# ELECTRICAL MACHINES - II

# COURSEFILE

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## GEETHANJALI COLLEGE OF ENGINEERING AND TECHNOLOGY

**DEPARTMENT OF** *Electrical and Electronics Engineering*

**(Name of the Subject / Lab Course) :** ***Electrical Machines - II***

**(JNTU CODE –A40212)** **Programme :** ***UG***

**Branch: Electrical and Electronics Engineering** **Version No :** ***01***

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| **Prepared by : 1) Name : G.SRIKANTH,** | **1) Name :** |
| **2) Sign :** | **2) Sign :** |
| **3) Design : Assoc. Prof** | **3) Design :** |
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**Approved by : (HOD ) 1) Name :**

**2) Sign :**

**3) Date :**

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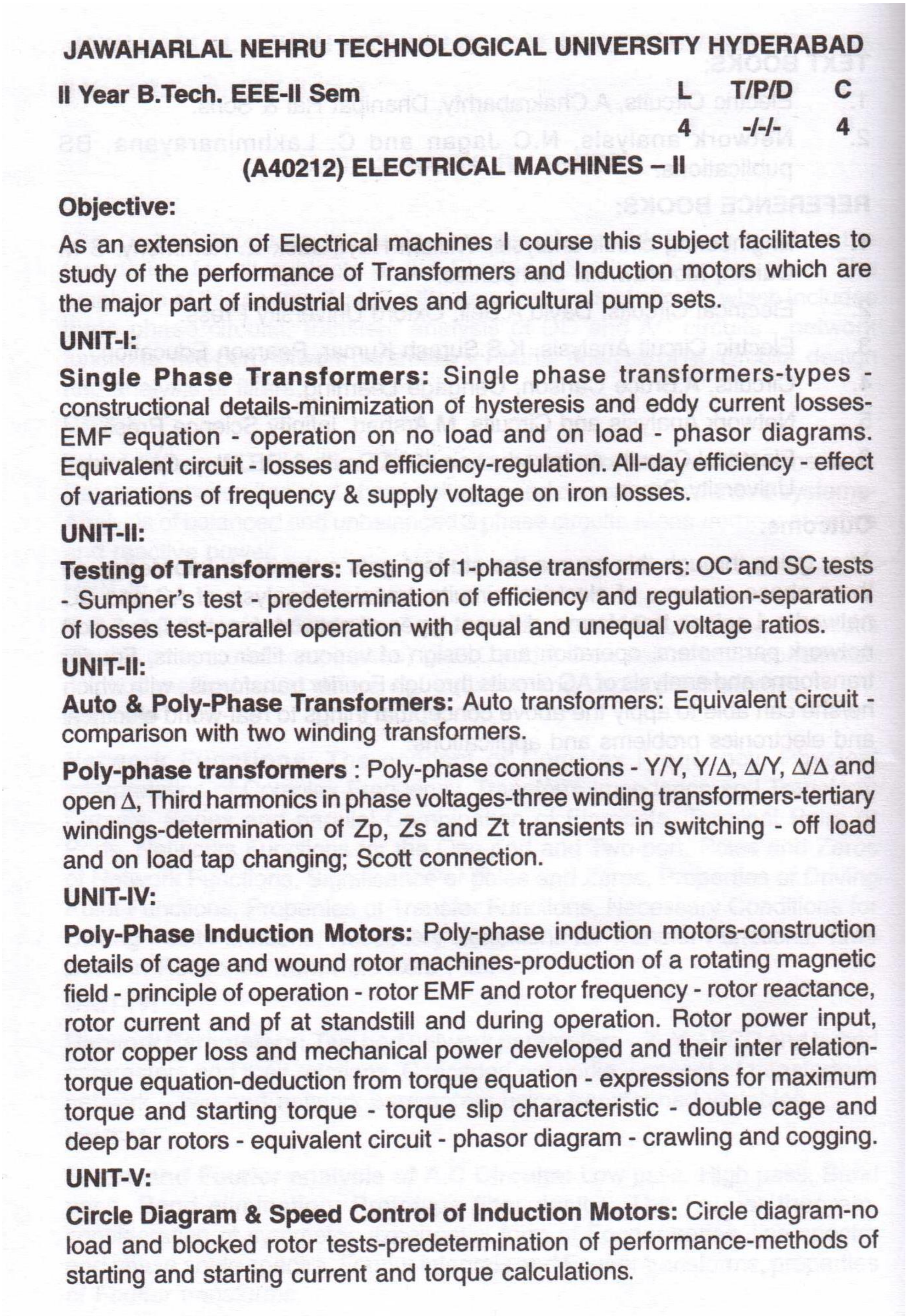
## 2. University Syallabus



### JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY HYDERABAD

| II Year B.Tech. EEE-II Sem | L | T/P/D | C |
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| | 4 | -/-/- | 4 |

### (A40212) ELECTRICAL MACHINES – II

**Objective:**

As an extension of Electrical machines I course this subject facilitates to study of the performance of Transformers and Induction motors which are the major part of industrial drives and agricultural pump sets.

**UNIT-I:**

**Single Phase Transformers:** Single phase transformers-types - constructional details-minimization of hysteresis and eddy current losses-EMF equation - operation on no load and on load - phasor diagrams. Equivalent circuit - losses and efficiency-regulation. All-day efficiency - effect of variations of frequency & supply voltage on iron losses.

**UNIT-II:**

**Testing of Transformers:** Testing of 1-phase transformers: OC and SC tests - Sumpner's test - predetermination of efficiency and regulation-separation of losses test-parallel operation with equal and unequal voltage ratios.

**UNIT-II:**

**Auto & Poly-Phase Transformers:** Auto transformers: Equivalent circuit - comparison with two winding transformers.

**Poly-phase transformers** : Poly-phase connections - Y/Y, Y/Δ, Δ/Y, Δ/Δ and open Δ, Third harmonics in phase voltages-three winding transformers-tertiary windings-determination of Zp, Zs and Zt transients in switching - off load and on load tap changing; Scott connection.

**UNIT-IV:**

**Poly-Phase Induction Motors:** Poly-phase induction motors-construction details of cage and wound rotor machines-production of a rotating magnetic field - principle of operation - rotor EMF and rotor frequency - rotor reactance, rotor current and pf at standstill and during operation. Rotor power input, rotor copper loss and mechanical power developed and their inter relation-torque equation-deduction from torque equation - expressions for maximum torque and starting torque - torque slip characteristic - double cage and deep bar rotors - equivalent circuit - phasor diagram - crawling and cogging.

**UNIT-V:**

**Circle Diagram & Speed Control of Induction Motors:** Circle diagram-no load and blocked rotor tests-predetermination of performance-methods of starting and starting current and torque calculations.

**Speed control:** change of frequency; change of poles and methods of consequent poles; cascade connection. Injection of an EMF into rotor circuit (qualitative treatment only)-induction generator-principle of operation.

## TEXT BOOKS:

1. Electrical machines-PS Bhimbra, Khanna Publishers.
2. Principles of Electrical Machines, V. K. Mehta, Rohit Mehta, S. Chand Publishing.

## REFERENCE BOOKS:

1. Electric Machines, I.J. Nagrath & D.P. Kothari, Tata Mc Graw – Hill Publishers.
2. Electric Machines, Mulukutla S. Sarma, Mukesh K. Pathak, Cengage Learning.
3. Fundamentals of Electric Machines, B. R. Gupta, Vandana Singhal, New Age International Publishers.
4. Electrical Machines, M. V. Deshpande, PHI Learning Private Limited.
5. Electrical Machines, R. K. Srivastava, Cengage Learning.
6. Performance and Design of AC Machines, MG.Say, BPB Publishers.
7. Theory of Alternating Current Machinery, Langsdorf, Tata McGraw-Hill Companies.
8. Electric machinery, A.E. Fitzgerald, C.Kingsley and S.Umans, Mc Graw Hill Companies.

## Outcome:

After going through this course the student gets a thorough knowledge on construction operation characteristics and testing of different types of Transformers and construction operation characteristics testing (concept of circle diagram) and speed control methods of poly-phase induction motors, with which he/she can able to apply the above conceptual things to real-world electrical and electronics problems and applications.

## 3. Vision of EEE

*To provide excellent Electrical and electronics education by building strong teaching and research environment*

## 4. Mission of EEE

*To offer high quality graduate program in Electrical and Electronics education and to prepare students for professional career or higher studies. The department promotes excellence in teaching, research, collaborative activities and positive contributions to society*

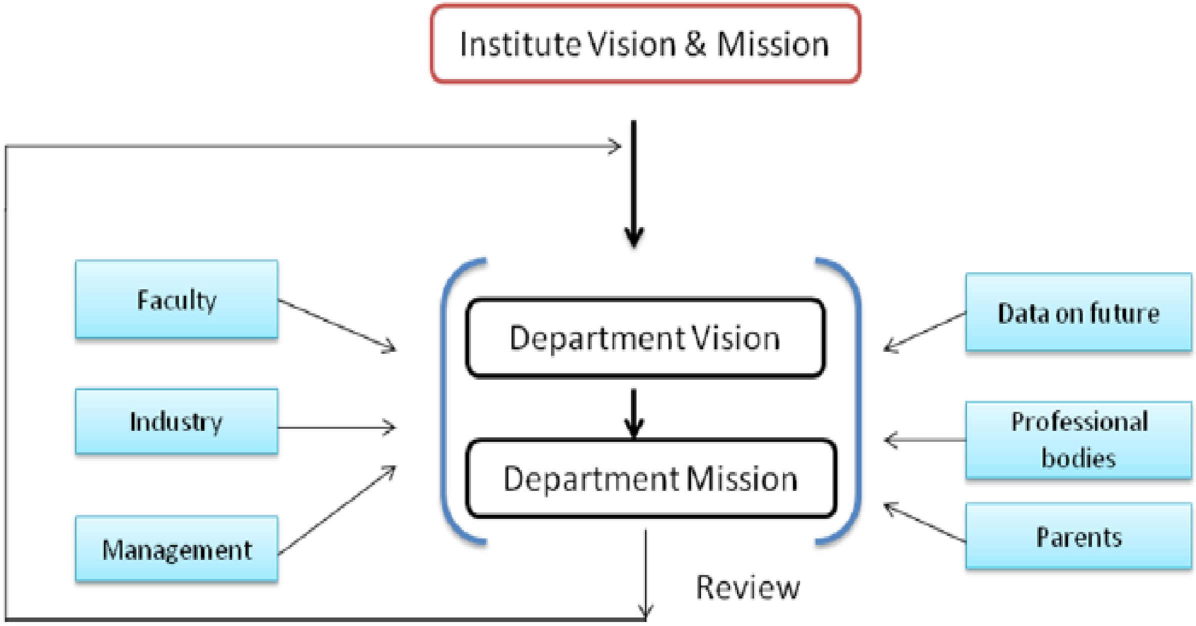

Figure 1.1: Process for defining Vision and Mission of the Department

# 5. PROGRAMME EDUCATIONAL OBJECTIVES

***PEO 1.** Graduates will excel in professional career and/or higher education by acquiring knowledge in Mathematics, Science, Engineering principles and Computational skills.*

***PEO 2.** Graduates will analyze real life problems, design Electrical systems appropriate to the requirement that are technically sound, economically feasible and socially acceptable.*

***PEO 3.**Graduates will exhibit professionalism, ethical attitude, communication skills, team work in their profession, adapt to current trends by engaging in lifelong learning and participate in Research & Development.*

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# PROGRAMME OUTCOMES

The Programme Outcomes of UG in Electrical and Electronics Engineering are as follows

**PO 1. An ability to apply the knowledge of Mathematics, Science and Engineering in Electrical and Electronics Engineering.**

**PO 2. An ability to design and conduct experiments pertaining to Electrical and Electronics Engineering.**

**PO 3. An ability to function in multidisciplinary teams**

**PO 4. An ability to simulate and determine the parameters such as nominal voltage current, power and associated attributes.**

**PO 5. An ability to identify, formulate and solve problems in the areas of Electrical and Electronics Engineering.**

**PO 6. An ability to use appropriate network theorems to solve electrical engineering problems.**

**PO 7. An ability to communicate effectively.**

**PO 8. An ability to visualize the impact of electrical engineering solutions in global, economic and societal context.**

**PO 9. Recognition of the need and an ability to engage in life-long learning.**

**PO 10 An ability to understand contemporary issues related to alternate energy sources.**

**PO 11 An ability to use the techniques, skills and modern engineering tools necessary for Electrical Engineering Practice.**

**PO 12 An ability to simulate and determine the parameters like voltage profile and current ratings of transmission lines in Power Systems.**

**PO 13 An ability to understand and determine the performance of electrical machines namely speed, torque, efficiency etc.**

**PO 14 An ability to apply electrical engineering and management principles to Power Projects.**

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# 6. COURSE OBJECTIVES

| S.No. | Objectives |
|---|---|
| 1 | To acquire the basic knowledge of construction, working and operation of transformer and induction motor |
| 2 | To know about the insulation of the machines and to choose good insulator for better performance and efficiency |
| 3 | Can test the given transformer and induction motor in the laboratory |
| 4 | Can design the speed controlling techniques for the induction motor |
| 5 | Able to select a particular transformer/induction motor depending on the application |
| 6 | To design a particular transformer for the application |

## COURSE OUTCOMES

On successful completion of this subject, students will be able to:

1. Understand the working principles of Transformer and Induction Motor.
2. Calculate the Performance of both transformer and induction motor.
3. Identify different speed controlling techniques of Induction motor for the given application.
4. Identify suitable transformer depending on the application of transmission and distribution.
5. Calculate the load sharing of different transformers in the power engineering.

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Signature of HOD

Date:

Signature of faculty

Date:

# 7. Brief notes on the importance of the course and how it fit into the curriculum

This is the fundamental course for the Electrical Engineering program. Also an extension to the previous semester subject, Electrical Machines –I. It introduces the basic working principle and operation of different types of transformers. It also provides the basic information of losses existing in the operation and construction of transformers. It also gives their performance when connected in the power circuits.

It also gives the invention of Induction motors and their analogy with transformer construction and operation. As the induction motor is one of the important load used in all applications it is very much necessary to know about the construction, types, losses and working of different types of induction motors. It also tells us the different methods of finding the efficiency of induction motor. Also tells us different speed controlling techniques available for induction motors.

Finally this subject gives the information of two important electrical utilities in the power transmission, distribution and utilization.

# 8. Prerequisites

The fundamental knowledge of Engineering Physics, Mathematics .

The fundamental knowledge of Electromagnetic field theory, fundamental of machine operation

Information about different magnetic materials, insulation, etc.

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# 9. Instructional Learning Outcomes:

UNIT-I

| Sl No. | Module | Outcomes |
|---|---|---|
| 1 | Single Phase Transformer | Understands the construction of transformer |
| | | Able to try for the methods for minimizing hysteresis and eddy current losses |
| | | Able to calculate the electromotive force under no load and loaded conditions |
| | | Ability to calculate the efficiency of the transformer |
| | | Able to analyze the effect of variation of supply frequency and magnitude on the losses and thereby efficiency |

UNIT-II

| Sl No. | Module | Outcomes |
|---|---|---|
| 1 | Testing | Can perform different practical tests to test the transformer and can predetermine the efficiency |
| 2 | Parallel Operation | Able to understand the logic and theory of operating more than one transformer in different ways i.e., parallel operation |

UNIT-III

| Sl No. | Module | Outcomes |
|---|---|---|
| 1 | Auto Transformers | Able to understand the construction and operation of special type of transformer and its applications |
| 2 | Poly – Phase Transformers | Ability to identify the difference between different poly phase transformers |
| | | Ability to do harmonic analysis for poly phase transformers |
| | | Understands different possible connections of poly phase transformers |

UNIT-IV

| Sl No. | Module | Outcomes |
|---|---|---|
| 1 | Poly phase Induction Motors | Able to understand the construction and operation of different types of Induction motors |
| | | Ability to calculate emf value along with the calculations of losses |
| | | Ability to obtain the performance characteristics of different induction motors |
| | | Ability to identify the effects of loading of induction motors |

UNIT-V

| Sl No. | Module | Outcomes |
|---|---|---|
| 1 | Polyphase Induction Motors | Ability to predetermine the performance of Polyphase Induction motor |
| | | Understandability of starting and stopping techniques of |

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|  |  |  |
|---|---|---|
|  |  | Induction motor |
|  |  | Ability to control the speed of Induction motor |
| 2 | Induction Generator | Understandability of working of an induction generator |

# 11.Class Time Table:

# 12.Individual Time Table:

# 13. Lecture Schedule:

**GEETHANJALI COLLEGE OF ENGINEERING & TECHNOLOGY**
**Cheeryal(V), Keesara (M), Ranga Reddy(Dist.)**
**DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING**
***LESSON PLAN***

**Name of the faculty: D.Radhika** **Sub: Electrical Machines-II**
**Year: II B.Tech-II Semester** **Branch: EEE**

| Unit No. | S. No | Name of the Topic | Referred books/sites | No. of periods | Remarks |
|---|---|---|---|---|---|
| I | 1 | Single-phase transformer construction, operation | B.L.THERAJA | 1 |  |
|  | 2 | Classification, emf equation |  | 1 |  |
|  | 3 | Problems |  | 1 |  |
|  | 4 | No-load, load phaser diagrams,problems |  | 2 |  |
|  | 5 | Hysterises, eddy current losses |  | 1 |  |
|  | 6 | Problems |  | 2 |  |
|  | 7 | Equalent circuit , measurement of RO1, XO1 |  | 1 |  |
|  | 8 | Losses, efficiency , Allday efficency | B.L.THERAJA | 2 |  |
|  | 9 | Problems |  | 1 |  |
| II | 10 | Testing of transformers | B.L.THERAJA | 2 |  |
|  | 11 | OC,SC tests,Problems |  | 2 |  |
|  | 12 | Sumpens tests |  | 2 |  |
|  | 13 | Predetermination of efficiency, regulation |  | 1 |  |
|  | 14 | Seperation of losses, Problems |  | 1 |  |
|  | 15 | Parallel operation with equal and unequal voltage ratios |  | 2 |  |
| III | 16 | Auto transformer equalent diagram, operation |  | 2 |  |
|  | 17 | Comparison with two winding transformer |  | 1 |  |
|  | 18 | Polyphase transformers | BIMBRA | 1 |  |
|  | 19 | Third harmonics in phase voltages |  | 1 |  |
|  | 20 | Three winding transformers, tertiary windings |  | 2 |  |
|  | 21 | Determination of ZP, ZS, ZT |  | 2 |  |
|  | 22 | Offload, load tab changing |  | 1 |  |
|  | 23 | Scott connection |  | 2 |  |
| IV | 24 | Polyphase induction motors, types | B.L.THERAJA | 1 |  |
|  | 25 | Construction details, rotating magnetic fields |  | 1 |  |
|  | 26 | Rotor emf , speed , frequency, power factor calculations |  | 4 |  |
|  | 27 | Rotor input , loses, mechanical power developed | B.L.THERAJA | 2 |  |
|  | 28 | Torque equation, problems |  | 1 |  |
|  | 29 | Maximum torque, torque ,slip characteristics |  | 2 |  |
|  | 30 | Double cage motors ,circuit diagram |  | 1 |  |
|  | 31 | Phasor diagrams, crawling and cogging |  | 3 |  |

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|  |  |  |  |  |  |
|---|---|---|---|---|---|
| V | 32 | No load & blocked tests, circle diagram | BIMBRA | 3 |  |
|  | 33 | Predetermination of performance |  | 1 |  |
|  | 34 | Methods of starting |  | 2 |  |
|  | 35 | Merits and Demerits |  | 1 |  |
|  | 36 | Current & torque calculations ,problems |  | 3 |  |
|  | 37 | Speed control methods | BIMBRA | 2 |  |
|  | 38 | Cascade connection |  | 1 |  |
|  | 39 | Injection of an emf into rotor |  | 2 |  |
|  | 40 | Induction generator |  | 2 |  |
|  | 41 | Principle of Operation |  | 2 |  |
|  |  |  | **Total Classes Required** | 68 |  |

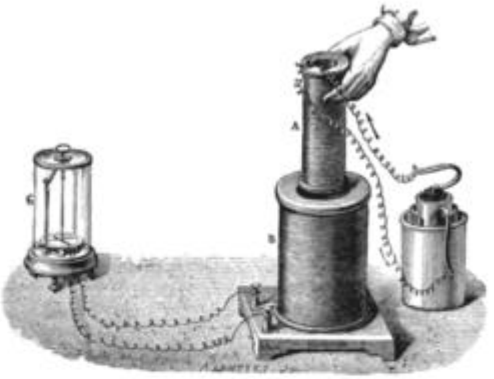
**Head of the Dept.** **Signature of the Faculty**

# 14. Detailed Notes:

## TRANSFORMERS

A **transformer** is a device that transfers electrical energy from one circuit to another through inductively coupled conductors—the transformer's coils. A varying current in the first or primary winding creates a varying magnetic flux in the transformer's core and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force (EMF), or "voltage", in the secondary winding. This effect is called inductive coupling.

### Discovery



Faraday's experiment with induction between coils of wire

The phenomenon of electromagnetic induction was discovered independently by Michael Faraday and Joseph Henry in 1831. However, Faraday was the first to publish the results of his experiments and thus receive credit for the discovery. The relationship between electromotive force (EMF) or "voltage" and magnetic flux was formalized in an equation now referred to as "Faraday's law of induction":

$$|\mathcal{E}| = \left|\frac{d\Phi_B}{dt}\right|$$

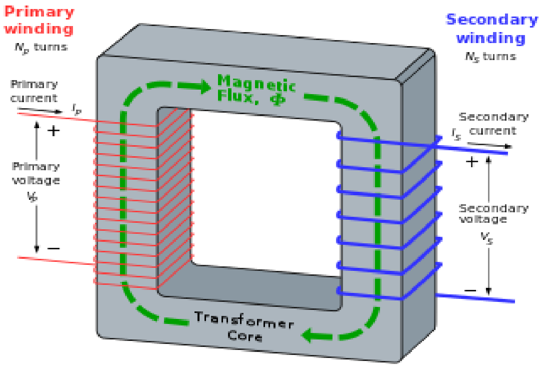
where $|\mathcal{E}|$ is the magnitude of the EMF in volts and $\Phi_B$ is the magnetic flux through the circuit in webers.

Faraday performed the first experiments on induction between coils of wire, including winding a pair of coils around an iron ring, thus creating the first toroidal closed-core transformer.

### WORKING PRINCIPLE OF TRANSFORMER:

### Introduction

The main advantage of alternating currents over direct current is that, the alternating currents can be easily transferable from low voltage to high voltage or high voltage to low. Alternating voltages can be raised or lowered as per requirements in the different stages of electrical network as generation, transmission, distribution and utilization. This is possible with a static device called transformer. The transformer works on the



principle of mutual induction. It transfer an electric energy from one circuit to other when there is no electrical connection between the tow circuits. Thus we can define transformer as below :

**Key point** : The transformer is a static piece of apparatus by means of which an electrical power is transformed from one alternating current circuit to another with the desired change in voltage and current, without any change in the frequency.

The use of transformers in transmission system is shown in the Fig 1.1.

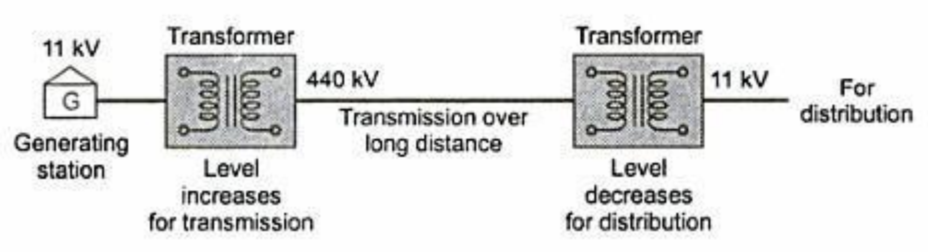


**Fig. 1.1 Use of transformer in transmission system**

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## PRINCIPLE OF WORKING

The principle of mutual induction states that when tow coils are inductively coupled and if current in one coil is changed uniformly then an e.m.f. gets induced in the other coil. This e.m.f can drive a current, when a closed path is provided to it. The transformer works on the same principle. In its elementary form, it consists of tow inductive coils which are electrically separated but linked through a common magnetic circuit. The two coils have high mutual inductance. The basic transformer is shown in the Fig 1.2.

One of the two coils is connected to source of alternating voltage. This coil in which electrical energy is fed with the help of source called primary winding (P). The other winding is connected to load. The electrical energy transformed to this winding is drawn out to the load.

