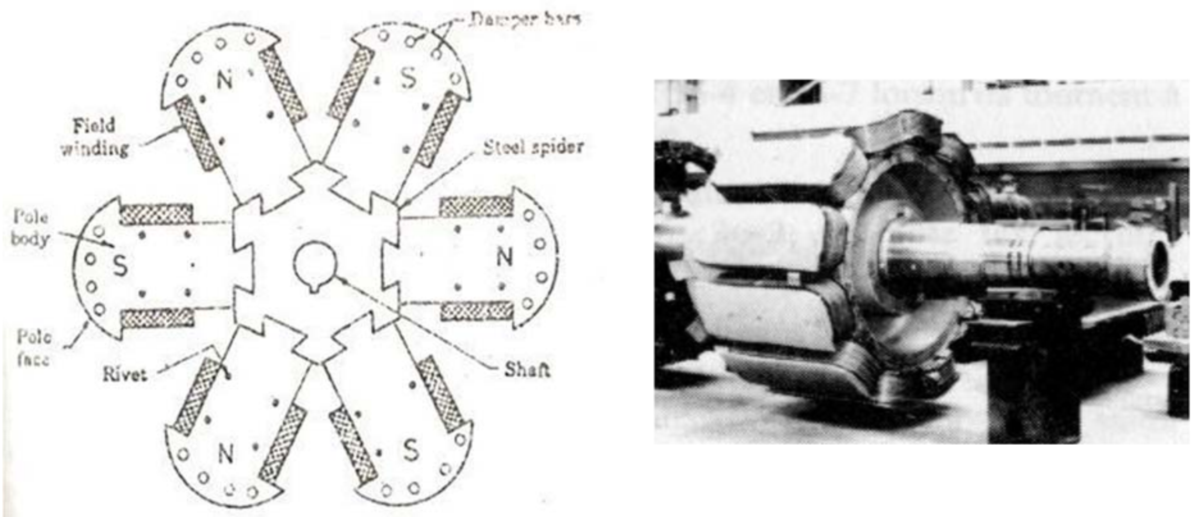
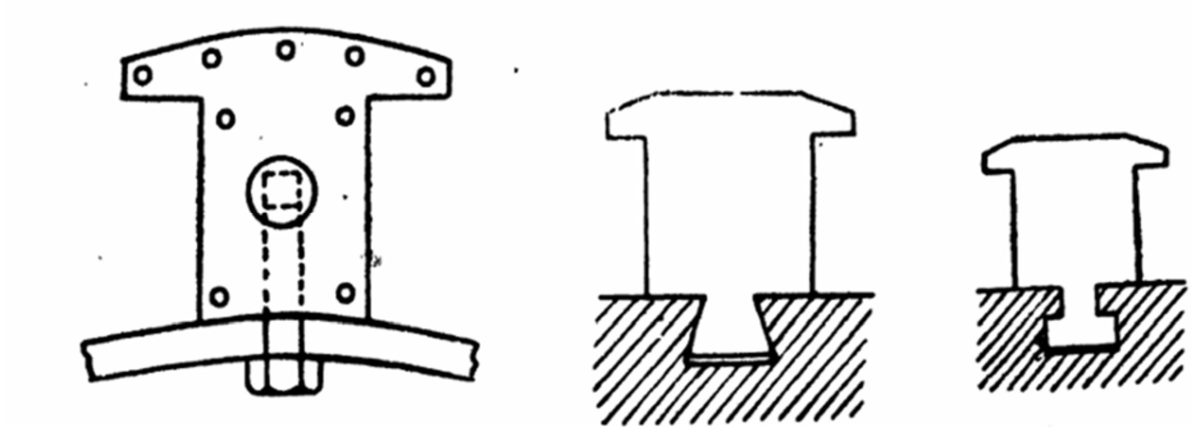


Figure V. 5 : Salient pole rotor

Salient pole construction is use for low and medium speed applications. To achieve the required frequency, they have a large number of poles and therefore a large diameter and small axial length. They are used as synchronous generators in hydroelectric and diesel engines. The mainly parts of rotor of salient pole alternator are:

1. **Spider:** The "spider" is a central part of the rotor's mechanical construction. Spider is keyed to the shaft. It carries rotor core and poles are radially fitted onto the core. It is constructed from cast iron in order to ensure a low-reluctance path for the magnetic flux.
2. **Pole Core and Pole Shoe:** Are attached to a rotor and made of laminated steel sheet material riveted together reduce eddy current losses. The pole core provides the least reluctance path for the magnetic field, the pole shoe covers about 2/3 rd of pole pitch it reduces magnetic reluctance, spreads the magnetic flux from the pole core over a larger area of the armature core to produce a sinusoidal wave.
   The poles of generators with peripheral speeds of up to 20 m/s are bolted to the yoke (Figure I.6.a). For water wheel generators with peripheral speeds ranging from 20 to 60 m/s, the dove tail (Figure I.6.b) or T-head style of design (Figure I.6.c) is employed to fixe the pole to the yoke.

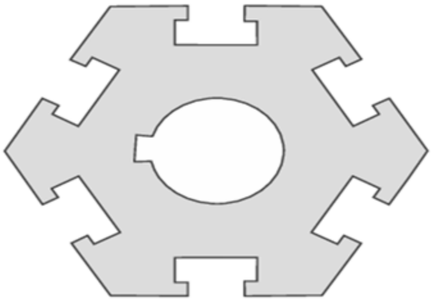


(a) Bolted on pole construction **(b)** Dove tail construction **(c)** T-head construction

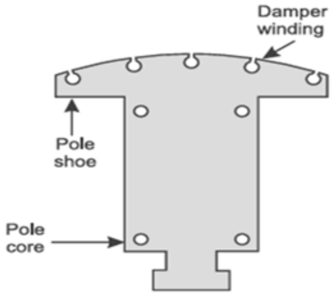
Figure V.6 : Rotor pole attachment

3. **Field Winding:** It is wound on a winding former and then positioned around the pole core. Slip rings provide it with a direct current supply (DC). When direct current flows through the field winding, the necessary magnetic field is generated.
4. **Damper Winding**: Most alternators exhibit a significant oscillation. Damper windings are a type of partial squirrel-cage winding used to dampen the transient oscillations and

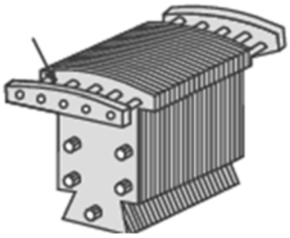
facilitate the start-up operation. At the pole faces, holes are provided in which copper bars are inserted and short-circuited at both sides by rings.