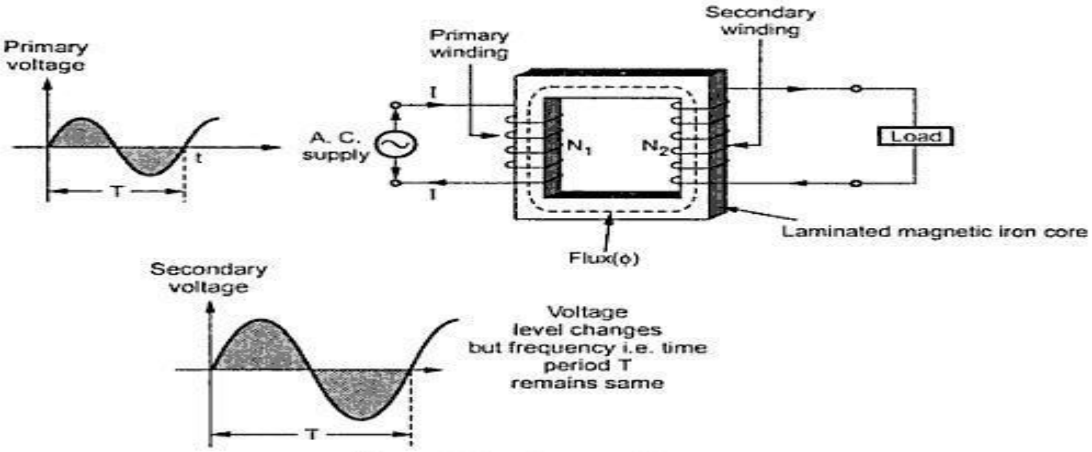

**Fig.1.2 Basic transformer**

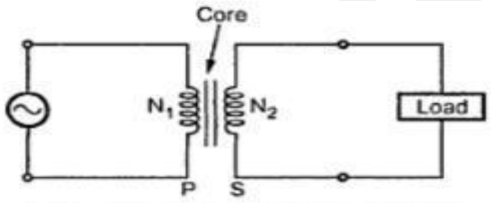

**Fig 1.3 Symbolic representation**

This winding is called secondary winding (S). The primary winding has $N_1$ number of turns while the secondary winding has $N_2$ number of turns. Symbolically the transformer is indicated as shown in the Fig 1.3.

When primary winding is excited by an alternating voltage, it circulates an alternating current. This current produces an alternating flux ($\Phi$)which completes its path through common magnetic core as shown dotted in the Fig 1.2. Thus an alternating, flux links with the secondary winding. As the flux is alternating, according to Faraday's law of an electromagnetic induction, mutually induced e.m.f. gets developed in the secondary winding. If now load is connected to the secondary winding, this e.m.f. drives a current through it.

Thus through there is no electrical contact between the two windings, an electrical energy gets transferred from primary to the secondary.

**Key point** : The frequency of the mutual induced e.m.f. is same as that of the alternating source which is supplying energy to the primary winding.

## Can D.C. Supply be used for Transformer?

The d.c. supply can not be used for the transformers.

The transformer works on the principle of mutual induction, for which current in one coil must change uniformly. If d.c. supply is given, the current will not change due to constant supply and transformer will not work.

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Practically winding resistance is very small. For d.c., the inductive reactance $X_L$ is zero as d.c. has no frequency. So total impedance of winding is very low for d.c. Thus winding will draw very high current if d.c. supply is given to it. This may cause the burning of windings due to extra heat generated and may cause permanent damage to the transformer.

There can be saturation of the core due to which transformer draws very large current from the supply when connected to d.c.

**Thus d.c. supply should not be connected to the transformers.**

## CONSTRUCTION OF TRANSFORMER:

There are two basic parts of a transformer i) Magnetic Core ii) Winding or Coils.

The core of the transformer is either square or rectangular in size. It is further divided into tow parts. The vertical position on which coils are wound is called limb while the top and bottom horizontal portion is called yoke of the core. These parts are shown in the Fig.1(a).

Core is made up of lamination. Because of laminated type of construction, eddy current losses get minimised. Generally high grade silicon steel laminations (0.3 to 0.5 mm thick) are used. These laminations are insulated from each other by using insulation like varnish. All laminations are varnished. Laminations are overlapped so that to avoid the air gap at joints. For this generally 'L' shaped or 'I' shaped laminations are used which are shown in the Fig 1(b).

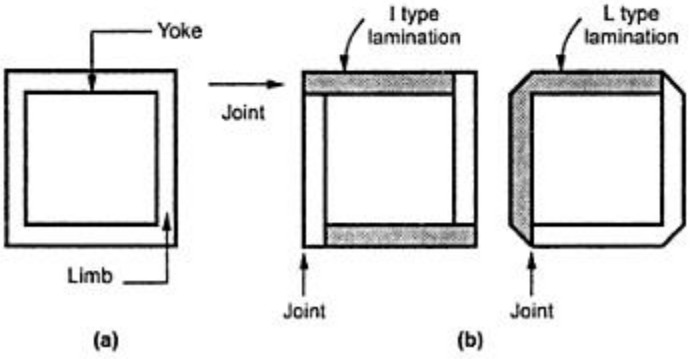


**Fig. 1 Construction of transformer**

The cross-section of the limb depends on the type of coil to be used either circular or rectangular. The different cross-section of limbs, practically used are shown in the Fig. 2.

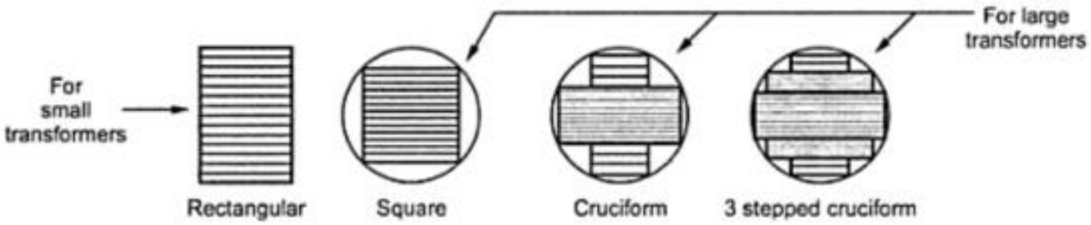


**Fig. 2  Different cross-sections**

## Types of Windings

The coils used are wound on the limbs and are insulated from each other. In the basic transformer shown in the Fig 1.2 the two windings wound are shown on two different limbs i.e. primary on one limb while secondary on other limb. But due to this leakage flux increases which effects the transformer performance badly. Similarly it is necessary that the windings should be very closes to each other to have high mutual inductance. To achieve this, the two windings are split into number of coils and are wound adjacent to each other on the same limb. A very common arrangement is cylindrical coils as shown in the Fig. 3.

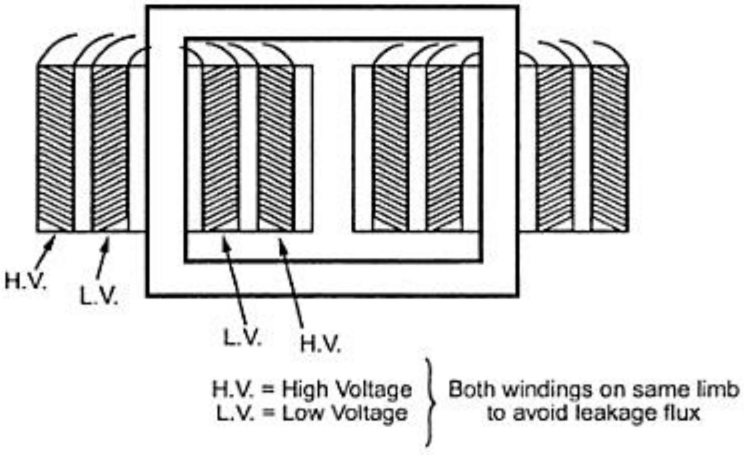


**Fig. 3   Cylindrical concentric coils**

Such cylindrical coils are used in the core type transformer. Theses coils are mechanically strong. These are wound in the helical layers. The different layers are insulated from each other by paper, cloth or mica. The low voltage winding is placed near the core from ease of insulating it from the core. The high voltage is placed after it.

The other type of coils which is very commonly used for the shell type of transformer is sandwiching coils. Each high voltage portion lies between the two low voltage portion sandwiching the high voltage portion. Such subdivision of windings into small portion reduces the leakage flux. Higher the degree of subdivision, smaller is the reactance. The sandwich coil is shown in the Fig. 4. The top and bottom coils are low voltage coils. All the portion are insulated from each other by paper.

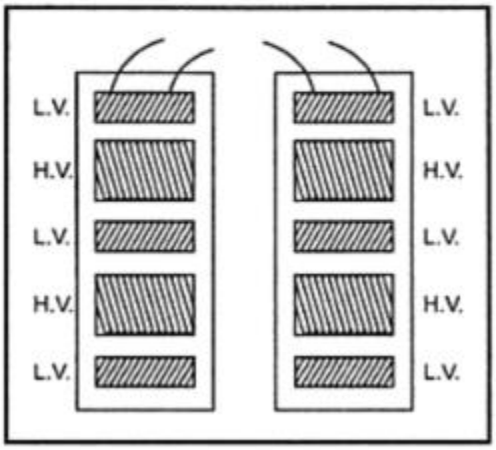


**Fig. 4 Sandwich coils**

The various types of depending on the construction of core used for the single phase transformers are,

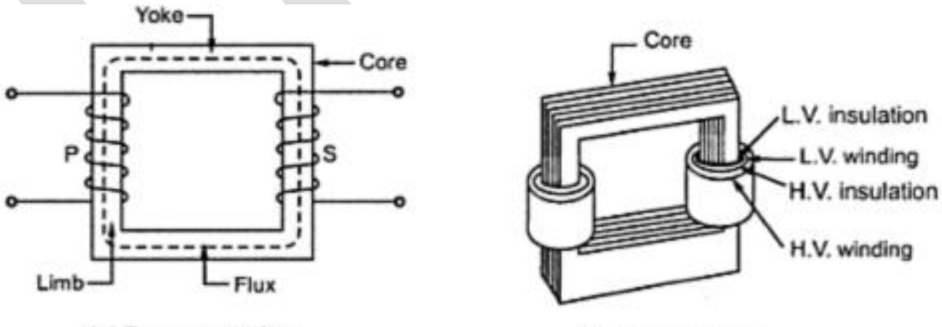
1. Core type 2. shell type and 3. Berry type

## 1. Core Type Transformer

It has a single magnetic circuit. The core rectangular having two limbs. The winding encircles the core. The coils used are of cylindrical type. As mentioned earlier, the coils are wound in helical layers with different layers insulated from each other by paper or mica. Both the coils are placed on both the limbs. The low voltage coil is placed inside near the core while high voltage coil surrounds the low voltage coil. Core is made up of large number of thin laminations.

As The windings are uniformly distributed over the two limbs, the natural cooling is more effective. The coils can be easily removed by removing the laminations of the top yoke, for maintenance.

The Fig. 1(a) shows the schematic representation of the core type transformer while the Fig 1(b) shows the view of actual construction of the core type transformer.



(a) Representation (b) Construction

**Fig. 1 Core type transformer**

## 2. Shell Type Transformer

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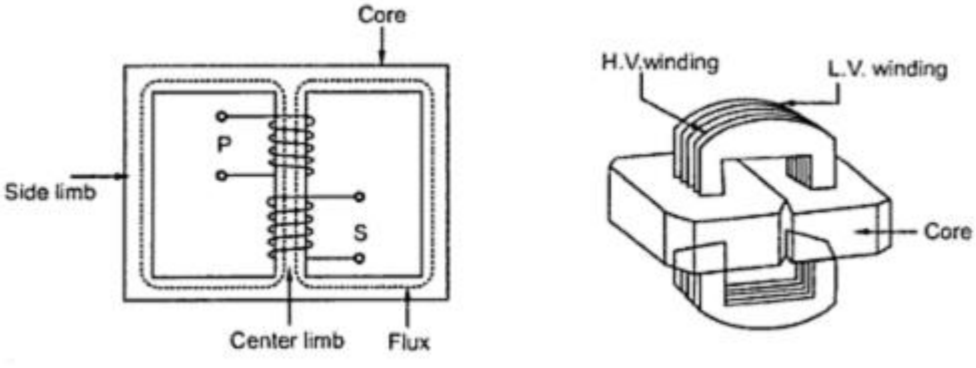
It has a double magnetic circuit. The core has three limbs. Both the windings are placed on the central limb. The core encircles most part of the windings. The coils used are generally multilayer disc type or sandwich coils. As mentioned earlier, each high voltage coil is in between tow low voltage coils and low voltage coils are nearest to top and bottom of the yokes.

The core is laminated. While arranging the laminations of the core, the care is taken that all the joints at alternate layers are staggered. This is done to avoid narrow air gap at the joint, right through the cross-section of the core. Such joints are called over lapped or imbricated joint. Generally for very high voltage transformers, the shell type construction is preferred. As the windings are surrounded by the core, the natural cooling does not exist. For removing any winding for maintenance, large number of laimnations are required to be removed.

The Fig. 2(a) shows the schematic representation while the Fig. 2(b) shows the outaway view of the construction of the shell type transformer.



(a) Representation (b) Construction

**Fig 2 Shell type transformer**

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**3. Berry Type Transformer**

This has distributed magnetic circuit. The number of independent magnetic circuits are more than 2. Its core construction is like spokes of a wheel. Otherwise it is symmetrical to that of shell type.

Diagramatically it can be shown as in the Fug. 3.

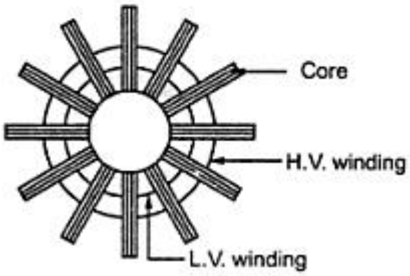

**Fig. 3 Berry type transformer**

The transformers are generally kept in tightly fitted sheet metal tanks. The tanks are constructed of specified high quality steel plate cut, formed and welded into the rigid structures. All the joints are painted with a solution of light blue chalk which turns dark in the presence of oil, disclosing even the minutes leaks. The tanks are filled with the special insulating oil. The entire transformer assembly is immersed in the oil. Oil serves two functions : i) Keeps the coil cool by circulation and ii) Provides the transformers an additional insulation.

The oil should be absolutely free from alkalies, sulphur and specially from moisture. Presence of very small moisture lowers the dielectric strength of oil, affecting its performance badly. Hence the tanks are sealed air tight to avoid the contact of oil with atmospheric air and moisture. In large transformers, the chambers called breather are provided. The breathers prevent the atmospheric moisture to pass on to the oil. The breathers contain the silica gel crystal which immediately absorb the atmospheric moisture. Due to long and continuous use, the sludge is formed in the oil which can contaminate the oil. Hence to keep such sludge separate from the oil in main tank, an air tight metal drum is provided, which is placed on the top of tank. This is called conservator.

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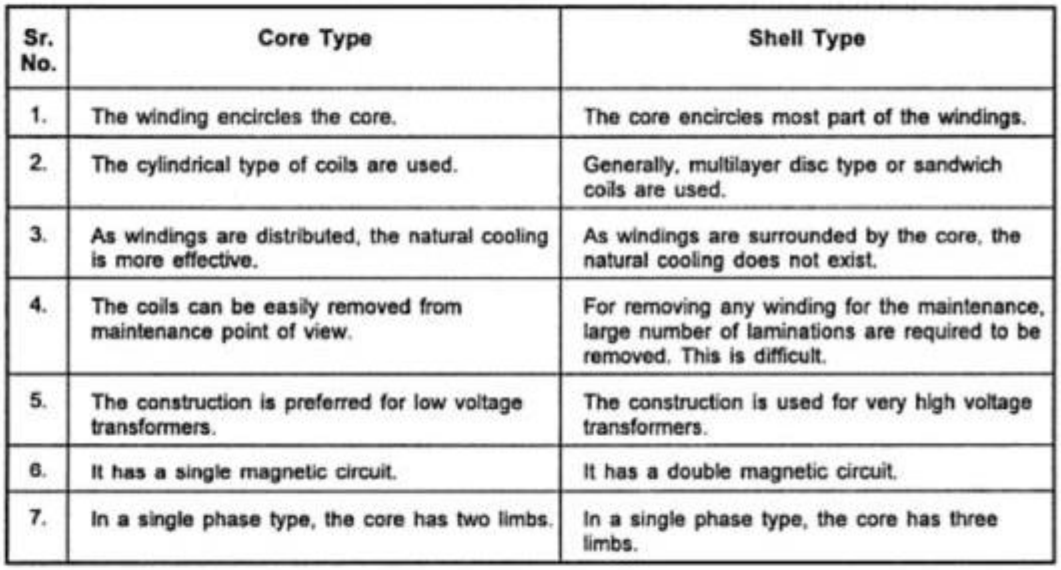
**Comparison of Core and Shell Type Transformers**



| Sr. No. | Core Type | Shell Type |
|---|---|---|
| 1. | The winding encircles the core. | The core encircles most part of the windings. |
| 2. | The cylindrical type of coils are used. | Generally, multilayer disc type or sandwich coils are used. |
| 3. | As windings are distributed, the natural cooling is more effective. | As windings are surrounded by the core, the natural cooling does not exist. |
| 4. | The coils can be easily removed from maintenance point of view. | For removing any winding for the maintenance, large number of laminations are required to be removed. This is difficult. |
| 5. | The construction is preferred for low voltage transformers. | The construction is used for very high voltage transformers. |
| 6. | It has a single magnetic circuit. | It has a double magnetic circuit. |
| 7. | In a single phase type, the core has two limbs. | In a single phase type, the core has three limbs. |

## E.M.F EQUATION OF TRANSFORMER:

When the primary winding is excited by an alternating voltage $V_1$, it circulates alternating current, producing an alternating flux $\Phi$. The primary winding has $N_1$ number of turns. The alternating flux $\Phi$ linking with the primary winding itself induces an e.m.f in it denoted as $E_1$. The flux links with secondary winding through the common magnetic core. It produces induced e.m.f. $E_2$ in the secondary winding. This is mutually induced e.m.f. Let us derive the equations for $E_1$ and $E_2$.

The primary winding is excited by purely sinusoidal alternating voltage. Hence the flux produced is also sinusoidal in nature having maximum value of $\Phi_m$ as show in the Fig. 1.

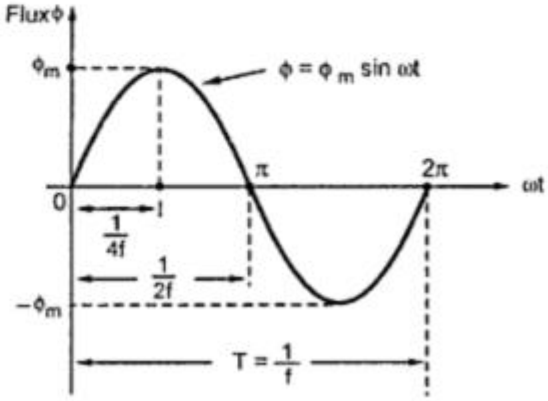


**Fig. 1 Sinusoidal flux**

The various quantities which affect the magnitude of the induced e.m.f. are :

$\Phi$ = Flux

$\Phi_m$ = Maximum value of flux

$N_1$ = Number of primary winding turns

$N_2$ = Number of secondary winding turns

f = Frequency of the supply voltage

$E_1$ = R.M.S. value of the primary induced e.m.f.

$E_2$ = R.M.S. value of the secondary induced e.m.f.

From Faraday's law of electromagnetic induction the voltage e.m.f. induced in each turn is proportional to the average rate of change of flux.

$\therefore$ average e.m.f. per turn = average rate of change of flux

$\therefore$ average e.m.f. per turn = $d\Phi/dt$

Now $d\Phi/dt$ = Change in flux/Time required for change in flux

Consider the 1/4 th cycle of the flux as shown in the Fig.1. Complete cycle gets completed in 1/f seconds. In 1/4 th time period, the change in flux is from 0 to $\Phi_m$.

$\therefore$ $d\Phi/dt = (\Phi_m - 0)/(1/4f)$ as dt for 1/4 th time period is 1/4f seconds

$= 4\ f\ \Phi_m$ Wb/sec

$\therefore$ Average e.m.f. per turn = $4\ f\ \Phi_m$ volts

As is sinusoidal, the induced e.m.f. in each turn of both the windings is also sinusoidal in nature. For sinusoidal quantity,

From factor = R.M.S. value/Average value = 1.11

$\therefore$ R.M.S. value of induced e.m.f. per turn

$= 1.11 \times 4\ f\ \Phi_m = 4.44\ f\ \Phi_m$

There are number of primary turns hence the R.M.S value of induced e.m.f. of primary denoted as is $E_1$,

$E_1 = N_1 \times 4.44\ f\ \Phi_m$ volts

While as there are number of secondary turns the R.M.S values of induced e.m.f. of secondary denoted is $E_2$ is,

$E_2 = N_2 \times 4.44\ f\ \Phi_m$ volts

The expression of $E_1$ and $E_2$ are called e.m.f. equation of a transformer.

Thus e.m.f. equations are,

$E_1 = 4.44\ f\ \Phi_m\ N_1$ volts ............(1)

$E_2 = 4.44\ f\ \Phi_m\ N_2$ volts ............(2)

**Transformation Ratio(k)**

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Consider a transformer shown in Fig.1 indicating various voltages and currents.

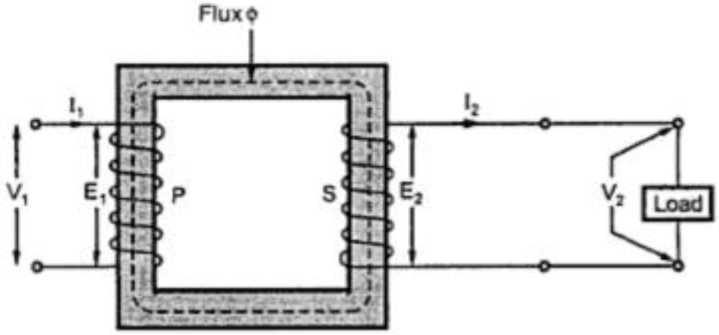

**Fig. 1 Ratios of transformer**

## 1. Voltage Ratio

We known from the e.m.f. equations of a transformer that

$$E_1 = 4.44\ f\ \Phi_m\ N_1 \quad \text{and} \quad E_2 = 4.44\ f\ \Phi_m\ N_2$$

Taking ratio of the two equations we get,

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

This ratio of secondary induced e.m.f. to primary induced e.m.f. is known as voltage transformation ratio denoted as K,

Thus,

$$E_2 = K\ E_1 \qquad \text{where} \quad K = \frac{N_2}{N_1}$$

1. If $N_2 > N_1$ i.e. $K > 1$, $E_2 > E_1$ we get then the transformer is called step-up transformer.
2. If $N_2 < N_1$ i.e. $K < 1$, we get $E_2 < E_1$ then the transformer is called step-down transformer.
3. If = i.e. K= 1, we get $E_2 = E_1$ then the transformer is called isolation transformer or 1:1 transformer.

## 2. Concept of Ideal Transformer

A transformer is said to be ideal if it satisfies following properties :

i) It has no losses.
ii) Its windings have zero resistance.
iii) Leakage flux is zero i.e. 100% flux produced by primary links with the secondary.
iv) Permeability of core is so high that negligible current is required to establish the flux in it.

**Key point** : For an ideal transformer, the primary applied voltage $V_1$ is same as the primary induced e.m.f. $V_2$ as there are no voltage drops.

Similarly the secondary induced e.m.f. $E_2$ is also same as the terminal voltage $V_2$ across the load. Hence for an ideal transformer we can write,

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$$\frac{E_2}{E_1} = \frac{V_2}{V_1} = K$$

No transformer is ideal in practice but the value of $E_1$ is almost equal to $V_1$ for properly designed transformer.

### 3. Current ratio

For an ideal transformer there are no losses. Hence the product of primary voltage $V_1$ and primary current $I_1$, is same as the product of secondary voltage $V_2$ and the secondary current $I_2$.

So $V_1 I_1$ = input VA and $V_2 I_2$ = output VA

For an ideal transformer,

$V_1 I_1 = V_2 I_2$

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

Key point : Hence the currents are in the inverse ratio of the voltage transformation ratio.

### 4. Voltage ampere rating

When electrical power is transferred from primary winding to secondary there are few power losses in between. These power losses appear in the form of heat which increase the temperature of the device.Now this temperature must be maintained below certain limiting values as it is always harmful from insulation point of view. As current is the main cause in producing heat, the output maximum rating is generally specified as the product of output voltage and output current i.e.$V_2 I_2$. This always indicates that when transformer is operated under this specified rating, its temperature rise will not be excessive. The copper loss ($I^2R$) in the transformer depends on the current 'I' through the winding while the iron or core loss depends on the voltage 'V' as frequency of operation is constant. None of these losses depend on the power factor (cos $\Phi$) of the load. Hence losses decide the temperature and hence the rating of the transformer. As losses depend on V and I only, the rating of the transformer is specified as a product of these two parameters VxI.

**Key point** : Thus the transformer rating is specified as the product of voltage and current called VA rating.

On both sides, primary and secondary VA rating remains same. This rating is generally expresses in KVA (kilo volt amperes rating).

Now $V_1 / V_2 = I_2 / I_1 = K$

$\therefore$ $V_1 I_1 = V_2 I_2$

$$\text{kVA rating of a transformer} = \frac{V_1 I_1}{1000} = \frac{V_2 I_2}{1000}$$

If $V_1$ and $V_2$ are the terminal voltages of primary and secondary then from specified KVA rating we can decide full load currents of primary and secondary, $I_1$ and $I_2$. This is the safe maximum current limit which may carry, keeping temperature rise below its limiting value.