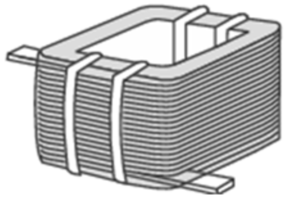
(a) Spider



(b) Pole core and pole shoe



(c) Damper winding

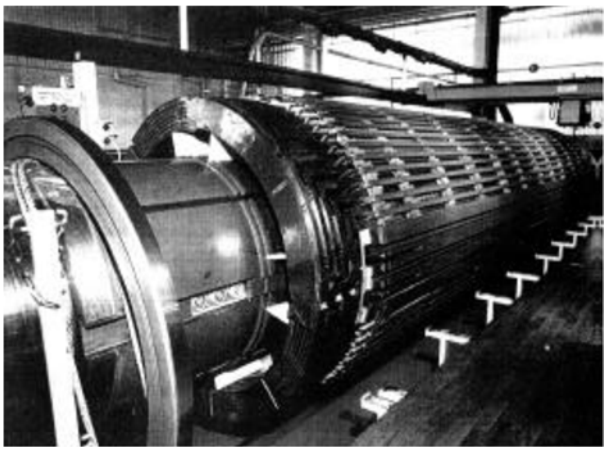


(d) Windings

Figure V.7: Main parts of salient-pole rotor

- **Non-Salient Pole Rotor**

1. **Rotor core:** The rotor exhibits a smooth cylindrical shape; characterized by a small diameter and has a long axial length. It is fabricated from solid forgings of alloy steel than laminated sheets because their mechanical and electromagnetic requirements differ from those of stators and salient-pole rotors. The rotor may incorporate two or four poles. The rotor is then mounted directly on the shaft to ensure precise alignment and reliable mechanical performance during rotation.
2. **Excitation rotor windings:** The excitation (or rotor) windings are accommodated via properly carved slots along the rotor's outside perimeter. These windings are carefully positioned within the slots, and when supplied with current through slip rings, they generate magnetic poles according to the required configuration, producing the magnetic field necessary for electromechanical energy conversion.



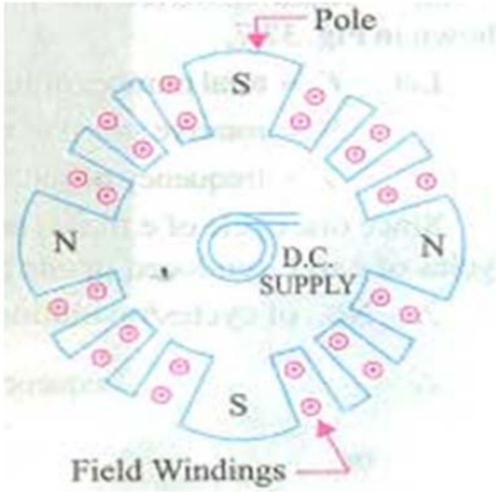


Figure V.8 : Non-salient-pole rotor

Non-salient pole rotors present various advantages, including decreased losses, reduced noise levels due to a regular air gap, do not require damper windings, which simplifies the both designs and operation of the machine. Moreover, they offer a better E.M.F waveform than salient pole rotor. Their robust construction further contributes to their better durability, making them highly suitable for high-speed applications such as steam and gas turbines.

V.2.2.3 Auxiliary Components

- **Brushes:** Brushes, composed of carbon material slide across the slip rings. The brushes receive a DC supply and send current to the slip rings, which subsequently passes it to the exciting windings.
- **Bearings:**Bearings are placed between the shaft's both ends to reduce the friction and ensure smooth rotational of the rotor. They are made of high-carbon steel or high-strength alloy, which increases longevity, decreases wear, and offers mechanical stability.
- **Shaft:** The shaft, which is made of mild steel and serves as the central mechanical part, takes or gives mechanical power to the machine based on the mode of operation.

V.2.2.4 Applications of synchronous machines

It is used in :

- Electric power generation (alternators).

- Reactive power compensation : A synchronous motor operating under no-load conditions providing a leading(capacotive) power factor is connected to the power grid where the use of static capacitor are not suitable.
- Applications requiring constant speed independently of load variation.

Cost is its main disadvantage.

V.3 Design of synchronous machine

V.3.1Output equation

The output equation for polyphase AC machines is:

$$Q = C_0 D^2 L n_s \qquad \text{(KVA)}$$

Where

C_0 is the output coefficient and is given by:

$$C_0 = 1.11\pi^2 B_{av}\, ac\, K_{ws} 10^{-3}$$

D: Diameter of stator core (m).

L : Length of stator core (m).

n_s: Synchronous speed (rps).

B_{av} : Specific magnetic loading (W/m^2).

ac: Specific electric loading (W/m^2).

K_{ws}: Stator winding factor.

In term of periphiral speed the output equation is:

$$Q = (1.11 B_{av}\, ac\, K_{ws} 10^{-3})\, V_a^2 L / n_s \qquad \text{(KVA)}$$

V.3.2 Specific magnetic loading

A high average air-gap flux density B_{av} increases the efficiency and heating of the machine, as well as the saturation of the teeth and the stator magnetic circuit in high-voltage machines. Furthermore, it reduces synchronous reactance, leading to higher short-circuit currents and greater electrodynamic forces on the windings.

On the other hand, the reduction in synchronous reactance improves the operational stability of the alternator and allows for better load sharing when several alternators are operating in parallel.

The value for the air-gap flux density are:

- Salient-pole machines: 0.52-0.65 W/m^2.
- Turbo-alternators :0.54-0.65 W/m^2.

V.3.3 Specific electric loading

When the specific electrical load is high ac, copper losses, stray-load losses and heating increase resulting in lower efficiency. Therefore, its value should be chosen according to the cooling method employed. Additionally, synchronous reactance rises, which minimises the short-circuit current but deteriors voltage regulation. However, when the synchronous reactance increases, the machine becomes less stable.

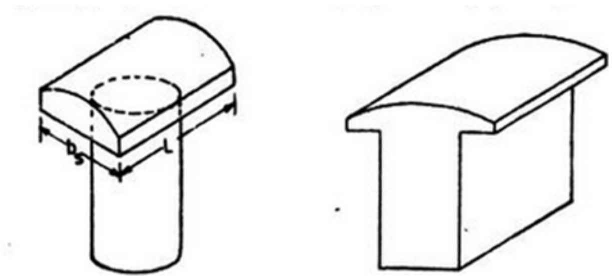
For low voltage machines, a higher ac value can be used because there is less space needed for insulation. Thus, the following electrical load values are advised:

- Salient-pole machines: 20000-40000 A/m.
- Turbo-alternators :50000-75000 A/m.

V.3.4 Main dimensions of pole salient machine

The diameter D of the stator core and the outer diameter D_r of the rotor are nearly equals. The selection of D depends on the type of poles used and the permissible periphical speed.

There are two types of poles used in salient pole machines; round poles and rectangular poles (Figure V.9).



(a) : Round pole **(b) :** Rectangular pole

Figure V.9 : Shape of non-salient pole rotor

- For round poles the ratio of pole arc to pole pitch L/τ usually lies between from 0.6to 0.7.
- For rectangular poles the ratio L/τ generally ranges from 1 to 5 and should not exceed 3 in normal machine designs to maintain an economical construction.

The periphiral speed determines the diameter. The rotor should be built to resist centrifugal forces generated under runway speeds. The rotor diameter should be large enough to generate a sufficient flywheel effect. The recommended peripheral speeds for various types of pole attachments are:

- Bolted on pole construction V_a =50m/s.
- Dovetailed and T head construction V_a =80m/s.

Example :

Determine the main dimensions for a $1000\ kVA$, $50Hz$, $3\ phases$, $375\ rmp$ alternator. The average air gap flux density is $0.55\ Wb/m^2$ and the ampers conductors per metre ac are 28000 .

Use rectangular poles and assume a suitable value for ratio of core length to pole pitch in order that bolted on pole construction is used for which the maximum permissible peripheral speed is $50\ m/s$. The run away speed is 1.80 times the synchronous speed.

Solution:

Synchronous speed $n_s = \frac{375}{60} = 6.25\ r.p.s$

Number of poles $p = 2 \times \frac{50}{6.25} = 13$

Assume a winding factor of 0.955

Output co-efficient $C_0 = 11.\ K_{ws}.B_{av}.ac.10^{-3}$

$$= 11 \times 0.955 \times 0.55 \times 28000 \times 10^{-3} = 162$$

Product $D^2L = \frac{Q}{C_0\ n_s} = \frac{1000}{162 \times 6.25}\ 0.987\ m^2$

Taking $\frac{L}{\tau} = 2$

We have $L = 0.393\ D$

$$0.393\ D^2 = 0.987$$

$$D = 1.36\ m\ and\ L = 0.335m$$

Peripheral speed $V_a = \pi D n_s = \pi * 1.36 * 6.25 = 26.7\ m/s$

Peripheral speed at run-way speed $1.8 \times 26 = 48\ m/s$. This is below $50\ m/s$ and therefore a simple bolted on pole construction can be used.

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