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$$I_1 \text{ full load} = \frac{\text{kVA rating} \times 1000}{V_1} \qquad \text{... (1000 to convert kVA to VA)}$$

$$I_2 \text{ full load} = \frac{\text{kVA rating} \times 1000}{V_2}$$

**Key point** : The full load primary and secondary currents indicate the safe maximum values of currents which transformer windings can carry.

**Example 1** : A single phase, 50 Hz transformer has 80 turns on the primary winding and 400 turns on the secondary winding. The net cross-sectional area of the core is 200 $cm^2$. If the primary winding is connected at a 240 V , 50 Hz supply, determine :

i) The e.m.f. induced in the secondary winding.
ii) The maximum value of the flux density in the core.

**Solution**

$N_1 = 80$ , $f = 50$ Hz , $N_2 = 400$ , $a = 200\ cm^2 = 200 \times 10^{-4}\ cm^2$
$E_1 = 240$
$K = N_2 / N_1 = 400/80 = 5/1$
$\therefore$ $K = E_2 / E_1 = E_2 / 240 = 5/1$
$E_2 = 5 \times 240 = 1200$ V
Now $E_1 = 4.44\ f\ \Phi_m N_1$
$240 = 4.44 \times 50 \times \Phi_m \times 80$
$\therefore$ $\Phi_m = 240/(4.44 \times 50 \times 80) = 0.01351$ Wb
$\therefore$ $B_m = \Phi_m / a = 0.01351/(200 \times 10^{-4}) = 0.6756\ Wb/m^2$

**Example 2** : For a single phase transformer having primary and secondary turns of 440 and 880 respectively, determine the transformer KVA rating if half load secondary current is 7.5 A and maximum value of core flux is 2.25 Wb.

**Solution**

$N_1 = 440$ , $N_2 = 880$ , $(I_2)_{H.L.} = 7.5$ A,
$f_m = 2.25$ mWb , $E_2 = 4.44\ \Phi_m\ f\ N_2$
Assuming $f = 50$ Hz,
$\therefore$ $E_2 = 4.44 \times 2.25 \times 10^{-3} \times 50 \times 880 = 439.56$ V
$(I_2)_{F.L.} = \text{KVA rating} / E_2$
And $(I_2)_{H.L.} = 0.5\ (I_2)_{F.L.}$
$\therefore$ $(I_2)_{H.L.} = 0.5 \times (\text{KVA rating} / E_2)$
$\therefore$ $7.5 = 0.5 \times (\text{KVA rating} / 439.56)$
$\therefore$ KVA rating $= 2 \times 7.5 \times 439.56 \times 10^{-3}$
$= 6.5934$ KVA .....($10^{-3}$ for KVA)

**Example 3** : A single phase transformer has 350 primary and 1050 secondary turns. The primary is connected to 400 V, 50 Hz a.c. supply. If the net cross-sectional area of the core is 50 $cm^2$, calculate i) The maximum value of the flux density in the core ii) The induced e.m.f. in the secondary winding.

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**Solution**

The given value are,

$N_1$ = 350 turns, $N_2$ = 1050 turns

$V_1$ = 400 V , A = 50 $cm^2$= 50 x $10^{-4}$ $m^2$

The e.m.f. of the transformer is,

$E_1 = 4.44\ f\ \Phi_m N_1$

$E_1 = 4.44\ B_m A\ f\ N_1$ as $\Phi_m = B_m A$

Flux density $B_m = E_1 / (4.44\ A\ f\ N_1)$

$= 400 / (4.44 \times 50 \times 10^{-4} \times 50 \times 350)$ assume $E_1 = V_1$

$= 1.0296\ Wb/m^2$

$K = N_2 / N_1 = 1050/350 = 3$

And $K = E_2 / E_1 = 3$

$\therefore$ $E_2 = 3 \times E_1 = 3 \times 400 = 1200$ V

## IDEAL TRANSFORMER ON NO-LOAD:

Consider an ideal transformer on no load as shown in the Fig. 3. The supply voltage is and as it is $V_1$ an no load the secondary current $I_2 = 0$.

The primary draws a current $I_1$ which is just necessary to produce flux in the core. As it magnetising the core, it is called magnetising current denoted as $I_m$. As the transformer is ideal, the winding resistance is zero and it is purely inductive in nature. The magnetising current is $I_m$ is very small and lags $V_1$ by $30^o$ as the winding is purely inductive. This $I_m$ produces an alternating flux Φ which is in phase with $I_m$.

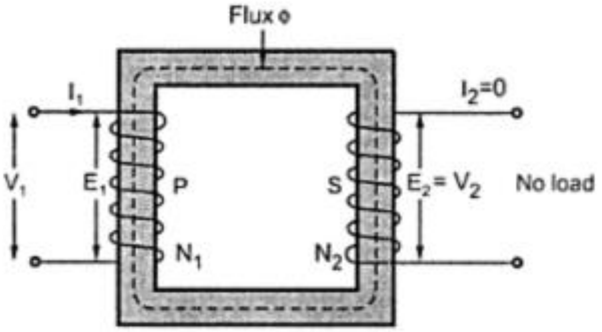

**Fig. 1 Ideal transformer on no load**

The flux links with both the winding producing the induced e.m.f.s $E_1$ and $E_2$ , in the primary and secondary windings respectively. According to Lenz's law, the induced e.m.f. opposes the cause producing it which is supply voltage $V_1$. Hence $E_1$ is in antiphase with $V_1$ but equal in magnitude. The induced $E_2$ also opposes $V_1$ hence in antiphase with $V_1$ but its magnitude depends on $N_2$. Thus $E_1$ and $E_2$ are in phase.

The phasor diagram for the ideal transformer on no load is shown in the Fig. .2.

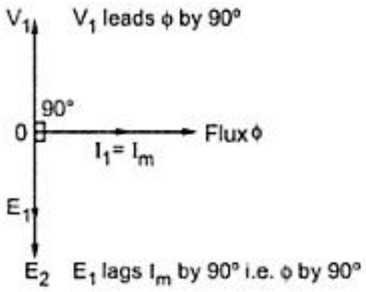

**Fig. 2 Phasor diagram for ideal transformer on no load**

It can be seen that flux $\Phi$ is reference. $I_m$ produces $\Phi$ hence in phase with $\Phi$. $V_1$ leads $I_m$ by $90^o$ as winding is purely inductive so current has to lag voltage by $90^o$.

$E_1$ and $E_2$ are in phase and both opposing supply voltage .

The power input to the transformer is $V_1 I_1 \cos (V_1 \wedge I_1)$ i.e. $V_1 I_m \cos(90^o)$ i.e. zero. This is because on no load output power is zero and for ideal transformer there are no losses hence input power is also zero. Ideal no load p.f. of transformer is zero lagging.

## PRACTICAL TRANSFORMER ON NO-LOAD:

Actually in practical transformer iron core causes hysteresis and eddy current losses as it is subjected to alternating flux. While designing the transformer the efforts are made to keep these losses minimum by,

1. Using high grade material as silicon steel to reduce hysteresis loss.
2. Manufacturing core in the form of laminations or stacks of thin lamination to reduce eddy current loss.

Apart from this there are iron losses in the practical transformer. Practically primary winding has certain resistance hence there are small primary copper loss present.

Thus the primary current under no load condition has to supply the iron losses i.e. hysteresis loss and eddy current loss and a small amount of primary copper loss. This current is denoted as $I_o$.

Now the no load input current $I_o$ has two components :

1. A purely reactive component $I_m$ called magnetising component of no load current required to produce the flux. This is also called wattless component.
2. An active component $I_c$ which supplies total losses under no load condition called power component of no load current. This also called wattful component or core loss component of $I_o$.

Th total no load current $I_o$ is the vector addition of $I_m$ and $I_c$.

$$\boxed{\bar{I}_o = \bar{I}_m + \bar{I}_c} \qquad \dots (1)$$

In practical transformer, due to winding resistance, no load current $I_o$ is no longer at $90^o$ with respect to $V_1$. But it lags $V_1$ by angle $\Phi_o$ which is less than $90^o$ . Thus $\cos \Phi_o$ is called no load power factor of practical transformer.

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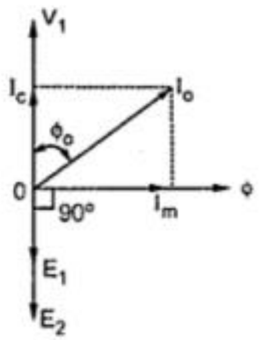


**Fig 1. Practical transformer on no load**

The phasor diagram is shown in the Fig. 1. It can be seen that the two components $I_o$ are,

$$\boxed{I_m = I_o \sin \phi_o} \quad \text{... (2)}$$

This is magnetising component lagging $V_1$ exactly by $90^o$ .

$$\boxed{I_c = I_o \cos \phi_o} \quad \text{... (3)}$$

This is core loss component which is in phase with$V_1$.
The magnitude of the no load current is given by,

$$\boxed{I_o = \sqrt{I_m^2 + I_c^2}} \quad \text{... (4)}$$

While $\Phi_o$ = no load primary power factor angle
The total power input on no load is denoted as $W_o$ and is given by,

$$\boxed{W_o = V_1\, I_o \cos \phi_o = V_1\, I_c} \quad \text{... (5)}$$

It may be denoted that the current is very small, about 3 to 5% of the full load rated current. Hence the primary copper loss is negligibly small hence $I_c$ is called core loss or iron loss component. Hence power input $W_o$ on no load always represent the iron losses, as copper loss is negligibly small. The iron losses are denoted as $P_i$ and are constant for all load conditions.

$$\therefore \quad \boxed{W_o = V_1\, I_o \cos \phi_o = P_i = \text{iron loss}} \quad \text{... (6)}$$

**Example 1** : The no load current of a transformer is 10 A at a power factor 0f 0.25 lagging, when connected to 400 V, 50 Hz supply. Calculate,

a) Magnetising component of the no load current
b) Iron loss and c) Maximum value of flux in the core.
Assume primary winding turns as 500.

**Solution** : The given value are, = 10 A, cos = 0.25, = 400 V and f = 50 Hz

a) $I_m = I_o \sin \Phi_o =$ magnetising component

$\Phi_o = \cos^{-1}(0.25) = 75.522^o$

∴ $I_m = 10 \times \sin(75.522^o) = 9.6824$ A

b) $P_i$ = iron loss = power input on no load

$= W_o = V_1 I_o \cos \Phi_o = 400 \times 10 \times 0.25$

= 1000 W

c) On no load, $E_1 = V_1 = 400$ V and $N_1 = 500$

Now $E_1 = 4.44 f \Phi_m N_1$

∴ $400 = 4.44 \times 50 \times \Phi_m \times 500$

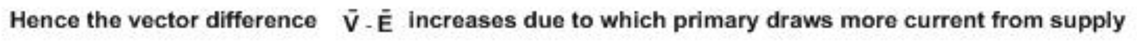
∴ $\Phi_m = 3.6036$ mWb

## TRANSFORMER ON LOAD (M.M.F Balancing on Load)

When the transformer is loaded, the current $I_2$ flows through the secondary winding. The magnetic and phase of $I_2$ is determined by the load. If load is inductive, $I_2$ lags $V_2$. If load is capacitive, $I_2$ leads $V_2$ while for resistive load, $I_2$ is in phase with$V_2$.

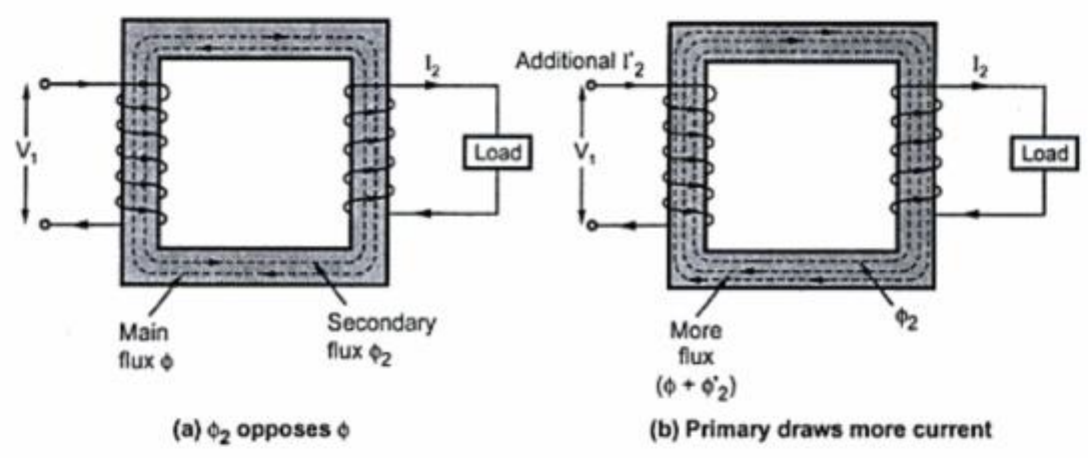
There exists a secondary m.m.f. $N_2 I_2$ due to which secondary current sets up its own flux $\Phi_2$. This flux opposes the main flux Φ which is produced in the core due to magnetising component of no load current. Hence the m.m.f. is $N_2 I_2$ called demagnetising ampere-turns. This is shown in the Fig.1(a).

The flux $\Phi_2$ momentarily reduces the main flux Φ, due to which the primary induced e.m.f. also $E_1$ reduces.



Hence the vector difference $\bar{V} - \bar{E}$ increases due to which primary draws more current from supply

This additional current drawn by primary is due to the load hence called load component of primary current denoted as $I_2'$ as shown in the Fig.1(b).



(a) $\phi_2$ opposes φ

(b) Primary draws more current

**Fig. 1 Transformer on load**

This current $I_2'$ is in antiphase with $I_2$. The current sets up its own flux $\Phi_2'$ which opposes the flux $\Phi_2$ and helps the main fluxΦ. This flux $\Phi_2'$ neutralises the flux $\Phi_2$ produced by $I_2$. The m.m.f. i.e. ampere turns $N_2 I_2'$ balances the ampere turns $N_2 I_2$. Hence the net flux in the core is again maintained at constant level.

**Key point** : Thus for any load condition, no load to full load the flux in the core is practically constant.

The load component current $I_2'$ always neutralises the changes in the loads. Hence the transformer is called constant flux machine.

As the ampere turns are balanced we can write,

$$N_2 I_2 = N_2 I_2'$$

$$\therefore \quad I_2' = (N_2/N_1) = K I_2 \qquad \text{..................(1)}$$

Thus when transformer is loaded, the primary current $I_1$ has two components :

1. The no load current $I_o$ which lags $V_1$ by angle $\Phi_o$. It has two components $I_m$ and $I_c$.

2. The load component $I_2'$ which in antiphase with $I_2$. And phase of $I_2$ is decided by the load.

Hence primary current $I_1$ is vector sum of $I_o$ and $I_2'$.

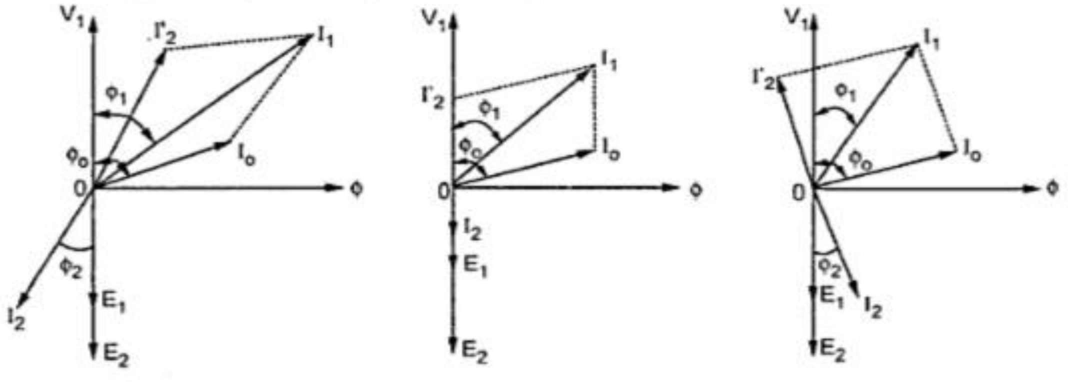
$$\therefore \quad \bar{I}_1 = \bar{I}_o + \bar{I}_2 \qquad \text{...............(2)}$$

Assume inductive load, $I_2$ lags $E_2$ by $\Phi_2$, the phasor diagram is shown in the Fig. 2(a).

Assume purely resistive load, $I_2$ in phase with $E_2$, the phasor diagram is shown in the Fig.2(b).

Assume capacitive load, $I_2$ leads $E_2$ by $\Phi_2$, the phasor diagram is shown in the Fig. 2(c).

Note that $I_2'$ is always in antiphase with $I_2$.



(a) Inductive load (b) Resistive load (c) Capacitive load

**Fig. 2**

Actually the phase of $I_2$ is with respect to $V_2$ i.e. angle $\Phi_2$ is angle between $I_2$ and $V_2$. For the ideal case, $E_2$ is assumed equal to $V_2$ neglecting various drops.

The current ratio can be verified from this discussion. As the no load current $I_o$ is very small, neglecting $I_o$ we can write,

$$I_1 \simeq I_2'$$

Balancing the ampere turns,

$$N_1 I_1 = N_1 I_1 = N_2 I_2$$

$$\therefore \quad N_2 / N_1 = I_1 / I_2 = K$$

Under full load conditions when $I_o$ is very small compared to full load currents, the ratio of primary and secondary current is constant.

**Example** : A 400/200 V transformer takes 1 A at a power factor of 0.4 on no load. If the secondary supplies a load current of 50 A at 0.8 lagging power factor, calculate the primary current.

**Solution** : The given values are

$I_o = 1$ A, $\cos \Phi_o = 0.4$, $I_2 = 50$ A and $\cos \Phi_2 = .08$
$K = E_2/E_1 = 200/400 = 0.5$
$\therefore \quad I_2' = K\, I_2 = 0.5 \times 50 = 25$ A
The angle of $I_2'$ is to be decided from $\cos \Phi_2 = 0.8$
Now $\quad \cos \Phi_2 = 0.8$
$\therefore \quad \Phi_2 = 36.86^o$
$I_2'$ is antiphase with $I_2$ which lags $E_2$ by $36.86^o$
Consider the phasor diagram shown in the Fig. 3. The flux Φ is the reference.

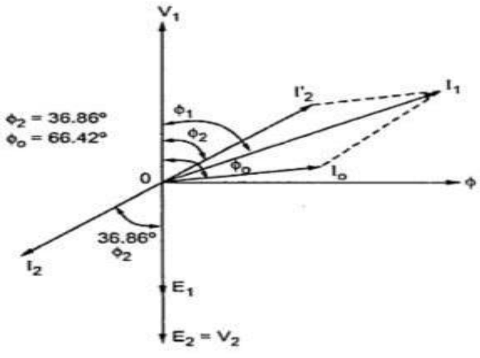


Fig. 3

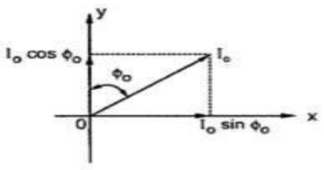


Fig. 3 (a)

Now $\quad \cos \Phi_o = 0.4$
$\therefore \quad \Phi_o = 66.42^o$
$\bar{I}_1 = \bar{I}_2' + \bar{I}_o$ ............ vector sum
Resolve $I_o$ and $I_2'$ into two components, along reference Φ and in quadrature with Φ in phase with $V_1$.
x component of $I_o = I_o \sin \Phi_o = 0.9165$ A
y component $I_o = I_o \cos \Phi_o = 0.4$ A
$\therefore \quad \bar{I}_o = 0.9165 + j\, 0.4$ A
x component of $I_2' = I_2' \sin \Phi_2 = 25 \sin (36.86^o) = 15$ A
y component of $I_2' = I_2' \cos \Phi_2 = 25 \times 0.8 = 20$ A
$\therefore \quad I_2' = 15 + j\, 20$ A
$\bar{I}_1 = 0.9165 + j\, 0.4 + 15 + j\, 20 = 15.9165 + j\, 20.4$ A
Thus the two components of $I_1$ are as shown in the Fig.3(c).

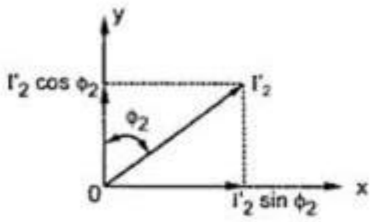


Fig. 3 (b)

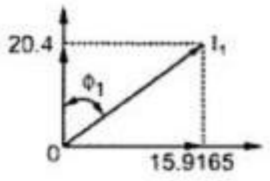


Fig. 3 (c)

∴ $I_1 = \sqrt{((15.9165)^2 + (20.4)^2)} = 25.874$ A

This is the primary current magnitude.

While $\tan \Phi_1 = 15.9165/20.4$

∴ $\Phi_1 = 37.96^o$

Hence the primary power factor is,

$\cos \Phi_1 = \cos (37.96^o) = 0.788$ lagging

**Key point** : Remember that $\Phi_1$ is angle between $V_1$ and $I_1$ and as $V_1$ is vertical, $\Phi_1$ is measured with respect to $V_1$. So do not convert rectangular to polar as it gives angle with respect to x-axis and we want it with respect to y-axis.

## Effect OF Winding Resistances

A practical transformer windings process some resistances which not only cause the power losses but also the voltage drops. Let us see what is the effect of winding resistance on the performance of the transformer.

Let $R_1$ = primary winding resistance in ohms

$R_2$ = secondary winding resistance in ohms

Now when current $I_1$ flows through primary, there is voltage drop $I_1 R_1$ across the winding. The supply voltage $V_1$ has to supply this drop. Hence primary induced e.m.f. $E_1$ is the vector difference between $V_1$ and $I_1 R_1$.

$$\therefore \quad \bar{E}_1 = \bar{V}_1 - \overline{I_1 R_1} \qquad \dots (1)$$

Similarly the induced e.m.f. in secondary is $E_2$. When load is connected, current $I_2$ flows and there is voltage drop $I_2 R_2$. The e.m.f. $E_2$ has to supply this drop. The vector difference between $E_2$ and $I_2 R_2$ is available to the load as a terminal voltage.

$$\therefore \quad \bar{V}_2 = \overline{E_2} - \overline{I_2 R_2} \qquad \dots (2)$$

The drops $I_1 R_1$ and $I_2 R_2$ are purely resistive drops hence are always in phase with the respective currents $I_1$ and $I_2$.

## Equivalent Resistance

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The resistance of the two windings can be transferred to any one side either primary or secondary without affecting the performance of the transformer. The transfer of the resistances on any one side is advantageous as it makes the calculations very easy. Let us see how to transfer the resistances on any one side.

The total copper loss due to both the resistances can be obtained as,

total copper loss = $I_1^2 R_1 + I_2^2 R_2$

$= I_1^2\{ R_1 + (I_2^2/I_1^2) R_2\}$

$= I_1^2\{R_1 + (1/K^2) R_2\}$ .......(3)

Where $I_2/I_1 = 1/K$ neglecting no load current.

Now the expression (3) indicates that the total copper loss can be expressed as $I_1^2 R_1 + I_1^2 . R_2/K^2$. This means $R_2/K^2$ is the resistance value of $R_2$ shifted to primary side which causes same copper loss with $I_1$ as $R_2$ causes with. This value of resistance which $R_2/K^2$ is the value of $R_2$ referred to primary is called equivalent resistance of secondary referred to primary. It is denoted as $R_2'$.

$R_2' = R_2/K^2$ ........(4)

Hence the total resistance referred to primary is the addition of $R_1$ and $R_2'$ called equivalent resistance of transformer referred to primary and denoted as $R_{1e}$.

$= R_1 + R_2' = R_1 + R_2/K^2$ .........(5)

This resistance $R_{1e}$ causes same copper loss with $I_1$ as the total copper loss due to the individual windings.

total copper loss = $I_1^2 R_{1e} = I_1^2 R_1 + I_2^2 R_2$ ......(6)

So equivalent resistance simplifies the calculations as we have to calculate parameters on one side only.

Similarly it is possible to refer the equivalent resistance to secondary winding.

total copper loss = $I_1^2 R_1 + I_2^2 R_2$

$= I_2^2 \{(I_1^2/I_2^2) R_1 + R_2\}$

$= I_2^2 ( K^2 R_1 + R_2)$ ........(7)

Thus the resistance $K^2 R_1$ is primary resistance referred to secondary denoted as $R_1'$.

$R_1' = K^2 R_1$ .......(8)

Hence the total resistance referred to secondary is the addition of $R_2$ and $R_1'$ called equivalent resistance of transformer referred to secondary and denoted as $R_{2e}$.

$R_{2e} = R_2 + R_1' = R_2 + K^2 R_1$ .........(9)

total copper loss = $I_2^2 R_{2e}$ ........(10)

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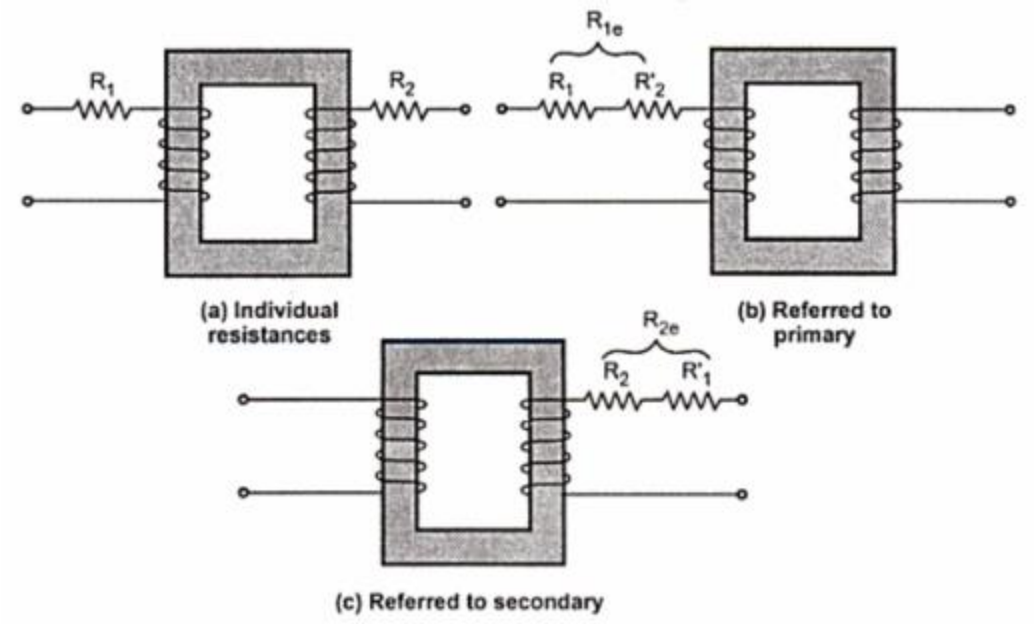
The concept of equivalent resistance is shown in the Fig. 1(a), (b) and (c).



(a) Individual resistances

(b) Referred to primary

(c) Referred to secondary

**Fig. 1 Equivalent resistance**

**Key Point** : When resistance are transferred to primary, the secondary winding becomes zero resistance winding for calculation purpose. The entire copper loss occurs due to $R_{1e}$. Similarly when resistances are referred to secondary, the primary becomes resistanceless for calculation purpose. The entire copper loss occurs due to $R_{2e}$.

**Important Note** : When a resistance is to be transferred from the primary to secondary, it must be multiplied by $K^2$. When a resistance is to be transferred from the secondary to primary, it must be divided by $K^2$. Remember that K is $N_1/N_2$.

The result can be cross-checked by another approach. The high voltage winding is always low current winding and hence the resistance of high voltage side is high. The low voltage side is high current side and hence resistance of low voltage side is low. So while transferring resistance from low voltage side to high voltage side, its value must increase while transferring resistance from high voltage side to low voltage side, its value must decrease.

**Key point** :
**High voltage side → Low current side → High resistance side**
**Low voltage side → High current side → Low resistance side**

**Example 1** : A 6600/400 V single phase transformer has primary resistance of 2.5 Ω and secondary resistance of 0.01 Ω calculate total equivalent resistance referred to primary and secondary.

**Solution** : The given values are,

$R_1 = 2.5\ \Omega \qquad R_2 = 0.01\ \Omega$

$K = 400/6600 = 0.0606$

While finding equivalent resistance referred to primary, transfer to primary as,

$R_2' = R_2/K^2 = 0.01/(0.0606)^2 = 2.7225\ \Omega$
$R_{1e} = R_1 + R_2' = 2.5 + 2.7225 = 5.2225\ \Omega$

It can be observed that primary is high voltage hence high resistance side hence while transferring from low voltage to on high voltage, its value increases.

To find total equivalent resistance referred to secondary, first calculate ,
$R_1' = K^2\ R_1 = (0.0606)^2 \times 25 = 0.00918\ \Omega$
$R_{2e} = R_2 + R_1' = 0.01 + 0.00918 = 0.01918\ \Omega$

## Effect of Leakage Reactance

Uptill now it is assumed that the entire flux produced by the primary links with the secondary winding. But in practice it is not possible. Part of the primary flux as well as the secondary flux completes the path through air and links with the respecting winding only. Such a flux is called leakage flux. Thus there are two leakage fluxes present as shown in the Fig. 1.

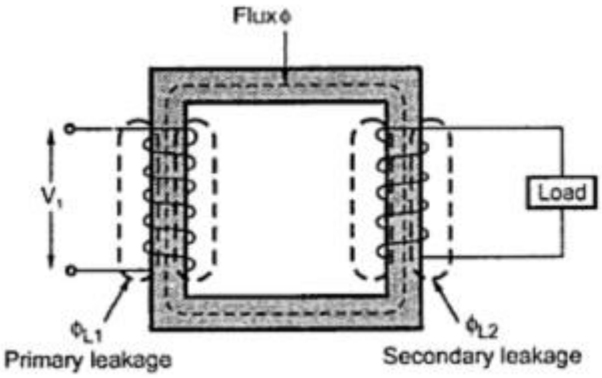


**Fig .1 Individual impedance**

The flux $\Phi_{L1}$ is the primary leakage flux which is produced due to primary current $I_1$. It is in phase with $I_1$ and links with primary only.

The flux $\Phi_{L2}$ is the secondary leakage flux which is produced due to current $I_2$. It is in phase with $I_2$ and links with the secondary winding only.

Due to the leakage flux $\Phi_{L1}$ there is self induced e.m.f. $e_{L1}$ in primary. While due to leakage flux $\Phi_{L2}$ there is self induced e.m.f. $e_{L2}$ in secondary. The primary voltage $V_1$ has to overcome this voltage $e_{L1}$ to produce $E_1$ while induced e.m.f. $E_2$ has to overcome $e_{L2}$ to produce terminal voltage $V_2$. Thus the self induced e.m.f.s are treated as the voltage drops across the fictitious reactance placed in series with the windings. These reactances are called leakage reactance of the winding.

So $X_1$ = Leakage reacatnce of primary winding.
and $X_2$ = Leakage reactance of secondary winding.

The value of $X_1$ is such that the drop $I_1\ X_1$ is nothing but the self induced e.m.f. $e_{L1}$ due to flux$\Phi_{L1}$. The value of $X_2$ is such that the drop $I_2\ X_2$ is equal to the self induced e.m.f. $e_{L2}$ due to flux $\Phi_{L1}$.

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Leakage fluxes with the respective windings only and not to both the windings. To reduce the leakage, as mentioned, int eh construction both the winding's are placed on same limb rather than on separate limbs.

## Equivalent Leakage Reactance

Similar to the resistances, the leakage reactances also can be transferred from primary to secondary or viceversa. The relation through $K^2$ remains same for the transfer of recatnaces as it is studied earlier for the resistances.

Let $X_1$ is leakage reactance of primary and $X_2$ is leakage reactance of secondary.
Then the total leakage reacatance referred to primary is $X_{1e}$ given by,

$$X_{1e} = X_1 + X_2' \text{ where } \quad X_2' = X_2/K^2$$

While the total leakage reacatnce referred to secondary is given by ,

$$X_{2e} = X_2 + X_1' \text{ where } X_1' = K^2 X_1$$

And $K = N_2/N_1$ =transformation ratio

## Equivalent Impedance

The transformer primary has resistance $R_1$ and reactance $X_1$. While the transformer secondary has resistance $R_2$ and reacatnce $X_2$. Thus we can say that the total impedance of primary winding is $Z_1$ which is,

$$Z_1 = R_1 + j X_1 \ \Omega \qquad \text{..........(1)}$$

And the total impedance of the secondary winding is which is ,

$$Z_2 = R_2 + j X_2 \ \Omega \qquad \text{...........(2)}$$

This is shown in the Fig. 1.

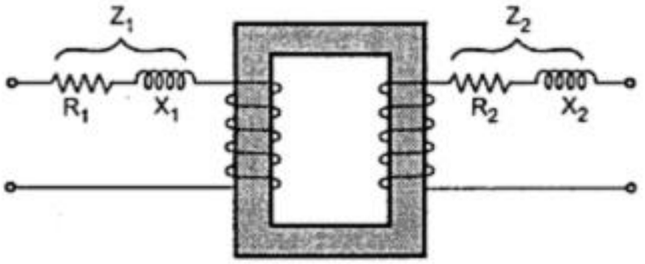

**Fig. 1 Individual impedance**

The individual magnitudes of and are,

$$Z_1 = \sqrt{(R_1^2 + X_1^2)} \qquad \text{...........(3)}$$

and

$$Z_2 = \sqrt{(R_2^2 + X_2^2)} \qquad \text{.........(4)}$$

Similar to resistance and reactance, the impedance also can be referred to any one side.

Let $Z_{1e}$ = total equivalent impedance referred to primary

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then $Z_{1e} = R_{1e} + j\,X_{1e}$

$Z_{1e} = Z_1 + Z_2' = Z_1 + Z_2/K^2$ ............(5)

Similarly $Z_{2e}$ = total equivalent impedance referred to secondary

then $Z_{2e} = R_{2e} + j\,X_{2e}$

$Z_{2e} = Z_2 + Z_1' = Z_2 + K^2 Z_1$ ............(6)

The magnitude of $Z_{1e}$ and $Z_{2e}$ are,

$Z_{1e} = \sqrt{(R_{1e}^2 + X_{1e}^2)}$ ........(7)

and $Z_{2e} = \sqrt{(R_{2e}^2 + X_{2e}^2)}$ ...........(8)

It can be denoted that,

$Z_{2e} = K^2 Z_{1e}$ and $Z_{1e} = Z_{2e}/K^2$

The concept of equivalent impedance is shown in the Fig. 2.

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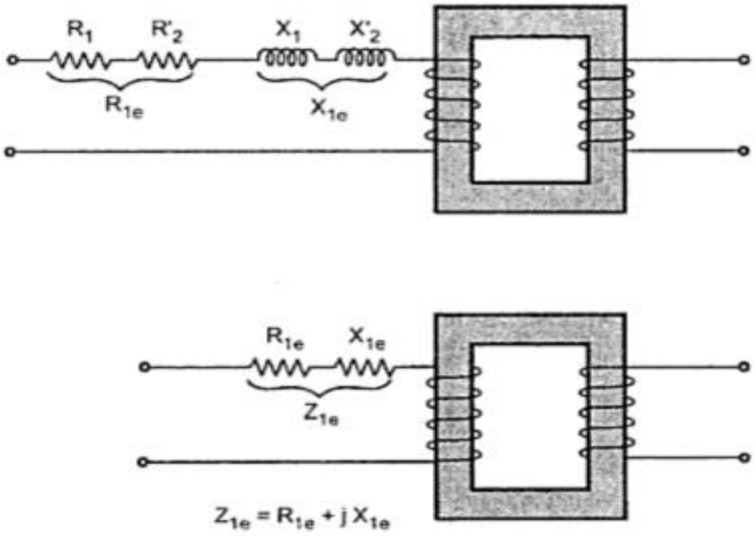
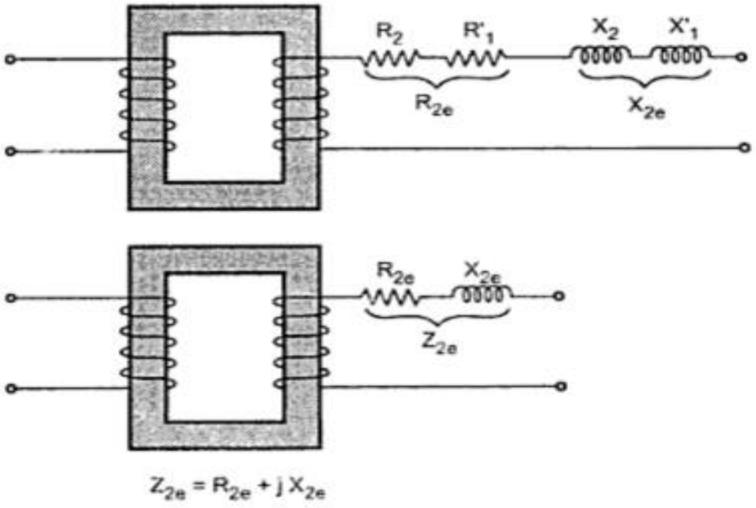


(a) Referred to primary



(b) Referred to secondary

**Fig 2 Equivalent impedance**

**Example 1** :A 15 KVA, 2200/110 V transformer has $R_1 = 1.75\Omega$, $R_2 = 0.0045\ \Omega$ the leakage reactance are $X_1 = 2.6\ \Omega$ and $X_2 = 0.0075\ \Omega$ Calculate,

a) equivalent resistance referred to primary

b) equivalent resistance referred to secondary

c) equivalent reactance referred to primary

d) equivalent reactance referred tosecondary

e) equivalent impedance referred to primary

f) equivalent impedance referred to secondary

g) total copper loss

**Solution** : The given values are, $R_1 = 1.75\ \Omega$, $R_2 = 0.0045\Omega$, $X_1 = 2.6\ \Omega$, $X_2 = 0.0075\ \Omega$

$K = 110/2200 = 1/20 = 0.05$

a) $R_{1e} = R_1 + R_2' = R_1 + R_2/K^2 = 1.75 + 0.0045/0.05^2 = 3.55\ \Omega$

b) $R_{2e} = R_2 + R_1' = R_2 + K^2\ R_1 =$

$= 0.0045 + (0.05)^2 \text{ x } 1.75 = 0.00887\ \Omega$

c) $X_{1e} = X_1 + X_2' = X_1 + X_2/K^2 = 2.6 + 0.0075/(0.05)^2 = 5.6\ \Omega$

d) $X_{2e} = X_2 + X_1' = X_2 + K^2\ X_1$

$= 0.0075 + (0.05)^2 \text{ x } 2.6 = 0.014\ \Omega$

e) $Z_{1e} = R_{1e} + j\ X_{1e} = 3.55 + j\ 5.6\ \Omega$

$Z_{1e} = \sqrt{}(3.55^2 + 5.6^2) = 6.6304\ \Omega$

f) $Z_{2e} = R_{2e} + j\ X_{2e} = 0.00887 + j\ 0.014\ \Omega$

$Z_{2e} = \sqrt{}(0.00887^2 + 0.014^2) = 0.01657\ \Omega$

g) To find the load copper loss, calculate full load current.

$(I_1)$ F.L. = (KVA x 1000)/$V_1$ = (25 x 1000)/2200 = 11.3636 A

total copper loss = $((I_1)\text{F.L.})^2\ R_{1e}$ = $(11.3636)^2$ x 355 = 458.4194 W

This can be checked as,

$(I_2)$ F.L.= (KVA x 1000)/$V_2$ = (25 x 1000/110 = 227.272 A

total copper loss = $I_1^2\ R_1 + I_2^2\ R_2$

$= (11.3636)^2 \text{ x } 1.75 + (227.373)^2 \text{ x } 0.0045$

$= 225.98 + 232.4365 = 458.419$ W

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## Equivalent circuit of Transformer

The term equivalent circuit of a machine means the combination of fixed and variable resistances and reactances, which exactly simulates performance and working of the machine.

For a transformer, no load primary current has two components,

$I_m = I_o \sin\Phi_o$ = Magnetizing component

$I_c = I_o \cos\Phi_o$ = Active component

$I_m$ produces the flux and is assumed to flow through reactance $X_o$ called no load reractance while $I_c$ is active component representing core losses hence is assumed to flow through the reactance $R_o$. Hence equivalent circuit on no load can be shown as in the Fig. 1. This circuit consisting of $R_o$ and $X_o$ in parallel is called exciting circuit. From the equivalent circuit we can write,

$R_o = V_1/I_c$

and $X_o= V_1/I_m$

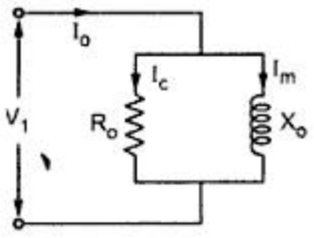

**Fig. 1 No load equivalent circuit**

When the is connected to the transformer then secondary current $I_2$ flows. This causes voltage drop across $R_2$ and $R_2$. Due to $I_2$, primary draws an additional current

$I_2' = I_2/K$. Now $I_1$ is the phasor addition of $I_o$ and $I_2'$. This $I_1$ causes the voltage drop across primary resistance $R_1$ and reactance $X_1$.

Hence the equivalent circuit can be shown as in the Fig. 2.

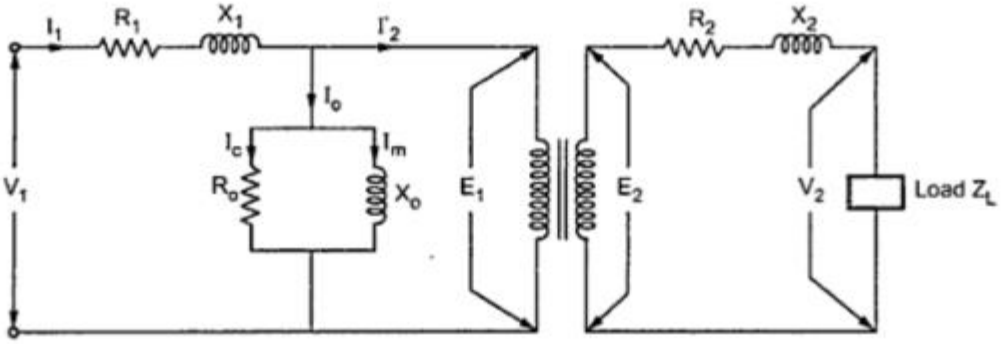

**Fig. 2**

But in the equivalent circuit, windings are not shown and it is further simplified by transferring all the values to the primary or secondary. This makes the transformer calculation much easy.

So transferring secondary parameters to primary we get,

$R_2' = R_2/K^2$ , $X_2' = X_2/K^{2'}$ , $Z_2' = Z_2/K^2$

While $E_2' = E_2/K'$ $I_2' = K I_2$

Where $K = N_2/N_1$

While transferring the values remember the rule that

Low voltage winding High current Low impedance

High voltage winding Low current High impedance

Thus the exact equivalent circuit referred to primary can be shown as in the Fig. 3.

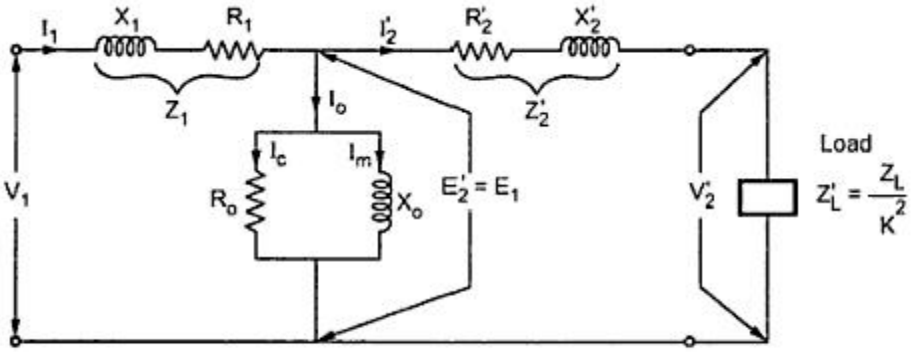

**Fig. 3 Exact equivalent circuit referred to primary**

Similarly all the primary value can be referred to secondary and we can obtain the equivalent circuit referred to secondary.

$R_1' = K^2 R_1$ , $X_1' = K^2 X_1$, $Z_1' = K^2 Z_1$

$E_1' = K E_1$, $I_o' = I_1/K'$ $I_o' = I_o/K$

Similarly the exciting circuit parameters also gets transferred to secondary as $R_o'$ and $X_o'$. The circuit is shown in the Fig.4.

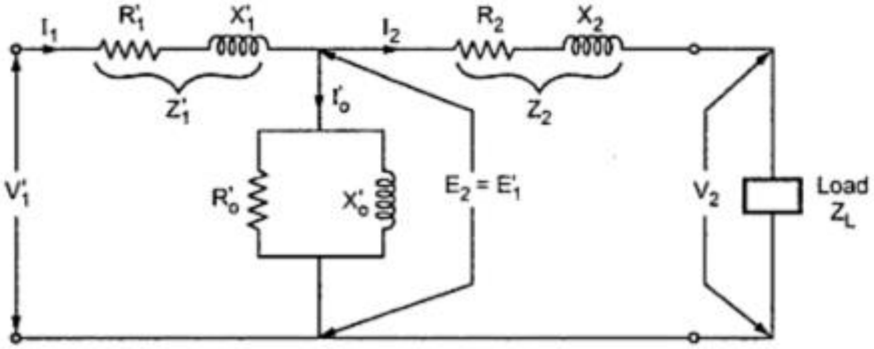

**Fig. 4 Exact equivalent circuit referred to secondary**

Now as long as no load branch i.e. exciting branch is in between $Z_1$ and $Z_2$', the impedances can not be combined. So further simplification of the circuit can be done. Such circuit is called approximate equivalent circuit.

**<u>Approximate Equivalent Circuit</u>**

To get approximate equivalent circuit, shift the no load branch containing $R_o$ and $X_o$ to the left of $R_1$ and $X_1$. By doing this we are creating an error that the drop across $R_1$ and $X_1$due to $I_o$ is neglected. Hence such an equivalent circuit is called approximate equivalent circuit.

So approximate equivalent circuit referred to primary can be as shown in the Fig. 5.

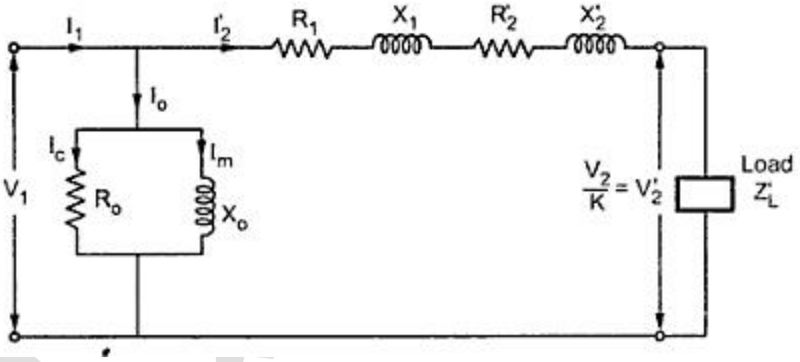

Fig. 5 Approximate equivalent circuit referred to primary

In this circuit now $R_1$ and $R_2$' can be combined to get equivalent resistance referred to primary $R_{1e}$ as discussed earlier. Similarly $X_1$and $X_1$' can be combined to get $X_{1e}$. And equivalent circuit can be simplified as shown in the Fig. 6.

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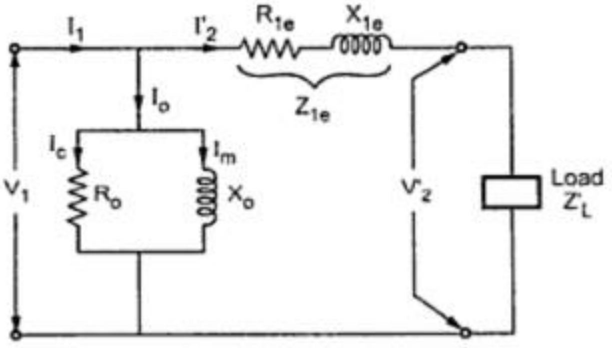

**Fig. 6**

We know that, $R_{1e} = R_1 + R_2' = R_1 + R_2/K^2$

$X_{1e} = X_1 + X_2' = X_1 + X_2/K^2$

$Z_{1e} = R_{1e} + j\, X_{1e}$

$R_o = V_1/I_c$ and $X_o = V_1/I_m$

$I_c = I_o \cos\Phi_o$ and $Im = I_o \sin\Phi_o$

In the similar fashion, the approximate equivalent circuit referred to secondary also can be obtained.

## Approximate Voltage Drop in Transformer

Consider the equivalent circuit referred to secondary as shown in the Fig. 1.

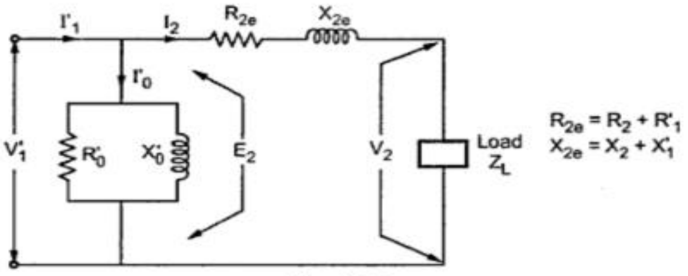

Fig. 1.33

Fig. 1

From the Fig. 1 we can write,

$$\bar{E}_2 = \overline{I_2 R_{2e}} + \overline{I_2 X_{2e}} + \bar{V}_2 = \bar{V}_2 + \bar{I}_2 (R_{2e} + j\, X_{2e})$$

$$\therefore \quad \bar{E}_2 = \bar{V}_2 + \overline{I_2 Z_{2e}}$$

As primary parameters are referred to secondary, there are no voltage drops in primary.

When there is no load, $I_2 = 0$ and we get no load terminal voltage $V_{20}$ as $E_2$.

$\therefore$ $V_{20} = E_2$ = No load terminal voltage

while $V_2$ = Terminal voltage on load

Consider the phasor diagram for lagging p.f. load. The current $I_2$ lags $V_2$ by angle $\Phi_2$. Take $V_2$ as reference phasor. $I_2 R_{2e}$ is in phase with $I_2$ while $I_2 X_{2e}$ leads $I_2$ by 90°. The phasor diagram is shown in the Fig.2.

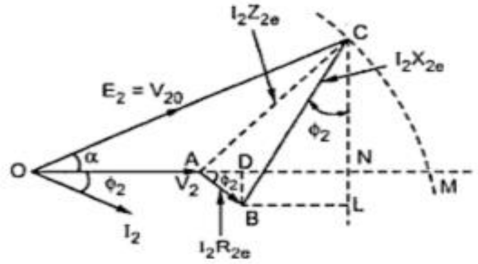

**Fig. 2**

To derive the expression for approximate voltage drop, draw the circle with O as centre and OC as redius, cutting extended OA at M. As OA = $V_2$ and now OM = $E_2$, the total voltage drop is AM = $I_2 Z_{2e}$.

But approximating this voltage drop is equal to AN instead of AM where N is intersection of perpendicular drawn from C on AM. This is because angle is practically very very small and in practice M and N are very close to each other.

Approximate voltage drop = AN

Draw perpendicular from B on AM intersecting it at D and draw parallel to DN from B to the point L shown in the Fig. 2.

$\therefore$ $AD = AB \cos \Phi_2 = I_2 R_{2e} \cos \Phi_2$

and $DN = BL = BC \sin \Phi_2 = I_2 X_{2e} \sin \Phi_2$

$\therefore$ $AN = AD + DN = I_2 R_{2e} \cos \Phi_2 + I_2 X_{2e} \sin \Phi_2$

Assuming $\Phi_2 = \Phi_1 = \Phi$

$\therefore$ Approximate voltage drop = $I_2 R_{2e} \cos \Phi + I_2 X_{2e} \sin \Phi$

If all the parameters are referred to primary then we get,

Approximate voltage drop = $I_1 R_{1e} \cos \Phi + I_1 X_{1e} \sin \Phi$

If the load has leading p.f. then we get the phasor diagram as shown in the Fig. 3. The $I_2$ leads $V_2$ by angle $\Phi_2$ .

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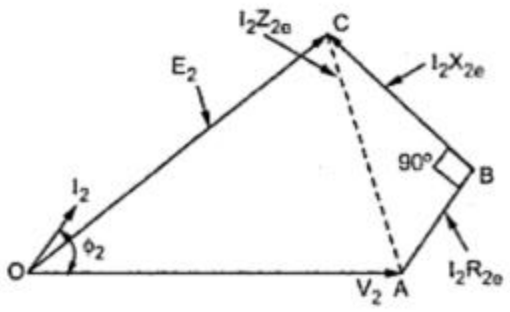

**Fig. 3**

In this case, the expression for approximate voltage drop remains same but the sign of $I_2 X_{2e} \sin \Phi$ reverses.

Approximate voltage drop $= I_2 R_{2e} \cos \Phi - I_2 X_{2e} \sin \Phi$ ....... Using referred to secondary values
$= I_1 R_{1e} \cos \Phi - I_1 X_{1e} \sin \Phi$ ...........Using referred to primary values

It can be noticed that for leading power factor $E_2 < V_2$.

For the unity power factor, the phasor diagram is simple and is shown in the Fig. 4. For this case, as $\cos \Phi = 1$ and $\sin \Phi = 0$, the approximate voltage drop is $I_2 R_{2e}$ or $I_1R_{1e}$.

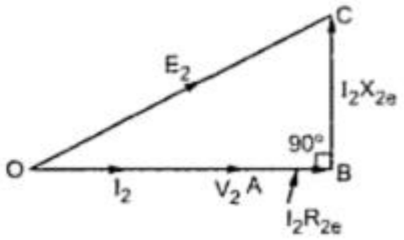

**Fig. 4**

Thus the general expression for the total approximate voltage drop is,

Approximate voltage drop $= E_2 - V_2$
$= I_{2e} R_{2e} \cos\Phi \quad I_{2e} X_{2e} \sin \Phi$ ........Using referred to secondary values
$= I_{1e} R_{1e} \cos \Phi \quad I_{1e} X_{1e} \sin \Phi$ ........Using referred to primary values

+ sing for lagging power factor while - sign for leading power factor loads.

## VOLTAGE REGULATION OF TRANSFORMER

Because of the voltage drop across the primary and secondary impedances it is observed that the secondary terminal voltage drops from its no load value ($E_2$) to load value ($V_2$) as load and load current increases.

This decrease in the secondary terminal voltage expressed as a fraction of the no load secondary terminal voltage is called regulation of a transformer.

The regulation is defined as change in the magnitude of the secondary terminal voltage, when full load i.e. rated load of specified power factor supplied at rated voltage is reduced to no load, with primary voltage maintained constant expressed as the percentage of the rated terminal voltage.

Let $E_2$ = Secondary terminal voltage on no load
$V_2$ = Secondary terminal voltage on given load
then mathematically voltage regulation at given load can be expressed as,

$$\boxed{\%\text{ voltage regulation} = \frac{E_2 - V_2}{V_2} \times 100}$$

The ratio ($E_2$ - $V_2$ / $V_2$ ) is called per unit regulation.

The secondary terminal voltage does not depend only on the magnitude of the load current but also on the nature of the power factor of the load. If $V_2$ is determined for full load and specified power factor condition the regulation is called full load regulation.

As load current increases, the voltage drops tend to increase $V_2$ and drops more and more. In case of lagging power factor $V_2 < E_2$ and we get positive voltage regulation, while for leading power factor $E_2 < V_2$ and we get negative voltage regulation.

The voltage drop should be as small as possible hence less the regulation better is the performance of a transformer.

## Expression for Voltage Regulation

The voltage regulation is defined as,

$$\%R = (E_2 - V_2 / V_2) \text{ x } 100 = (\text{Total voltage drop}/V_2) \text{ x } 100$$

The expression for the total approximate voltage drop is already derived.
Total voltage drop = $I_2 R_{2e} \cos \Phi \pm I_2 X_{2e} \sin \Phi$
Hence the regulation can be expressed as,

$$\boxed{\%\ R = \frac{I_2 R_{2e} \cos\phi \pm I_2 X_{2e} \sin\phi}{V_2} \times 100}$$

'+' sing for lagging power factor while '-' sing for leading power factor loads.
The regulation van be further expressed interms of $I_1$ , $V_1$, $R_{1e}$ and $X_{1e}$.

$$V_2 / V_1 = I_1 / I_2 = K$$

$\therefore$ $V_2 = KV_1$ , $I_2 = I_1/K$
while $R_{1e} = R_{2e}/K^2$ , $X_{1e} = X_{2e}/K^2$
Substituting in the regulation expression we get,

$$\boxed{\%\ R = \frac{I_1 R_{1e} \cos\phi \pm I_1 X_{1e} \sin\phi}{V_1} \times 100}$$

## Zero Voltage Regulation

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We have seen that for lagging power factor and unity power factor condition $V_2 < E_2$ and we get positive regulation. But as load becomes capacitive, $V_2$ starts increasing as load increase. At a certain leading power factor we get $E_2 = V_2$ and the regulation becomes zero. If the load is increased further, $E_2$ becomes less than $V_2$ and we get negative regulation.

$\therefore$ for zero voltage regulation,

$E_2 = V_2$

$\therefore$ $E_2 - V_2 = 0$

or $V_R \cos\Phi - V_x \sin\Phi = 0$ .......... -ve sing as leading power factor

where $V_R = I_2 R_{2e}/V_2 = I_1 R_{1e}/V_1$ and $V_x = I_2 X_{2e}/V_2 = I_1 X_{1e}/V_1$

$\therefore$ $V_R \cos\Phi = V_x \sin\Phi$

$\therefore$ $\tan\Phi = V_R/V_x$

$\therefore$ $\cos\Phi = \cos\{\tan^{-1}(V_R/Vx)\}$

This is the leading p.f. at which voltage regulation becomes zero while supplying the load.

## Constants of a Transformer

From the regulation expression we can define constants of a transformer.

$$\%R = ((I_2 R_{2e} \cos\Phi \pm I_2 X_{2e} \sin\Phi)/E_2) \times 100$$

$$= \{(I_2 R_{2e}/E_2) \cos\Phi \pm (I_2 X_{2e}/E_2) \sin\Phi\} \times 100$$

The ratio $(I_2 R_{2e}/E_2)$ or $(I_1 R_{1e}/E_1)$ is called per unit resistive drop and denoted as $V_R$.

The ratio $(I_2 X_{2e}/E_2)$ or $(I_1 X_{1e}/E_1)$ is called per unit reactive drop and is denoted as Vx.

The terms $V_R$ and Vx are called constants of a transformer because for the rated output $I_2$, $E_2$, $R_{1e}$, $X_{1e}$, $R_{2e}$, $X_{2e}$ are constants. The regulation can be expressed interms of $V_R$ and Vx as,

$$\%R = (V_R \cos\Phi \pm Vx \sin\Phi) \times 100$$

On load condition, $E_2 = V_2$ and $E_1 = V_1$

where $V_1$ and $V_2$ are the given voltage ratings of a transformer. Hence $V_R$ and Vx can be expressed as,

$$V_R = I_2 R_{2e}/V_2 = I_1 R_{1e}/V_1$$

and

$$Vx = I_2 R_{2e}/V_2 = I_1 X_{1e}/V_1$$

where $V_1$ and $V_2$ are no load primary and secondary voltages,

$V_R$ and Vx can be expressed on percentage basis as,

Percentage resistive drop = $V_R \times 100$

Percentage reactive drop = $Vx \times 100$

Key Point : Note that and are also called per unit resistance and reactance respectively.

## Losses in a Transformer

In a transformer, there exists two types of losses.

i) The core gets subjected to an alternating flux, causing core losses.

ii) The windings carry currents when transformer is loaded, causing copper losses.

### 1.1 Core or Iron Losses

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Due to alternating flux set up in the magnetic core of the transformer, it undergoes a cycle of magnetisation and demagnetisation. Due to hysteresis effect there is loss of energy in this process which is called hysteresis loss.

It is given by, hysteresis loss = $K_h B_m^{1.67} f v$ watts

where $K_h$ = Hysteresis constant depends on material.

$B_m$ = Maximum flux density.

$f$ = Frequency.

$v$ = Volume of the core.

The induced e.m.f. in the core tries to set up eddy currents in the core and hence responsible for the eddy current losses. The eddy current loss is given by,

Eddy current loss = $K_e B_m^2 f^2 t^2$ watts/ unit volume

where $K_e$ = Eddy current constant

$t$ = Thickness of the core

As seen earlier, the flux in the core is almost constant as supply voltage $V_1$ at rated frequency f is always constant. Hence the flux density $B_m$ in the core and hence both hysteresis and eddy current losses are constants at all the loads. Hence the core or iron losses are also called constant losses. The iron losses are denoted as $P_i$.

The iron losses are minimized by using high grade core material like silicon steel having very low hysteresis loop by manufacturing the core in the form of laminations.

### 1.2 Copper Losses

The copper losses are due to the power wasted in the form of $I^2 R$ loss due to the resistances of the primary and secondary windings. The copper loss depends on the magnitude of the currents flowing through the windings.

Total Cu loss = $I_1^2 R_1 + I_2^2 R_2 = I_1^2 ( R_1 + R_2' )= I_2^2 ( R_2 +R_1' )$

$= I_1^2 R_{1e} = I_2^2 R_{2e}$

The copper looses are denoted as. If the current through the windings is full load current, we get copper losses at full load. If the load on transformer is half then we get copper losses at half load which are less than full load copper losses. Thus copper losses are called variable losses. For transformer VA rating is or. As is constant, we can say that copper losses are proportional to the square of the KVA rating.

So, $P_{cu} \alpha I^2 \alpha (KVA)^2$

Thus for a transformer,

Total losses = Iron losses + Copper losses

$= P_i + P_{cu}$

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**Key point** : It is seen that the iron losses depend on the supply voltage while the copper losses depend on the current. The losses are not dependent on the phase angle between voltage and current. Hence the rating of the transformer is expressed as a product of voltage and current and called VA rating of transformer. It is not expressed in watts or kilo watts. Most of the times, rating is expressed in KVA.

## Losses: Additional Study:

Transformer losses are divided into losses in the windings, termed copper loss, and those in the magnetic circuit, termed iron loss. Losses in the transformer arise from:

### Winding resistance

Current flowing through the windings causes resistive heating of the conductors. At higher frequencies, skin effect and proximity effect create additional winding resistance and losses.

### Hysteresis losses

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core. For a given core material, the loss is proportional to the frequency, and is a function of the peak flux density to which it is subjected.[42]

### Eddy currents

Ferromagnetic materials are also good conductors and a core made from such a material also constitutes a single short-circuited turn throughout its entire length. Eddy currents therefore circulate within the core in a plane normal to the flux, and are responsible for resistive heating of the core material. The eddy current loss is a complex function of the square of supply frequency and inverse square of the material thickness.[42] Eddy current losses can be reduced by making the core of a stack of plates electrically insulated from each other, rather than a solid block; all transformers operating at low frequencies use laminated or similar cores.

### Magnetostriction

Magnetic flux in a ferromagnetic material, such as the core, causes it to physically expand and contract slightly with each cycle of the magnetic field, an effect known as magnetostriction. This produces the buzzing sound commonly associated with transformers[29] that can cause losses due to frictional heating. This buzzing is particularly familiar from low-frequency (50 Hz or 60 Hz) mains hum, and high-frequency (15,734 Hz (NTSC) or 15,625 Hz (PAL)) CRT noise.

### Mechanical losses

In addition to magnetostriction, the alternating magnetic field causes fluctuating forces between the primary and secondary windings. These incite vibrations within nearby metalwork, adding to the buzzing noise and consuming a small amount of power.[43]

### Stray losses

Leakage inductance is by itself largely lossless, since energy supplied to its magnetic fields is returned to the supply with the next half-cycle. However, any leakage flux that intercepts nearby conductive materials such as the transformer's support structure will give rise to eddy currents and

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be converted to heat.[44] There are also radiative losses due to the oscillating magnetic field but these are usually small.

## EFFICIENCY OF A TRANSFORMER

Due to the losses in a transformer, the output power of a transformer is less than the input power supplied.

∴ Power output = Power input - Total losses

∴ Power input = Power output + Total losses

$= \text{Power output} + P_i + P_{cu}$

The efficiency of any device is defined as the ratio of the power output to power input. So for a transformer the efficiency can be expresses as,

$\eta = \text{Power output}/\text{power input}$

∴ $\eta = \text{Power output}/(\text{power output} + P_i + P_{cu})$

Now power output = $V_2 I_2 \cos \Phi$

where $\cos \Phi$ = Load power factor

The transformer supplies full load of current $I_2$ and with terminal voltage $V_2$.

$P_{cu}$ = Copper losses on full load = $I_2^2 R_{2e}$

∴ $\eta = (V_2 I_2 \cos \Phi_2)/(V_2 I_2 \cos \Phi_2 + P_i + I_2^2 R_{2e})$

But $V_2 I_2$ = VA rating of a transformer

∴ $\eta = (\text{VA rating x} \cos \Phi) / (\text{VA rating x} \cos \Phi + P_i + I_2^2 R_{2e})$

∴

$$\boxed{\% \eta = \frac{(\text{VA rating}) \times \cos\phi}{(\text{VA rating}) \times \cos\phi + P_i + I_2^2 R_{2e}} \times 100}$$

This is full load percentage efficiency with,

$I_2$ = Full load secondary current

But if the transformer is subjected to fractional load then using the appropriate values of various quantities, the efficiency can be obtained.

Let n =Fraction by which load is less than full load = Actual load/Full load
For example, if transformer is subjected to half load then,
n = Half load/Full load = (1/2)/2 = 0.5
when load changes, the load current changes by same proportion.
∴ new $I_2 = n (I_2)$ F.L.

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Similarly the output $V_2\ I_2\ \cos\Phi_2$ also reduces by the same fraction. Thus fraction of VA rating is available at the output.

Similarly as copper losses are proportional to square of current then,
new $P_{cu} = n^2\,(P_{cu}\ )$ F.L.
**Key Point** : So copper losses get reduced by $n^2$.
In general for fractional load the efficiency is given by,

$$\boxed{\%\ \eta = \frac{n\,(\text{VA rating})\cos\phi}{n\,(\text{VA rating})\cos\phi + P_i + n^2\ (P_{cu})\,\text{F.L.}} \times 100}$$

where n = Fraction by which load power factor lagging, leading and unity the efficiency expression does not change, and remains same.

## O.C. AND S.C. TESTS ON SINGLE PHASE TRANSFORMER

The efficiency and regulation of a transformer on any load condition and at any power factor condition can be predetermined by indirect loading method. In this method, the actual load is not used on transformer. But the equivalent circuit parameters of a transformer are determined by conducting two tests on a transformer which are,

1. Open circuit test (O.C Test)
2. Short circuit test (S.C.Test)

The parameters calculated from these test results are effective in determining the regulation and efficiency of a transformer at any load and power factor condition, without actually loading the transformer. The advantage of this method is that without much power loss the tests can be performed and results can be obtained. Let us discuss in detail how to perform these tests and how to use the results to calculate equivalent circuit parameters.

### 1.1 Open Circuit Test (O.C. Test)

The experimental circuit to conduct O.C test is shown in the Fig. 1.

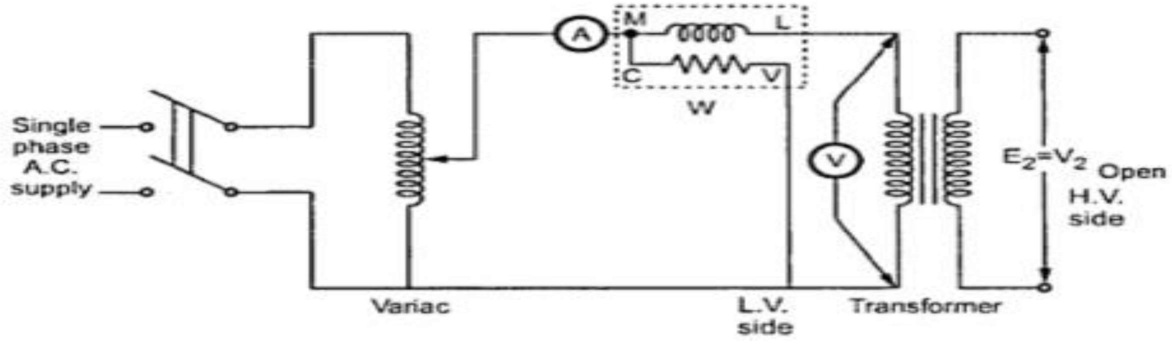

**Fig 1. Experimental circuit for O.C. test**

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The transformer primary is connected to a.c. supply through ammeter, wattmeter and variac. The secondary of transformer is kept open. Usually low voltage side is used as primary and high voltage side as secondary to conduct O.C test.

The primary is excited by rated voltage, which is adjusted precisely with the help of a variac. The wattmeter measures input power. The ammeter measures input current. The voltemeter gives the value of rated primary voltage applied at rated frequency.

Sometimes a voltmeter may be connected across secondary to measure secondary voltage which is $V_2 = E_2$ when primary is supplied with rated voltage. As voltmeter resistance is very high, though voltmeter is connected, secondary is treated to be open circuit as voltmeter current is always negligibly small.

When the primary voltage is adjusted to its rated value with the help of variac, readings of ammeter and wattmeter are to be recorded.

The observation table is as follows

| $V_o$ volts | $I_o$ amperes | $W_o$ watts |
|---|---|---|
| Rated | | |

$V_o$ = Rated voltage
$W_o$ = Input power
$I_o$ = Input current = no load current

As transformer secondary is open, it is on no load. So current drawn by the primary is no load current $I_o$. The two components of this no load current are,

$I_m = I_o \sin \Phi_o$
$I_c = I_o \cos \Phi_o$
where $\cos \Phi_o$ = No load power factor
And hence power input can be written as,
$W_o = V_o I_o \cos \Phi_o$
The phasor diagram is shown in the Fig. 2.

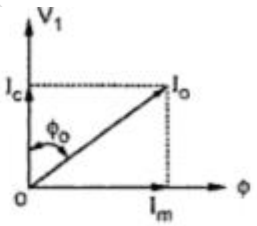

**Fig. 2**

As secondary is open, $I_2 = 0$. Thus its reflected current on primary is also zero. So we have primary current $I_1 = I_o$. The transformer no load current is always very small, hardly 2 to 4 % of its full load value. As $I_2 = 0$, secondary copper losses are zero. And $I_1 = I_o$ is very low hence copper losses on primary are also

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very very low. Thus the total copper losses in O.C. test are negligibly small. As against this the input voltage is rated at rated frequency hence flux density in the core is at its maximum value. Hence iron losses are at rated voltage. As output power is zero and copper losses are very low, the total input power is used to supply iron losses. This power is measured by the wattmeter i.e. $W_o$. Hence the wattmeter in O.C. test gives iron losses which remain constant for all the loads.

$\therefore \quad W_o = P_i$ = Iron losses

Calculations : We know that,

$W_o = V_o I_o \cos \Phi$

$\cos \Phi_o = W_o / (V_o I_o)$ = no load power factor

Once $\cos \Phi_o$ is known we can obtain,

$I_c = I_o \cos \Phi_o$

and $\quad I_m = I_o \sin \Phi_o$

Once $I_c$ and $I_m$ are known we can determine exciting circuit parameters as,

$R_o = V_o / I_c \ \Omega$

and $\quad X_o = V_o / I_m \ \Omega$

**Key Point** : The no load power factor $\cos \Phi_o$ is very low hence wattmeter used must be low power factor type otherwise there might be error in the results. If the meters are connected on secondary and primary is kept open then from O.C. test we get $R_o'$ and $X_o'$ with which we can obtain $R_o$ and $X_o$ knowing the transformation ratio K.

## 1.2 Short Circuit Test (S.C. Test)

In this test, primary is connected to a.c. supply through variac, ammeter and voltmeter as shown in the Fig. 3.

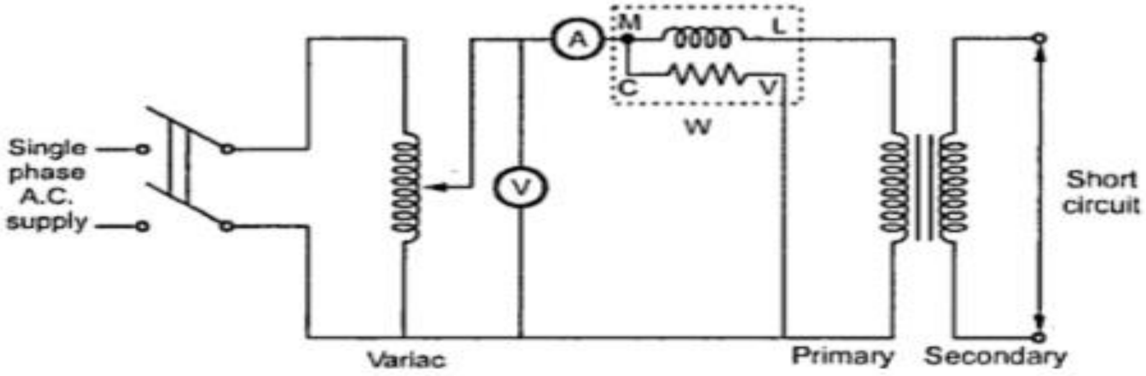

**Fig. 3 Fig 1. Experimental circuit for O.C. test**

The secondary is short circuited with the help of thick copper wire or solid link. As high voltage side is always low current side, it is convenient to connect high voltage side to supply and shorting the low voltage side.

As secondary is shorted, its resistance is very very small and on rated voltage it may draw very large current. Such large current can cause overheating and burning of the transformer. To limit this short circuit current, primary is supplied with low voltage which is just enough to cause rated current to flow through primary which can be observed on an ammeter. The low voltage can be adjusted with the help of variac.

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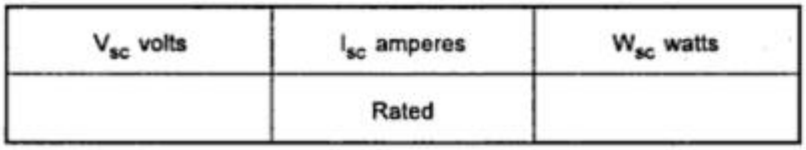
Hence this test is also called low voltage test or reduced voltage test. The wattmeter reading as well as voltmeter, ammeter readings are recorded. The observation table is as follows,



| $V_{sc}$ volts | $I_{sc}$ amperes | $W_{sc}$ watts |
|---|---|---|
| | Rated | |

Now the current flowing through the windings are rated current hence the total copper loss is full load copper loss. Now the voltage supplied is low which is a small fraction of the rated voltage. The iron losses are function of applied voltage. So the iron losses in reduced voltage test are very small. Hence the wattmeter reading is the power loss which is equal to full load copper losses as iron losses are very low.

$\therefore$ $W_{sc} = (P_{cu})$ F.L. = Full load copper loss

Calculations : From S.C. test readings we can write,

$W_{sc} = V_{sc} I_{sc} \cos \Phi_{sc}$

$\therefore$ $\cos \Phi sc = V_{sc} I_{sc} / W_{sc}$ = short circuit power factor

$W_{sc} = I_{sc}^2 R_{1e}$ = copper loss

$\therefore$ $R_{1e} = W_{sc} / I_{sc}^2$

while $Z_{1e} = V_{sc} / I_{sc} = \sqrt{(R_{1e}^2 + X_{1e}^2)}$

$\therefore$ $X_{1e} = \sqrt{(Z_{1e}^2 - R_{1e}^2)}$

Thus we get the equivalent circuit parameters $R_{1e}$, $X_{1e}$ and $Z_{1e}$. Knowing the transformation ratio K, the equivalent circuit parameters referred to secondary also can be obtained.

**Important Note** : If the transformer is step up transformer, its primary is L.V. while secondary is H.V. winding. In S.C. test, supply is given to H.V. winding and L.V is shorted. In such case we connect meters on H.V. side which is transformer secondary through for S.C. test purpose H.V side acts as primary. In such case the parameters calculated from S.C. test readings are referred to secondary which are $R_{2e}$, $Z_{2e}$ and $X_{2e}$. So before doing calculations it is necessary to find out where the readings are recorded on transformer primary or secondary and accordingly the parameters are to be determined. In step down transformer, primary is high voltage itself to which supply is given in S.C. test. So in such case test results give us parameters referred to primary i.e. $R_{1e}$, $Z_{1e}$ and $X_{1e}$.

**Key point** : In short, if meters are connected to primary of transformer in S.C. test, calculations give us $R_{1e}$ and $Z_{1e}$ if meters are connected to secondary of transformer in S.C. test calculations give us $R_{2e}$ and $Z_{2e}$.

## 1.3 Calculation of Efficiency from O.C. and S.C. Tests

We know that,

From O.C. test, $W_o = P_i$

From S.C. test, $W_{sc} = (P_{cu})$ F.L.

$$\therefore \quad \%\,\eta \text{ on full load } = \frac{V_2\,(I_2)\,\text{F.L.}\cos\phi}{V_2\,(I_2)\,\text{F.L.}\cos + W_o + W_{sc}} \times 100$$

Thus for any p.f. $\cos \Phi_2$ the efficiency can be predetermined. Similarly at any load which is fraction of full load then also efficiency can be predetermined as,

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$$\boxed{\%\ \eta \text{ at any load} = \frac{n \times (\text{VA rating}) \times \cos\phi}{n \times (\text{VA rating}) \times \cos\phi + W_o + n^2 W_{sc}} \times 100}$$

where n = fraction of full load

or
$$\%\ \eta = \frac{n\, V_2 I_2 \cos\phi}{n\, V_2 I_2 \cos\phi + W_o + n^2 W_{sc}} \times 100$$

where $I_2 = n\,(I_2)$ F.L.

## 1.4 Calculation of Regulation

From S.C. test we get the equivalent circuit parameters referred to primary or secondary.

The rated voltages $V_1$, $V_2$ and rated currents $(I_1)$ F.L. and $(I_2)$ F.L. are known for the given transformer. Hence the regulation can be determined as,

$$\boxed{\begin{aligned} \%\ R &= \frac{I_2 R_{2e} \cos\phi \pm I_2 X_{2e} \sin\phi}{V_2} \times 100 \\ &= \frac{I_1 R_{1e} \cos\phi \pm I_1 X_{1e} \sin\phi}{V_1} \times 100 \end{aligned}}$$

where $I_1$, $I_2$ are rated currents for full load regulation.
For any other load the currents $I_1$, $I_2$ must be changed by fraction n.
∴ $I_1$, $I_2$ at any other load = $n\,(I_1)$ F.L., $n\,(I_2)$ F.L.

**Key Point** : Thus regulation at any load and any power factor can be predetermined, without actually loading the transformer.

**Example** 1 : A 5 KVA, 500/250 V, 50 Hz, single phase transformer gave the following readings,
O.C. Test : 500 V, 1 A, 50 W (L.V. side open)
S.C. Test : 25 V, 10 A, 60 W (L.V. side shorted)
Determine : i) The efficiency on full load, 0.8 lagging p.f.
ii) The voltage regulation on full load, 0.8 leading p.f.
iii) The efficiency on 60% of full load, 0.8 leading p.f.
iv) Draw the equivalent circuit referred to primary and insert all the values in it.

**Solution** : In both the tests, meters are on H.V. side which is primary of the transformer. Hence the parameters obtained from test results will be referred to primary.

From O.C. test, $V_o = 500$ V, $I_o = 1$ A, $W_o = 50$ W
∴ $\cos\Phi_o = W_o/V_o I_o = 50/(500 \text{x} 1) = 0.1$
∴ $I_c = I_o \cos = 1 \text{ x } 0.1 = 0.1$ A
and $I_m = I_o \sin\Phi_o = 1 \text{ x } 0.9949 = 0.9949$ A
∴ $R_o = V_o / I_c = 500/0.1 = 5000\ \Omega$
and $X_o = V_o/I_m = 500/0.9949 = 502.52\ \Omega$
and $W_o = P_i$ = iron losses = 50 W

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From S.C. test, $V_{sc} = 25$ V, $I_{sc} = 10$ A, $W_{sc} = 60$ W

$\therefore$ $R_{1e} = W_{sc} / I_{sc}^2 = 60/(10)^2 = 0.6\ \Omega$

$Z_{1e} = V_{sc} / I_{sc} = 25/10 = 2.5\ \Omega$

$\therefore$ $X_{1e} = \sqrt{(2.5^2 - 0.6^2)} = 2.4269\ \Omega$

$(I_1)$ F.L. = VA rating/$V_1$

$= (5 \times 10^3)/500 = 10$ A

and $I_{sc} = (I_1)$ F.L.

$\therefore$ $W_{sc} = (P_{cu})$ F.L. = 60 W

i) η on full load, cos = 0.8 lagging

$$\% \eta = \frac{(\text{VA rating}) \cos \phi_2}{(\text{VA rating}) \cos \phi_2 + P_i + (P_{cu})\text{ F. L.}} \times 100$$

$$= \frac{5 \times 10^3 \times 0.8}{5 \times 10^3 \times 0.8 + 50 + 60} \times 100 = \mathbf{97.32\ \%}$$

ii) Regulation on full load, cos $\Phi_2$ = 0.8 leading

$$\% R = \frac{(I_1)\text{ F. L. } R_{1e} \cos \phi - (I_1)\text{ F. L. } X_{1e} \sin \phi}{V_1} \times 100$$

$$= \frac{10 \times 0.6 \times 0.8 - 10 \times 2.4269 \times 0.6}{500} \times 100$$

= - 1.95 %

iii) For 60% of full load, n = 0.6 and cos $\Phi_2$ = 0.8 leading]

$\therefore$ $P_{cu}$ = copper loss on new load = $n^2 \times (P_{cu})$ F.L.

$= (0.6)^2 \times 60 = 21.6$ W

= 97.103 %

iv) The equivalent circuit referred to primary is shown in the Fig. 4.

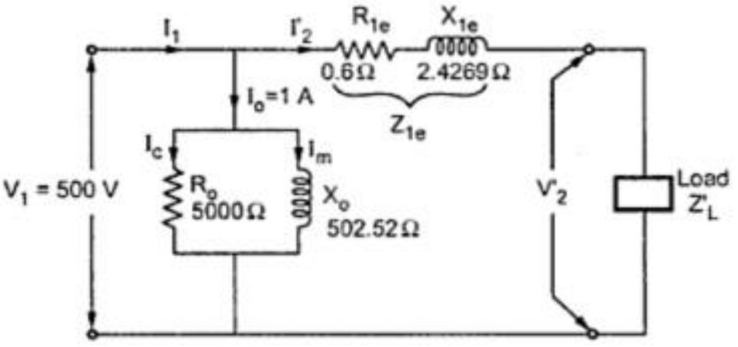

**Fig. 4**

**Example** 2 : The open circuit and short circuit tests on a 10 KVA, 125/250 V, 50 Hz, single phase transformer gave the following results :

O.C. test : 125 V, 0.6 A, 50 W (on L.V. side)
S.C. test : 15 V, 30 A. 100 W (on H.V. side)
Calculate : i) copper loss on full load
ii) full load efficiency at 0.8 leading p.f.
iii) half load efficiency at 0.8 leading p.f.
iv) regulation at full load, 0.9 leading p.f.

**Solution** : From O.C. test we can weite,

$$W_o = P_i = 50 \text{ W} = \text{Iron loss}$$

From S.C. test we can find the parameters of equivalent circuit. Now S.C. test is conducted on H.V. side i.e. meters are on H.V. side which is transformer secondary. Hence parameters from S.C. test results will be referred to secondary.

$V_{sc} = 15$ V, $I_{sc} = 30$ A, $W_{sc} = 100$ W

∴ $R_{2e} = W_{sc}/(I_{sc})^2 = 10/(30)^2 = 0.111\Omega$

$Z_{1e} = V_{sc}/I_{sc} = 15/30 = 0.5\ \Omega$

∴ $X_{2e} = \sqrt{(Z_{2e}^2 - R_{2e}^2)} = 0.4875\ \Omega$

i) Copper loss on full load

$(I_2)$ F.L. = VA rating/$V_2$ = $(10 \times 10^3)/250 = 40$ A

In short circuit test, $I_{sc} = 30$ A and not equal to full load value 40 A.

Hence $W_{sc}$ does not give copper loss on full load

∴ $W_{sc} = P_{cu}$ at 30 A = 100 W

Now $P_{cu} \alpha I^2$

$(P_{cu}$ at 30 A$)/(P_{cu}$ at 40 A$) = (30/40)^2$

$100/(P_{cu}$ at 40 A$) = 900/1600$

$P_{cu}$ at 40 A = 177.78 W

∴ $(P_{cu})$ F.L. = 177.78 W

ii) Full load η , cos $\Phi_2 = 0.8$

$$\%\ \eta \text{ on full load} = \frac{V_2(I_2)\text{ F. L. }\cos\phi_2}{V_2(I_2)\text{ F. L.}\cos\phi_2 + P_i + (P_{cu})\text{ F. L.}} \times 100$$

$$= \frac{250\times40\times0.8}{250\times40\times0.8+50+177.78}\times100 = \mathbf{97.23\ \%}$$

iii) Half load η , cos $\Phi_2 = 0.8$

n = 0.5 as half load, $(I_2)$ H.L. = 0.5 x 40 =

$$\therefore\ \%\ \eta \text{ on half load} = \frac{V_2(I_2)\text{ H. L. }\cos\phi_2}{V_2(I_2)\text{ H. L.}\cos\phi_2 + P_i + n^2(P_{cu})\text{ F. L.}}\times100$$

$$= \frac{n\,(\text{VA rating})\cos\phi_2}{n\,(\text{VA rating})\cos\phi_2 + P_i + n^2(P_{cu})\text{ F. L.}}\times100$$

$$= \frac{05\times10\times10^3\times0.8}{05\times10\times10^3\times0.8+50+(0.5)^2\times177.78}\times100$$

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= 97.69%

iv) Regulation at full load, cos Φ = 0.9 leading

$$\% R = \frac{(I_2)\,F.L.\,R_{2e}\cos\phi - (I_2)\,F.L.\,X_{2e}\sin\phi}{V_2}\times 100$$

$$= \frac{40\times 0.111\times 0.9 - 40\times 0.4875\times 0.4358}{250}\times 100$$

= -1.8015%

# The Polyphase Induction Motor

The polyphase induction motor is the most commonly used industrial motor, finding application in many situations where speed regulation is not essential. It is simple and relatively inexpensive, and the absence of sliding contacts in the squirrel-cage machine reduces maintenance to a minimum. There are two general types of polyphase induction motors: the squirrel-cage type and the wound-rotor machine. Both motors have an armature or stator structure similar to that of the alternating current generator, consisting of a hollow cylinder of laminated sheet steel in which are punched longitudinal slots.

A symmetrical polyphase winding is laid in these slots which, when connected to a suitable voltage source, produces a travelling MMF wave in the air gap, rotating at a synchronous speed equal to:

$$RPM_{sync} = 120\,\frac{f}{p}$$

where f is the frequency and p the number of poles for which the stator is wound.

The squirrel-cage type of rotor is made up of sheet steel laminations keyed to the shaft and having slots punched in the periphery. The number of slots in the rotor is never a multiple of the number in the stator, thereby preventing rotor locking under light load conditions. The rotor conductors in most machines are made of aluminum alloy either molded or extruded in place in the slots, with end rings being cast as an integral part of the structure and connecting all bars at both ends. The air-gap length between rotor and stator is kept as short as manufacturing tolerances will allow in order to minimize the

magnetizing current necessary for the production of normal air-gap flux. A simple twopole, three-phase, squirrel-cage induction motor is diagrammed in Fig. 1.

The wound-rotor induction motor has a rotor similar to that of the squirrel-cage machine except that the short-circuited squirrel-cage winding is replaced by a three-phase insulated winding similar to that on the stator. This winding is usually wye-connected with the terminals brought out to three slip rings on the shaft. Graphite brushes connected to the slip rings provide external access to the rotor winding which is connected to a rheostatic controller, the purpose of which is to insert additional resistance in each rotor phase to improve the starting characteristics.

In practically all induction motors, either the rotor or the stator slots are skewed one slot width as shown in Fig. 1(a). The purpose is to smooth the flux transition from2 one slot to the next, thereby reducing harmonics in the torque characteristic and improving the operation.

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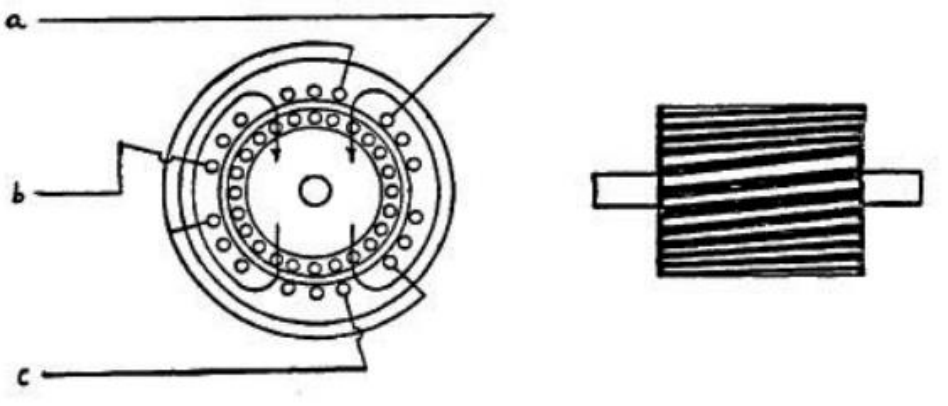


(a) (b)

**Fig. 1.** Physical construction of the squirrel-cage induction motor: (a) cross section showing stator and rotor, (b) rotor construction.

1. Basic operation of the induction motor

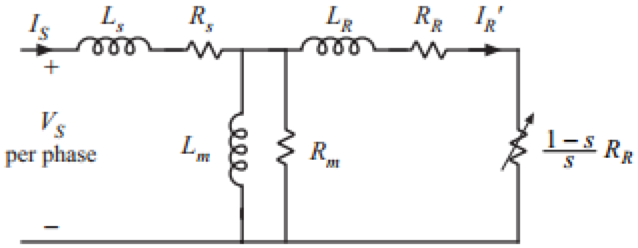
As previously shown, the phase displacement between the voltages applied to the stator windings produces a travelling MMF or rotating magnetic field in the uniform air gap. This field links the short-circuited rotor windings, and the relative motion induces shortcircuit currents in them, which move about the rotor in exact synchronism with the rotating magnetic field. It is well known that any induced current will react in opposition to the flux linkages producing it, resulting herein a torque on the rotor in the direction of the rotating field. This torque causes the rotor to revolve so as to reduce the rate of change of flux linkages reducing the magnitude of the induced current and the rotor frequency. If the rotor were to revolve at exactly synchronous speed, there would be no changing flux linkages about the rotor coils and no torque would be produced. However, the practical motor has friction losses requiring some electromagnetic torque, even at noload, and the system will stabilize with the rotor revolving at slightly less than synchronous speed. A mechanical shaft load will cause the rotor to decelerate, but this increases the rotor current, automatically increasing the torque produced, and stabilizing the system at a slightly reduced speed. The difference in speed between rotor and rotating magnetic field is termed “slip” which is numerically equal to:

$$\text{Slip} = s = \frac{\left(\textit{synchronous speed}\right) - \left(\textit{rotor speed}\right)}{\left(\textit{synchronous speed}\right)}$$

This varies from a fraction of one per cent at no-load to a maximum value of three or four per cent under full load conditions for most properly designed machines. The speed change between no-load and full-load is so small that the squirrel-cage motor is often termed a constant-speed machine.

## 2. Equivalent circuit model

Theoretical analyses of the induction machine consider it to be a transformer with a rotating secondary. The stator windings constitute primary windings that induce flux in the rotor and stator iron. The rotor windings constitute a secondary winding that is shorted. Hence, an equivalent circuit similar to that representing the transformer is derived and appears as in Fig. 2.



$$V_s \textit{ per phase} = \frac{V_{LL}}{\sqrt{3}}$$

**Fig. 2.** Equivalent circuit model of the induction machine, per phase.

Since the rotor frequency in the actual machine is dependent upon the rotor speed, all rotor quantities must be modified to be referred to the frequency and voltage bases of the stator for inclusion in the equivalent circuit. Since the circuit represents just one phase of the actual polyphase machine, all values are given on a per-phase basis. Once the equivalent circuit constants have been determined, the operating characteristics may be determined directly from it. The variable load resistance RR (1 –s)/s models the conversion of power from electrical to mechanical form. The power absorbed by this resistance is equal to the mechanical output power of the machine Po; for a three-phase machine, this power is equal to:

$$P_o = 3\left\| I_R' \right\|^2 \frac{1-s}{s} R_R$$

Similarly, the torque is proportional to the power divided by the speed. Since the speed is proportional to 1 – s, the torque is given by:

$$T = \frac{P_o}{(1-s)\omega_s} = 3\left\| I_R' \right\|^2 \frac{R_R}{s\omega_s}$$

Here, ωs is the synchronous speed, in radians per second. The torque is expressed in Newton-meters. Note that the synchronous speed in rpm is related to the applied stator frequency f according to Eq. (1). The torque expressed in the English units of foot-pounds is

$$T = 3K\left\| I_R' \right\|^2 \frac{R_R}{s} \text{ foot-pounds}$$

where K = 0.058 p/f.

The losses may be evaluated by realizing that Rs and RR represent stator and rotor resistances per phase respectively, and that Rm models the core loss. For the usual constant speed application, the mechanical windage (i.e., the resistance of air to rotation of the shaft) and bearing friction losses are constant; then Rm can also model these losses, and the total of these losses is called the stray power loss.

The inductance Lm models the magnetization characteristic of the complete flux path; this is dominated by the characteristic of the air gap between stator and rotor. A significant difference between the numerical values of the parameters of the induction machine vs. the transformer is the relatively low value of Lm (transformers typically do not contain air gaps and hence exhibit relatively large values of Lm). This low

Lm leads to a substantial magnetizing current that is typically similar in magnitude to the current in the effective load resistance RR (1 – s)/s at full load. In consequence, induction motors

exhibit relatively low power factors, especially at light load.

## 3. Measurement of model parameters

The equivalent circuit constants may be evaluated in much the same manner as those of the transformer. If the shaft coupling is disconnected, the power output will be zero and the load resistance RR(1 – s)/s approaches infinity. For all practical purposes, the series constants may be neglected and the shunt constants obtained by measuring the current, voltage, and power under these conditions where:

$$Z_m = \frac{V}{\sqrt{3}\, I}$$

$$R_m = \frac{V^2}{P}$$

$$L_m = \frac{1}{\omega \sqrt{\left(\frac{1}{Z_m}\right)^2 - \left(\frac{1}{R_m}\right)^2}}$$

with I = line current, P = total three-phase power, and V = line-to-line voltage.

If the rotor is blocked so as to prevent rotation and a balanced low-voltage threephase source connected to the stator terminals, the load resistance RR(1 – s)/s will reduce to zero, and the shunt branch may be neglected. Then:

$$R_e = R_R + R_s \text{ per phase} = \frac{P}{3I^2}$$

$$Z_e = \frac{V}{\sqrt{3}\, I}$$

$$L_e = L_R + L_s = \frac{1}{\omega}\sqrt{Z_e^2 - R_e^2}$$

Rs per phase may be determined by passing direct current through any two terminals of the stator, recording the voltage drop, and dividing the resultant resistance by two. Then RR = Re – Rs. It is usually accurate to assume equal stator and rotor leakage inductances, so that Ls = LR = Le/2.

## 4. Practical measurement considerations

Examination of the equivalent circuit of Fig. 2 suggests at least two methods for evaluating the shaft power output of the induction motor from test data. Since the currents Is and IR differ but slightly under load conditions, Rs and RR can be combined to the left of the shunt branch without introducing appreciable inaccuracy. Then the total copper losses will be:

$$P_{cu} = 3\left\| I_s \right\|^2 \left(R_s + R_R\right) = 3\left\| I_s \right\|^2 R_e$$

and the power output is:

$$P_o = P_{in} - P_{cu} - SP$$

where Pin is the total three-phase input power measured at the stator terminals under load conditions, and SP is the stray power loss. Returning to the original equivalent circuit, the power applied to the rotor portion is:

$$P_R = P_{in} - SP - 3\|I_s\|^2 R_s \tag{8}$$

Since this is all absorbed in the rotor resistance RR and the load resistance RR(1 – s)/s, the proportion absorbed in the load is (1 – s) of the total. Therefore:

$$P_o = \left[P_{in} - SP - 3\|I_s\|^2 R_s\right](1 - s) \tag{9}$$

Theoretically, expressions (8) and (9) should give nearly identical results. From a practical standpoint, (9) does not require the use of a blocked-rotor test for the evaluation of Re, but its accuracy is dependent upon the accuracy with which the slip is measured. Expression (8) is independent of speed, but does require a blocked-rotor test that is impractical for some types of motors.

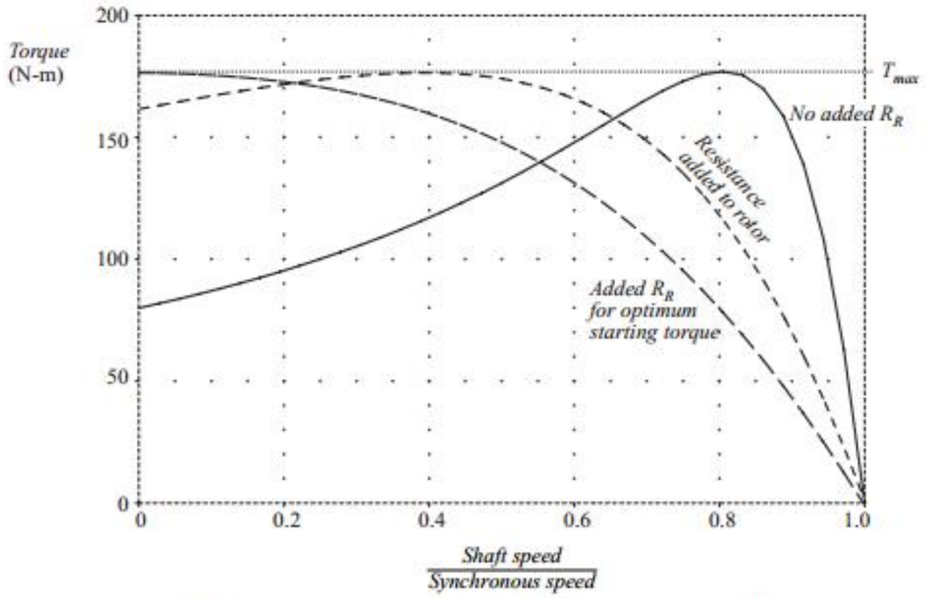


**Fig. 3.** Torque vs. speed characteristics of an induction machine example. Solid line: basic squirrel-cage machine, or wound-rotor machine with no added rotor resistance. Dashed lines: wound-rotor machine with added external rotor resistance.

## 5. Characteristics of the squirrel-cage and wound-rotor machines

Evaluation of the torque for various values of slip and constant applied voltage yields a characteristic similar to that shown as a solid trace in Fig. 3.

The maximum torque may be evaluated by maximizing the expression: T =3||IR’||2RR/s, and will be found to be independent of rotor resistance. However, the slip at which maximum torque is produced does vary with rotor resistance as shown by the dotted characteristics in Fig. 3. Normally the rotor resistance is maintained at as low a value as possible in order to keep the losses low and the efficiency high. This further leads to good speed regulation, i.e., small change in speed between no load and full load. However, the starting torque of the low-resistance squirrel-cage induction motor is relatively low as seen in Fig. 3. This can be explained in a practical manner by referring to the equivalent circuit and realizing that since the slip is 1 at start, the rotor branch impedance is simply RR + jωLR and the power factor is low. This low rotor power factor is responsible for the low starting torque. By adding the appropriate value of resistance to the rotor circuit, it is possible to improve the rotor power factor and to

produce maximum torque under starting conditions as shown by the dotted characteristic. However, if the motor is allowed to run in this condition, both the efficiency and speed regulation will be poor. The wound rotor is used where high starting torque is necessary so that additional resistance may be placed in the rotor circuit for improvement of the starting performance, and then removed as the motor accelerates towards normal operating speed. Unfortunately, the wound-rotor machine is more expensive than the squirrel-cage type, and is therefore not generally used where high starting performance is

not required. Another advantage of the wound rotor machine is that of limiting the starting current. The squirrel-cage motor usually draws about seven times rated current for an instant if started at rated voltage. To reduce the effects of this on the system, a few such motors are equipped with starting compensators which allow the motors to start at about one-half rated voltage, and then, after they accelerate to normal speed, apply rated voltage. The disadvantage is that the torque varies as the square of the applied voltage, and the use of a starting compensator worsens the already low starting torque. The wound-rotor machine always starts at rated voltage, and has excellent starting characteristics.

Although it is possible to vary the speed of the wound rotor machine at a given torque by varying the external rotor resistance, this method is rarely used because of the increased rotor losses and lowered efficiency. Sometimes induction motors are equipped with two or more stator windings by means of which the number of magnetic poles may be changed. By this means, several normal operating speeds may be obtained without sacrificing other operating characteristics.

In modern applications requiring variable speed control, a power electronics system is typically used to convert the fixed 50 Hz or 60 Hz utility ac to a variable frequency ac that is fed to the stator of a squirrel cage machine. This effective varies the synchronous speed of the machine, and hence it allows complete control of the rotor speed. The voltage magnitude must be scaled in proportion to the frequency, to maintain constant stator flux.

**PROBLEMS**

1. A certain three-phase 60 Hz induction machine exhibits the following (per-phase) model parameters:

RS = 0.20 Ω LS = 0.23 mH Rm = 250 Ω Lm = 35 mH RR = 0.19 Ω LR = 2.0 mH
The nameplate includes the following data: Rated speed 1745 rpm
Rated voltage 230 V

(a) How many poles does this machine have? What is the synchronous speed? What is the value of the slip at rated speed?

(b) For operation at rated speed, determine: the torque, the mechanical output power, the input line current, and the power factor.

(c) Plot the torque-speed curve of this machine.

2. A 60 Hz three-phase induction motor can be modeled by the conventional T model discussed in the text. For small slip s, the series impedances of this model (i.e., the stator and rotor winding resistances and leakage inductances), as well as the core loss, can be neglected entirely. The resulting simple model then

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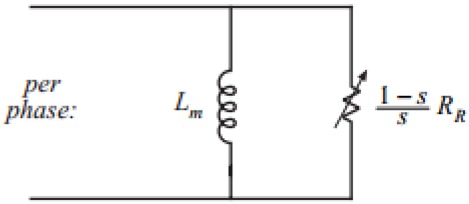
consists solely of a parallel-connected shunt inductor and resistor as shown below. You may use this approximation to solve this problem.



The machine is rated 1160 rpm, 50 hp, 415 V (line-to-line), 70 A.

(a) How many poles does this machine have? What is the slip under rated conditions?
(b) (b) What is the value of RR?
(c) (c) What is the value of Lm?
(d) (d) Find an expression for how the load torque and slip are related.
(e) (e) Find an expression for how the slip and power factor are related. As the load torque goes
(f) to zero, what happens to the power factor?

3. A three-phase induction motor is rated as follows:

873 rpm 480 V 50 hp 60 Hz

The results of blocked-rotor, no-load, and dc stator resistance tests are as follows:

| | | |
|---|---|---|
| 480V | 60V | 5Vdc |
| 46A | 102A | 50A |
| 1.6kW | 2.8kW | |

(a) Which data belongs to each test?
(b) Sketch the equivalent circuit for this machine, and label all element values.
(c) How many poles does this machine have? What is synchronous speed?
For part (d), to simplify the algebra, you may ignore the stator series impedances (i.e., set Rs = 0& Ls = 0).
(d) The machine now operates at rated speed and voltage. Determine the values predicted by your model of (i) the mechanical output power, and (ii) the power factor.

## V. Induction Generators

- Induction motor operating as a generator
  - consider a frictionless vehicle powered by a squirrel-cage induction motor that is directly coupled to the wheels
  - as the vehicle climbs a hill, the motor runs at slightly less than synchronous speed, delivering a torque sufficient to overcome the force of gravity
- electric energy converts to kinetic energy then potential energy
  - at the top of the hill or on level ground, the force of gravity does not come into play and the motor runs unloaded and very close to synchronous speed
  - as the vehicle descends a hill, the motor runs slightly faster than synchronous speed and develops a counter torque that opposes the increase in speed
- potential energy converts to kinetic energy then electric energy

## Generator Operation

- In generator operation
  - the rotor spins above synchronous speed
  - it develops a counter-torque that opposes the overspeed
- same effect as a brake
  - the rotor returned the power as electrical energy instead of dissipating it as heat
- referred to as asynchronous generation
- kinetic energy is converted into electrical energy
  - the motor delivers active power to the electrical system
  - the electrical system must provide reactive power to create the stator’s rotating magnetic field
  - higher engine speed produces greater electrical output
  - rated output power is reached at very small slips, |s | < 3%

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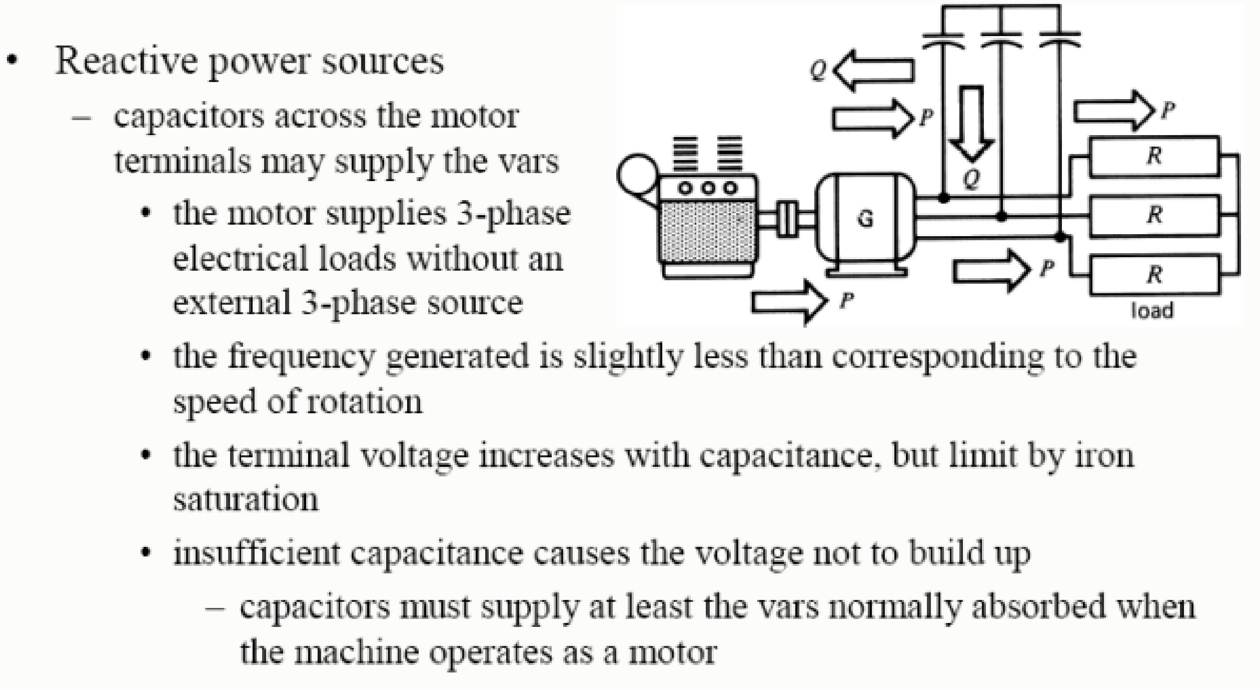
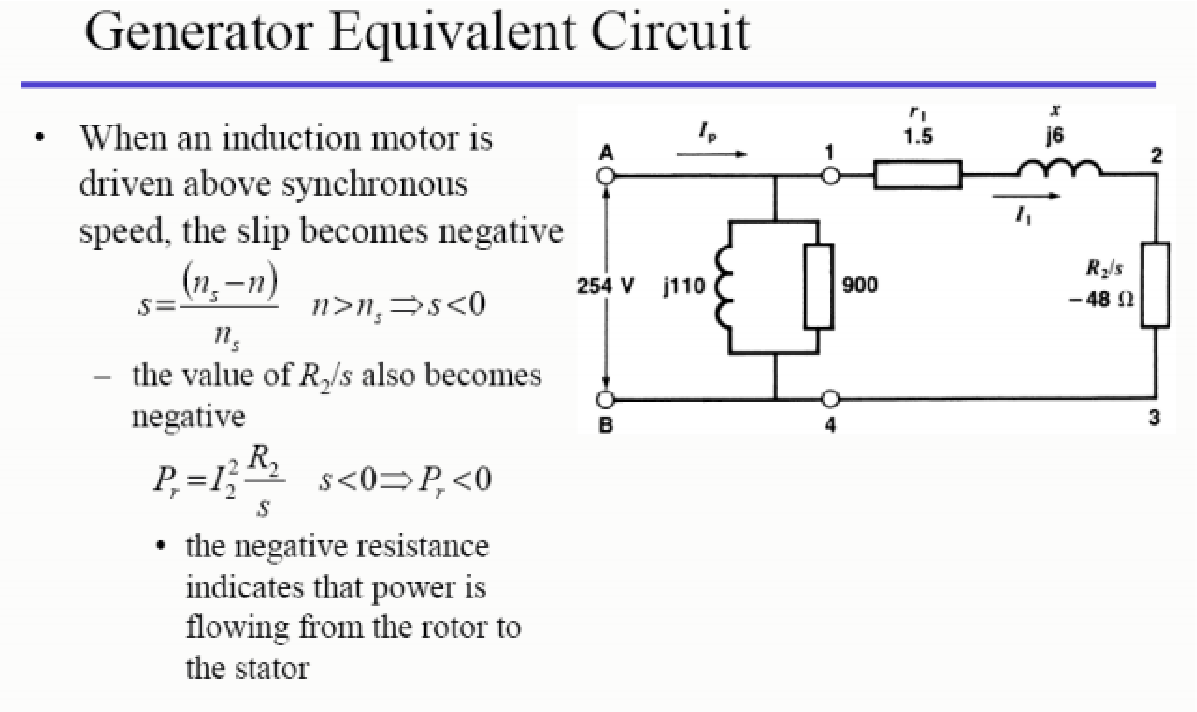


- Reactive power sources
  - capacitors across the motor terminals may supply the vars
    - the motor supplies 3-phase electrical loads without an external 3-phase source
    - the frequency generated is slightly less than corresponding to the speed of rotation
    - the terminal voltage increases with capacitance, but limit by iron saturation
    - insufficient capacitance causes the voltage not to build up
      - capacitors must supply at least the vars normally absorbed when the machine operates as a motor



## Generator Equivalent Circuit

- When an induction motor is driven above synchronous speed, the slip becomes negative

$$s = \frac{(n_s - n)}{n_s} \quad n > n_s \Rightarrow s < 0$$

  - the value of $R_2/s$ also becomes negative

$$P_r = I_2^2 \frac{R_2}{s} \quad s < 0 \Rightarrow P_r < 0$$

    - the negative resistance indicates that power is flowing from the rotor to the stator

### Comparison of synchronous and induction generators

There are two types of generators available: Synchronous and Induction types.

Synchronous generators have the DC field excitation supplied from batteries, DC generators or a rectified AC source. When DC generators are used they may be driven from the AC generator shaft directly or by means of a belt drive or they may be separately driven, independent from the AC generator. In any of the above applications, DC is applied to the field through brushes riding on slip rings attached to the rotor.

Brushless generators use a small AC generator driven directly from the shaft. The AC output is rectified and the DC is applied directly to the main generator field. The exciter generator configuration is reversed from the normal generator in that the armature is rotated with the main generator shaft and the field is fixed. In this way, the AC output can be fed to a rectifier assembly which also rotates and the resulting DC connected directly to the main generator field without brushes or slip rings.

Synchronous generators are rated in accordance with NEMA Standards on a continuous duty basis. The rating is expressed in KVA available at the terminals at 0.80 power factor. The corresponding KW should also be stated. For example, a 400 KW generator would be rated 500 KV A at 0.80 power factor.

An induction generator receives its excitation (magnetizing current) from the system to which it is connected. It consumes rather than supplies reactive power (KVAR) and supplies only real power (KW) to the system. The KVAR required by the induction generator plus the KVAR requirements of all other loads on the system must be supplied from synchronous generators or static capacitors on the system.

When a squirrel cage induction motor is energized from a power system and is mechanically driven above its synchronous speed it will deliver power to the system. Operating as a generator at a given percentage slip above synchronous speed, the torque, current, efficiency and power factor will not differ greatly from that when operating as a motor. The same slip below synchronous speed, the shaft torque and electric power flow is reversed. For example, a 3600 RPM squirrel cage induction motor which delivers full load output at 3550 RPM as a motor will deliver full rated power as a generator at 3650 RPM If the half-load motor speed is 3570 RPM, the output as a generator will be one-half of rated value when driven at 3630 RPM, etc. Since the induction generator is actually an induction motor being driven by a prime mover, it has several advantages.

1. It is less expensive and more readily available than a synchronous generator.
2. It does not require a DC field excitation voltage.
3. It automatically synchronizes with the power system, so its controls are simpler and less expensive.

The principal disadvantages of an induction generator are listed.

1. It is not suitable for separate, isolated operation
2. It consumes rather than supplies magnetizing KVAR
3. It cannot contribute to the maintenance of system voltage levels (this is left entirely to thesynchronous generators or capacitors)
4. In general it has a lower efficiency.

### Induction Generator Application

- With energy costs so high, energy recovery became an important part of the economics of most industrial processes. The induction generator is ideal for such applications because it requires very little in the way of control system or maintenance.
- Because of their simplicity and small size per kilowatt of output power, induction generators are also favored very strongly for small windmills. Many commercial windmills are designed to operate in parallel with large power systems, supplying a fraction of the customer’s total power needs. In such operation, the power system can be relied on for voltage & frequency control, and static capacitors can be used for power-factor correction.

## 15.Additional / Missing Topics:

## 16. University Previous Question Papers:

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Code No: T0222

SET - 2

II B.Tech II Semester (R07) Regular/Supply Examinations, Apr- 2010

# ELECTRICAL MACHINES - II

(Electrical and Electronics Engineering)

Time: 3 Hours Max Marks: 80

Answer any FIVE Questions
All Questions carry equal marks

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1. a) Draw and Explain Phasor diagram of single phase transformer operating on no load. (8M)

   b) A 1-Φ, 440V/110V, 50Hz transformer takes a no load current of 5A at 0.2 power factor lagging. If the secondary supplies a current of 120 A at a power factor of 0.8 lagging to a load, determine the primary current and the primary power factor. Also, draw the phasor diagram. (8M)

2. a) Derive the condition for maximum efficiency of a transformer. (8M)
   b) A single phase 150 kVA transformer has efficiency of 96 % at full load, 0.8 pf and at half load, 0.8 pf lagging. Find maximum efficiency of transformer and corresponding load. (8M)

3. a) What is auto transformer? How auto transformer is different from ordinary two winding transformer? What are the advantages & disadvantages of auto transformer? Explain the working principle of auto transformer (8M)
   b) Obtain the derivation for the copper saving in auto transformer compared to two winding transformer for identical rating. (8M)

4. a) Discuss the constructional details of the three phase transformers with necessary diagrams. Mention their advantages and disadvantages. (8M)
   b) Explain the principle of 3-Φ to 2-Φ conversion using Scott connection. Draw the phasor diagram of Scott connected transformer showing phase relationships of currents in case the secondary of teaser transformer supplying Unity pf load and secondary of main transformer is supplying load at 0.8 p.f lagging. (8M)

5. a) Explain why the rotor of polyphase induction motor can never attain synchronous speed. (8M)

   b) Discuss the points of similarities between a transformer and an induction machine. Hence, explain why an induction machine is called a generalized transformer. (8M)

6. a) Explain the torque development process in an induction motor and its dependence on rotor slip. (8M)
   b) The power Input to Rotor of a 440V, 50Hz, 6-pole, 3-Φ Induction Motor is 100KW. The Rotor electromotive force is observed to make 120 cycles per minute. Calculate i) Slip, ii) Rotor speed, iii) Mechanical power developed and iv) Speed of stator field with respect to rotor (8M)

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7. a) What are the various types of starters used for squirrel cage rotors? Discuss them. (8M)
b) A Squirrel Cage Induction Motor has a stating current of six times the Full-load current at a slip of 0.04. Calculate the line current and Starting torque in p .u of full-load values for the following methods of starting:
(i)Direct switching
(ii) Star-delta starting. (8M)

8. a) Explain the principle of operation of induction generator (8M)
b) Explain briefly the different methods of speed control from stator side of 3 phase induction motor. (8M)

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Code No: T0222 SET - 3

II B.Tech II Semester (R07) Regular/Supply Examinations, Apr- 2010

# ELECTRICAL MACHINES - II

(Electrical and Electronics Engineering)

Time: 3 Hours Max Marks: 80

Answer any FIVE Questions
All Questions carry equal marks

1. a) Draw and Explain Phasor diagram of single phase transformer operating on lagging load. (8M)
b) A transformer on load takes 1.5 Amps at a power factor of 0.2 lagging when connected across 50Hz, 230V supply. The ratio between primary and secondary number of turns is 3. Calculate the value of primary current when secondary is supplying a current of 40 amps at a power factor of 0.8 lagging. Neglect the voltage drop in the windings. Draw the relevant phasor diagram. (8M)

2. a) Define efficiency and regulation of a transformer. Show how the power factor affects both of them (8M)
b)A single phase 150KVA transformer has efficiency of 96% at full load, 0.8 pf and at half load, 0.8 pf lagging. Find the maximum efficiency of transformer and corresponding load. (8M)

3. a) What are the conditions required for the parallel operation of two transformers. (8M)
b)Two transformers A and B are connected in parallel to a load of (2+j1.5) Ω. The Impedance in secondary are $Z_A = (0.15+j0.15)\ \Omega$, $Z_B= (0.1+j0.1)\ \Omega$. Their no load terminal voltage are $E_A=(207+j0)$ V, $E_B= (205+j0)$ V. Find power output and Power factor of each transformer. (8M)

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4. a)Why is it preferable to operate a bank of transformers rather than three independent single phase transformers? (8M)

b)The no-load current of a transformer is 5.0A at 0.3 power factor when supplied at 230V, 50Hz. The number of turns on the primary winding is 200. Calculate

i) The maximum value of the flux in the core

ii) The core loss and

iii) The magnetizing current. (8M)

5. a) Explain with neat diagrams the construction and working of a 3 phase induction motor. (8M)

b)A balanced 3 phase induction motor has an efficiency of 0.85 when the output is 60HP. At this load the stator and rotor copper losses are equal to the core losses. The mechanical losses are ¼ of no load loss. Calculate the slip. (8M)

6. a) Show that in an induction motor the rotor input: power developed: rotor copper losses :: 1: (1-s) : s, where ‘s’ is the fractional slip. (8M)

b) A 3 phase star connected 220V (line to line), 50Hz, 4 pole induction motor has the following constants in ohm/phase: $r_1 = 0.3$, $r_2 = 0.15$, $X_1 = 0.5$, $X_2 = 0.2$ and magnetizing reactance $X_0 = 14$ ohm. The total friction, windage and core losses may be assumed to be constant at 420W independent of load. For slip of 2%, calculate (i) speed (ii) Output torque and (iii) Stator current of the motor. (8M)

7. A 3 ϕ, Δ connected, 20 HP, 440 V, 6-pole, 50 Hz Induction Motor gave the following test results:

No load Test: 440 V, 10 A, p.f = 0.2

Blocked rotor test: 200 V, 50 A, p.f = 0.4

All above are the line values. Plot the circle diagram and for full load find:

(a) The line current

(b) The power factor

(c) Slip

(d) Torque

(e) Efficiency

(f) Maximum Power factor

Given that rotor copper losses are equal to stator copper losses at stand still. (16M)

8. a) Explain the speed control of 3-ϕ Induction Motor using 'rotor emf injection method'. (8M)

b) A 2-pole, 3-ϕ, 50 Hz, slip ring induction motor has its rotor resistance of 0.2Ω/ph and full load speed of 2900 rpm. Calculate the external resistance per phase required to be added in rotor circuit to decrease the speed to 2500 rpm. The torque remains the same as before.

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Code No: T0222

SET - 4

II B.Tech II Semester (R07) Regular/Supply Examinations, Apr- 2010

# ELECTRICAL MACHINES - II

(Electrical and Electronics Engineering)

Time: 3 Hours Max Marks: 80

Answer any FIVE Questions
All Questions carry equal marks

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1. a) Explain the constructional details of a single phase transformer? (8M)

   b) When a 1-Φ transformer is supplied at 400V, 50Hz the hysteresis loss is found to be 310W and eddy current loss is found to be 260W. Determine the hysteresis loss and eddy current loss when the transformer is supplied at 800V, 100Hz. (8M)

2. a) Write a short note on All-day efficiency of the transformer. (8M)
   b) Find the All day efficiency of single phase transformer having maximum efficiency of 98 % at 15 KVA at UPF and loaded as follows.
   12 hours — 2 KW at 0.5 power factor lagging
   6 hours — 12 KW at 0.8 power factor lagging
   6 hours — no load (8M)

3. a) Explain the procedure for conducting Sumpner's test along with all precautions to be taken while conducting the test with neat diagram. (8M)

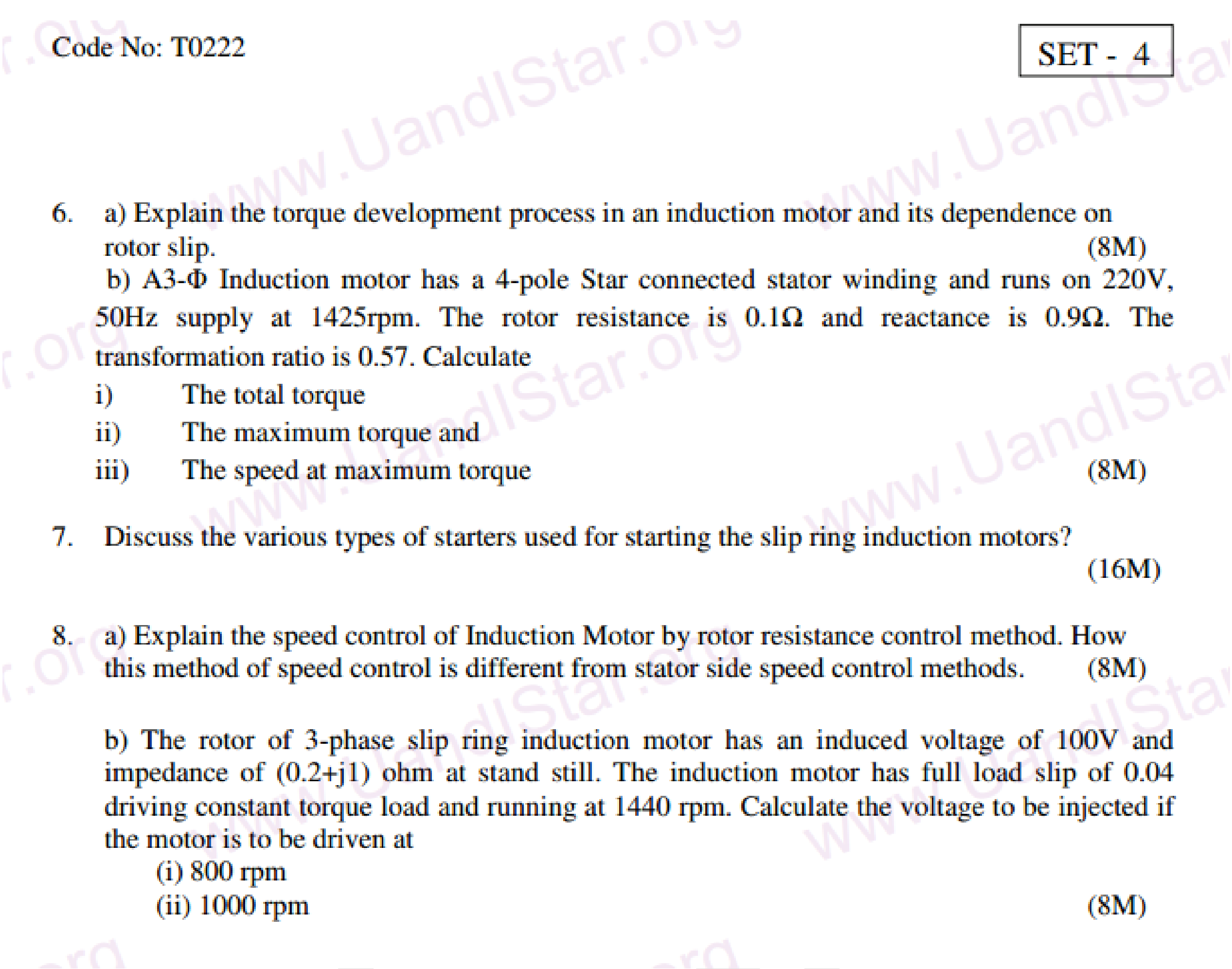
   b) The corrected instrument readings obtained from short circuit test on 10 KVA, 450/125V, 50Hz transformer are 9.65V, 22.2A, 120W, with low voltage winding short circuited. Compute voltage regulation for an 85% lagging load at 50% load. (8M)

4. a) Discuss the constructional details of the three phase transformers with necessary diagrams. Mention their advantages and disadvantages. (8M)

   b) A 3-ϕ, 1200 kVA, 6.6/1.1 kV transformer has Delta/Star connection. The per phase resistance is 2Ω and 0.03 Ω on primary & secondary respectively. Calculate the efficiency on full load at 0.9 pf lagging, if iron losses are 20 kW. (8M)

5. a) Explain the classification of induction motors based on construction of rotor. Explain the advantages & disadvantages of each. (8M)

   b) The frequency of stator EMF is 50 Hz for an 8-pole induction motor. If the rotor frequency is 2.5 Hz, calculate the slip and the actual speed of rotor. (8M)



Code No: T0222

SET - 4

6. a) Explain the torque development process in an induction motor and its dependence on rotor slip. (8M)

b) A3-Φ Induction motor has a 4-pole Star connected stator winding and runs on 220V, 50Hz supply at 1425rpm. The rotor resistance is 0.1Ω and reactance is 0.9Ω. The transformation ratio is 0.57. Calculate

i) The total torque
ii) The maximum torque and
iii) The speed at maximum torque (8M)

7. Discuss the various types of starters used for starting the slip ring induction motors? (16M)

8. a) Explain the speed control of Induction Motor by rotor resistance control method. How this method of speed control is different from stator side speed control methods. (8M)

b) The rotor of 3-phase slip ring induction motor has an induced voltage of 100V and impedance of (0.2+j1) ohm at stand still. The induction motor has full load slip of 0.04 driving constant torque load and running at 1440 rpm. Calculate the voltage to be injected if the motor is to be driven at

(i) 800 rpm
(ii) 1000 rpm (8M)

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# 17.Question Bank:

## UNIT-I

### Objective Questions

1. A transformer transforms: ( )
a) frequency
b) only voltage
c) only current
d) both voltage and current

2. An ideal transformer is defined as one ( )
a) whose windings have no resistance
b) whose core has no losses
c) whose core has infinite permeability
d) which has all the above properties

3. A transformer having 1000 primary turns is connected to a 250 v ac supply. For a secondary voltage of 400 V, the number of secondary turns should be ___________

4. A step up transformer increases ( )
a) voltage
b) current
c) power

d) frequency
5) . A transformer will work on ____________
(a)a.c only (b)d.c only (c)a.c as well as d.c (d)none of the above
6) The primary and secondary of a transformer are ___________ Coupled
(A) Electrically (b) magnetically (c) electrically magnetically
(d) None of the above
7) A transformer is an efficient device because it ___________
(a)is a static device (b)uses inductive coupling (c)Uses capacitive coupling
(d) Uses electric coupling
8) The voltage per turn of the primary of transformer is_____The voltage for turn of the secondary
a) more than b) less than c) the same as d) none of the above
9)How is magnetic leakage reduced to a minimum in commercial transforemer---------
10)Mention the factors on which hysterisis loss depends
11)________________ is not a basic element of a transformer
12)The main purpose of using core type of transforemer is_____________
13)In ideal transformer ________________
14)The main purpose of using core in a transformer is to___________
15)Transformer core is laminated inorder to reduce______________
16)A step up transformer increases___________________
17)The primary and secondary windings of an ordinary 2-winding transformer are always______________________
18)In a transformer, the leakage flux of each winding is propotional to the current in that winding because___________
19)In relation to transformer,the ratio 20:1 indicates that________________
20)The primary and secondary induced e.m.f's E1 and E2 in a two winding transformer are always___________-
21.The equivalent resistance of the primary of a transformer having $k=N_1/N_2=5$ and $r=0.1\ \Omega$, when referred to secondary, becomes ______ $\Omega$.
22.A transformer can have negative voltage regulation when its load power factor is ---
23)Transformers are rated in KVA instead of KW because _______
24)How eddy current loss can be minimized in an iron core?
25)How does a change in frequency affect the operation of a given transformer?
26)Which of the following is not a basic element of a transformer ( )
a) Core b)primary winding c) secondary winding d) shaft

27)When a 400 Hz transformer is operated at 50 Hz, its KVA rating is( )
a)reduced to 1/8 approximately
b)increased to 8 times approximately
c)unaffected d)increased 64 times approximately
28)The power efficiency of a given transformer is maximum ( )
a)at no load b)always at 50% rated KVA load c)always at its rated KVA load
d)when its copper loss equals iron loss.
29)The _______ loss of a transformer has a significant influence on its all day efficiency.
30)The maximum efficiency of a 100 KVA transformer having an iron loss of 900 KW and full load copper loss of 1600 W occurs at ________ KVA
31)If copper loss of a transformer at 7/8th full load is 4900 W, then its
32)At relatively light loads, transformer efficiency is low, because

33)The iron core is used to _________of the transformer
a) increase the weight b) provide tight magnetic coupling) reduce core losses
d) none of the above
34) The maximum flux produced in the core of a transformer is__________
a) Directly proportional to supply frequency b) inversely proportional to supply frequency
c) Inversely proportional to primary voltage d) none of the above

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35) When the primary of a transformer is connected to a d.c supply____________
(a) Primary draws small current (b) primary leakage reactance is increased (c) core losses are increased (d) primary may burn out
36)An ideal transformer is one which__________
(a)has no losses and leakage reactance (b)does not work (c)as same number of primary and secondary turns (d) none of the above
37) A transformer has an efficiency of 80% and works at 100V,4KW if the secondary voltage 240V,find the primary current
(a)40A (b)30A (c)20A (d)10A
38) In the above question, what is the secondary current?
(a)12.5A (b)9.42A (c)11.56A (d)13.33A
39)A 2000/200V,20KVA ideal transformer has 66 turns in the secondary the no.of primary turns is_____________
(a)440 (b)660 (c)550 (d)330
40)the no-load ratio of a 50Hz single phase transformer is 6000/250V the maximum flux in the core is 0.06Wb. What is the no.of primary turns
(a)450 (b)900 (c)350 (d)210
41)In the above question what is the no. of secondary turns?
(a)38 (b)19 (c)76 (d)104
42) A 20 turn iron cored indicator is connected to a 100V, 58Hz source. The maximum flux density in the core is 1Wb/m^2. the cross sectional area of the core is_________
(a)0.152m^2(b)0.345 m^2(c)0.056 m^2(d)0.0225 $m^2$
43) Calculate the core area required for a 1600 kVA, 6600/440V, 50Hz single phase core type power transformer. Assume a maximum flux density of 1.2 WB/m^2 and induced voltage per turn of 30 V.
(a) 975 $cm^2$ (b) 1100 $cm^2$ (c) 1125 $cm^2$ (d) 1224 $cm^2$

## UNIT – II

### Objective Questions

1.The reason why open circuit test is performed on the low voltage winding of the transformer is _______________
2.No-load test on a transformer is carried out to determine ( )
e)the copper loss
f) the voltage regulation of transformer
g) magnetizing current and no-load loss
h) efficiency of the transformer
3.The purpose of performing open-circuit test on a transformer is to measure its __________
4.During the short-circuit test on a transformer, its iron losses are negligible because __________
5.In relation to a transformer, the transformation ratio 20:1 indicates that _______
6.In performing short circuit test of a transformer ( )
a)The high voltage side is usually short-circuited.
b) The low voltage side is usually short-circuited
c)Either side may be short-circuited with no particular preference
d) Neither the high voltage side nor the low voltage side is shorted.
7.For a given magnitude of load current, a transformer has the maximum value for its regulation if the load power factor angle equals to ( )
a)zero
b) 90 lag
c)90 lead
d) Impedance angle of transformer
8.Two transformers A and B having equal output voltage ratios but unequal percentage impedances of 4% and 2% respectively are operating in parallel with load equal to the sum of ratings of A and B. Transformer B will be running over-load by _______ %.

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9. The essential conditions for effective parallel operation of two 1ϕ transformers ( )

a) same KVA rating

b) same primary and secondary voltage ratings

c) same percentage impedance

d) terminals of same polarity to be connected together while paralleling

10. The saving in copper achieved by converting a two-winding transformer into an auto-transformer is determined by _______

11. If the full-load iron loss of a transformer is 100 W, what will be its iron loss at half-load.

12. The open-circuit test on a transformer is performed with ( )

a) rated transformer voltage

b) rated transformer current

c) direct current

d) high frequency supplier

13. A transformer has $N_1$ and $N_2$ turns in primary and secondary windings respectively. Its secondary winding reactance of $X_2$, when referred to primary is ( )

a) $(N_2/N_1)^2 X_2$

b) $(N_2/N_1) X_2$

c) $(N_1/N_2)^2 X_2$

d) $(N_1/N_2) X_2$

14. Hysteresis loss in a transformer depends on ( )

e) applied primary voltage alone

f) frequency of the primary voltage alone.

g) Both primary voltage and its frequency

h) Neither primary voltage nor its frequency.

15. The efficiency of a transformer at full load 0.8 pf lag is 90%, then its efficiency at full-load 0.8pf lead is ( )

a. less than 90%

b. More than 90%

c. 90%

d. Not deducible from given data

16. The value of flux determining the rms value of the induced emf in a transformer is ( )

a. its rms value

b. its average value

c. its instantaneous value

d. its peak value

17. The no-load current in a transformer lags the applied voltage by( )

a) 90 b) about 75 c) 0 d) about 115

18. The power factor of a transformer on no-load is poor due to ( )

a) low ratio of magnetizing reactance to 'Core loss' resistance in the transformer equivalent to circuit

b) high ratio of magnetizing reactance to 'Core Loss; resistance in the transformer equivalent circuit.

c) Low primary winding resistance

d) Low no-load current

19. A 1ϕ transformer has a turns ratio of 4:1. If the secondary winding has a resistance of 1Ω, the secondary resistance referred to the primary will be: ( )

a) 16 Ω b) 4 Ω c) 0.25 Ω d) 0.06 Ω

20. The core of a transformer is made of: ( )

a) annealed copper

b) silicon steel) seas oned wood

21. A T-T transformer cannot be paralleled with __________ transformer.

22. A balanced load of 0.866pf is supplied by a V-V connected bank of transformer, then the average pf of the V-bank is _________

23. When a V-V connected bank of transformer is converted into a Δ - Δ system, by the addition of an additional single-phase transformer, then the increase in capacity of the system is _________ %.

24. Which of the following transformer connections is best suited for 3 ϕ, 4 wire service?( )

a. Δ - Δ
b. Y – Y
c. Δ – Y
d. Y – Δ

25. In a 3ϕ induction motor, relative speed of stator flux with respect to ________________ is zero.

26. When one transformer of a bank of Δ - Δ connected transformers is taken out of service, the capacity in KVA of the resulting V-V system is ____________ percent of the rating of the Δ - Δ bank.

27. The biggest advantage of a T-T connection over the V-V connection for 3ϕ power transformation is that it provides __________

28.In a three phase Y – Y transformer connection neutral is fundamental to the

29)When V-V system is converted to Δ - Δ system,increase in capacity of the system is_______________percent

30)If a load P.F is 0.8666,then the average p.f of V_V bank_____________

31)A T-T connection has higher ratio of utilization that a V-V bank is______

32)The biggest advantage of T-T connection over the V-V connection for 3-phase power transformation is thst it provides _________________

33)For supplying a balanced 3-phase load of 40-KVA,rating of each transformer in V-V bank should be nearly___KVA

34)Instrument transformers are used on a.c circuits for extending the range of ----

35) The percentage(%) voltage regulation of the Transformer is given by _______

a) $\frac{E_2 - V_2}{V_2}$ b) $\frac{E_2 - V_2}{E_2}$ c) $\frac{V_2 - E_2}{E_2} \times 100$ d) $\frac{E_2 - V_2}{E_2} \times 100$

36. The full load rating of a Transformer is 90 kW at power factor of 0.9 its KVA rating would be _____

## UNIT-III

## Objective Questions

1) Fundamental slip of an induction motor is the ratio of ( )
a. rotor copper loss / rotor input
b. stator copper loss / stator input
c. stator copper loss / rotor input
d. rotor copper loss / rotor output

2) An induction motor works with ( )
e. DC only b) AC only c) either AC or DC d) AC superimposed on DC

3) When an induction motor is standstill, the slip is ( )
f. 0 b) 1 c) α d) None

4) The synchronous speed of a given induction motor can be increased by ( )
g. reducing its mechanical friction
h. increasing the supply voltage
i. reconnecting it for a larger number of poles
j. Increasing the frequency of supply.

5) An induction motor has a synchronous speed of 1500 rpm, what is the value of slip, if it is running at a speed of 1440 rpm. ( )
a) 96% b) 60% c) 4% d) -4%

6)A 4 pole, 50 Hz, induction motor runs at a speed of 1440 rpm. The frequency of rotor currents is
a) 50 Hz b) 48 Hz c) 4 Hz d) 2 Hz

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7) 3 $\phi$ Induction motors are widely used in industries because
a) They provide excellent starting torque
b) Their speed can be controlled easily over a wide range
c) They are less expensive and rugged in construction
d) They have good operating power factors.

8) Mention different 3 $\phi$ transformer connections?

9). For 3$\phi$ induction motors, synchronous speed ($N_s$), stator frequency (f) and number of Poles (p) are related as
a) Ns=P/120f b) f=PNs/120 C) f=120Ns/P d) Ns=120P/f

10) An induction motor under full-load condition has a fractional slip of about: (     )
a) 0.03 b) 0.1 c) 0.3 d) 0

11) A 50 Hz, 3 $\phi$ induction motor operative under full-load has a speed of 720 rpm. The number of poles of motor is equal to (     )
a) 2 b) 4 c) 8 d) 16

12)The power supply in a 3$\phi$ induction motor is connected to (     )
a) The stator windings only
b) The rotor windings only
c) Both stator and rotor windings
d) the Stator winding, while a DC supply is connected to the rotor winding.

13) The rotor of a 3$\phi$ induction motor cannot run at synchronous speed, because:(     )
a) it would violate Lenz's Law
b) the rotor copper loss prevents it to do so.
c) the developed torque would then become zero
d) the mechanical structure of the motor breaks down at synchronous speed.

14} The slip on nduction motor normally does not depend upon
a)Rotor speed **GATE-2012**
b)Synchronous speed
c)Shaft torque
d)cross-loss component

15) A three phse 440V, 50HZ squirrel cage induction motor is running at a slip of 5%. The speed of stator magnetic field to the rotor magnetic field and speed of the rotor to the statorrotor magnetic field is
1000RPM -50RPM

16. Define crawling in a 3 phase induction motor?

17. Define cogging in a 3 phase induction motor?

18. Sketch the equivalent circuit of a 3 phase induction motor?

19. At slip equal to infinity the torque of a 3 phase induction motor is (     )
a) negative b) 0 c) very small d) high

20. In a 3 phase 50 Hz induction motor under normal operation the rotor core losses are (     )
a) higher than stator core losses
b) smaller than stator core losses
c) equal to stator core losses
d) zero

21. The squirrel cage rotor of 4 pole 3 phase induction motor can be used with a stator wound for the following number of poles (     )
a)only 4 b) with 4 or 8 poles
c)only an integral multiple of 4 d)any even number of the poles

22. A 3 phase 50 Hz ,4 pole squirrel cage induction motor has its stator rewound for 6 phases with out any alteration in the rotor. The stator would now run at a speed of about (     )
a)1000 rpm b) 1500 rpm c)3000 rpm d)0 rpm

23. In a 3 phase induction motor the maximum torque (     )
a) is proportional to $(r_2)^2$
b) is proportional to $r_2$
c) is proportional to $(r_2)^{1/2}$
d) does not depend upon $r_2$

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24. In a 3 phase wound rotor induction motor a 3 phase balanced delta supply is given to the rotor and stator winding is short circuited .Then the motor would ( )
a) not run
b) run in the direction of the rotating field set up by the stator
c) run in the opposite direction of the rotating field set up by the stator
d) continue to run in either direction if given an external start
25. The rotor of a synchronous motor run at synchronous speed if did so then ( )
1.Rotor emf would be zero
2.rotor current would be zero
3.rotor torque would be zero
26. choose the correct response from the following alternatives
a) assertion 1 is only is correct
b) assertion 2 is only is correct
c) assertion 3 is only is correct
d) all the three assertions are correct
27. Give the expression for the torque developed by a 3 phase induction motor in terms of its rotor circuit parameters slip and rotor emf per phase at stand still
28. If the rotor circuit resistance of a 3 phase induction motor is increased above its normal value the n the starting torque and the maximum torque developed are
29. A 3 phase 4 pole induction motor develops a torque of 200 Nm.. If the supply voltage is reduced to 200 V, then the torque developed will be
30. Sketch the torque slip characteristics of a 3 phase induction motor
31. If the stator voltage and frequency of an induction motor are reduced proportionately its ( )
a) Locked rotor current is reduced
b) Torque developed is increased
c) Magnetizing current is decreased
d) Both a& b
32. If the maximum torque of an induction motor is 200 Kg-m at a slip of 12%, the torque at 6% slip would roughly be
33. A 3 phase 6 pole, 50 Hz induction motor has a full load speed of 950 rpm .At half load its speed approximately be
34. A 3 phase 6 pole ,50 Hz induction motor has a full load speed of 950 rpm , and has rotor copper loss of 5 KW. Its rotor input is
35. The power factor of a squirrel cage induction motor is low at ( )
k. light loads only
l. heavy loads only
m. both heavy and light loads
n. rated load only
36. A 3 phase 4 pole ,50 Hz induction motor has a full load speed of 1440 rpm .The rotating magnetic field produced by the rotor currents rotates at a speed of _______________ with respect to rotor.

## *UNIT - IV*

### Objective Questions

1. Direct on line starting of a large induction motor should be avoided because ( )
a) the starting torque is very high
b) the rotor may run in reverse
c) the motor may pick up dangerously high speed
d) the motor takes about 5-7 times its full load current
2. An induction motor cannot run at synchronous speed give reasons?
3. Give the indications of winding failure in an induction motor
4. What factors determine the direction of rotation of an 3 phase induction motor

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5. How does the slip of an induction motor vary with load?

6. In the circle diagram of a 3 phase induction motor the diameter of the circle is( )

a) Rotor current
b) Exciting current
c) Total stator current
d) Total current referred to stator

7. In the circle diagram of an induction motor, point of maximum input lies on the tangent to the circle drawn parallel to

8. An induction motor has short circuit current 7 times the full load current and a full load slip of 4%. Its on line starting torque is _______________ Times the full load torque

9. For the purpose of starting of an induction motor a star –delta switch which is equivalent to an auto transformer starter of ratio________________ percent

10. If the starter voltage of a squirrel cage induction motor is reduced to 50 % of its rated value the torque developed is reduced to _____________ percent of its full load value

11. In a squirrel cage induction motor the starting torque with autotransformer starter of ratio 1: a is _________ times the starting torque with direct switching.

12. A six pole 3ϕ induction motor taking 25KW from a 50Hz supply is cumulatively cascaded to a 4 pole motor. Neglecting the losses, speed of the 4 pole motor would be __________________rpm and its output would be _________ KW.

13. How can induction motors be protected against single phasing?

14. What does phase splitter mean?

15. Describe the principle of operation of a Schrage motor?

16. A wound rotor induction motor can be reversed by transposing any two leads from the slip rings [T/F]

17. What is the standard direction of rotation of induction motor?

18. Pick out the wrong statement Blocked rotor test on a three phase induction motor helps to find ( )

a) short circuit current with normal voltage
b) short circuit power factor
c) fixed losses
d) motor resistance as referred to stator

19. If the frequency of 3- phase supply to the stator of a 3-phase induction motor is increased, then synchronous speed___________

a) is decreased
b) is increased
c) Remains un changed
d) None of the above

20. The synchronous speed of a 3-phase induction motor having 20-poles and frequency 50Hz is

a) 600rpm
b) 100rpm
c) 1200rpm
d) 300rpm

21. The relation among synchronous speed ($N_S$) rotor speed (N) and slip(S) is____________

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a) $N=N_S\ (S-1)$ b) $N=N_S\ (1-S)$
c) $N=N_S\ (S+1)$ d) $N=N_S\ S$

22. When the rotor of a 3- phase induction motor is blocked, the slip___________
a) 0 b) 0.5 c) .1 d) 1

23. A 4-pole induction motor has a synchronous speed of 1500 r.p.m then supply frequency
a) 50Hz b)25Hz
c) 60Hz d)none of the above

24. The rotor winding of a 3-phase wound rotor induction motor is generally________ connected
a) Star b) delta
c) partly star and partly delta d) none of the above

25. A wound rotor motor is mainly used in applications where ________
a) High starting torque b) speed control is required
c) less costly motor is not required d)high rotor resistances required

26. If the slip of a 3-phase induction motor increases, the p.f .of the circuit is ________
a) is increased b) is decreased c) remains unchanged d) none of the above

27. Which of the following is drawback of the Induction Motor
a) cheap in cost b) moderate efficiency
c) self starting d) speed control is complex

28. The frequency of induced e.m.f in case of rotor is _______
a) sf b) f/s
c) f+s d)f-s

29. The copper losses in the rotor of induction motor is ________
a) result in the eddy currents b) are lost as heat
c) result in noise d) are always negligible

30. The ratio of resistance to reactance for induction motor is ________
a) high b) unity
c) less than unity d) negligible

31. Power factor of induction motor during no load condition is ________
a) low b) high
c) zero d) unity

32. Which of the following is a rotational transformer ________
a) transformer b) D.C machine
c) Induction motor d) synchronous machine

33. An induction motor is ________
a) non self starting b) self starting with low torque

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c) self starting with high torque d) self starting with zero torque

34. At low slip the torque slip characteristic is ________

a) $T \propto S$ b) $T \propto S^2$ c) $T \propto \frac{1}{S^2}$ d) $T \propto \frac{1}{S}$

35. The relationship between rotor frequency $f_2$, slip s and stator frequency $f_1$ is given by

a) $f_2 = Sf$ b) $f_2 = \sqrt{Sf}$ c) $f_2 = f / S$ d) $f_2 = (1-S)f$

36)In a Schrage motor operating at super synchronous speed, the injected emf and the standstill secondary induced emf ( )

a) are in phase with each other

b) are at $90^0$ in time phase with each other

c) are in phase opposition

d) have a phase difference of between $45^0$ and $135^0$

37)For starting of a Schrage motor, 3 phase supply is connected to ________________

38) What is mean by plugging

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## 18.Assignment Topics:

1. Losses in Transformers and Minimization
2. All day Efficiency
3. Testing of Transformers
4. Performance Characteristics of Transformers
5. Parallel Operation of Transformers
6. Poly Phase Transformers
7. Harmonics in Poly Phase Transformers
8. Scott Connection – Necessity and Application
9. Performance Characteristics of Poly Phase Induction Motors
10. Crawling and Cogging
11. Speed Controlling Techniques of Induction Motor
12. Starting Methods of Induction Motor
13. Induction Generator – Principle of Operation

## 19.Unit wise Questions:

### *Unit – I*

### Essay Questions

1 a) Describe the construction of core-type and shell-type transformers with suitable sketches. Where is each type employed and why?

b) Derive the emf equation of a single phase transformer.

2) a) Explain the working principle of a single-phase transformer.

b) Explain various losses present in a transformer and the ways to minimize them

c) A 1000 / 200 V transformer takes 0.3 A at pf of 0.2 on open circuit, find the magnetizing and iron loss components of on-load primary current.

3) a) Draw and explain the no-load phasor diagram of a transformer. Explain how the primary current increases as the current on the secondary side of the transformer is increased?

b) a 400/200 V, single phase transformer is supplying a load of 25 A at pf of 0.855 lagging. On no-load, the current and pf are 2.0A, and 0.208 lag respectively. Calculate the current taken from the supply on load and specify its phase.

4) Explain the purpose of using iron core in a transformer?

5) What effects are produced by a change in the voltage applied to a 1ϕ transformer?

6) Mention the factors on which hysterisis loss depends?

7) Does a power transformer draw any current when its secondary is open? Why?

8. a) Draw and explain the approximate equivalent circuit of a transformer.

b) A 25 KVA, 2200/200 V, 50 Hz single phase transformer has the following resistances and leakage reactance's $r_1=0.8\ \Omega$, $r_2= 0.009\ \Omega$, $x_1=3.2\ \Omega$, $x_2=0.03\ \Omega$ Calculate the equivalent resistance and reactance as referred to both primary and secondary sides.

9 a) Draw and explain on-load phasor diagram of transformer

b) A 50 KVA, 1000/200 V, single phase, step down transformer takes 4A at a pf of 0.2 lagging, when the secondary is open circuited. Calculate the primary current and pf, when a load taking 250 A at a lagging pf of 0.8 is connected across the secondary. Assume the voltage drop in the winding to be negligible.

10 a) A 5 KVA, 200/400 V, single phase transformer has a resistance of 0.12 Ω and a reactance of 0.32 Ω as referred to the L.V. side. Calculate the per unit values of 1) resistance 2) Reactance 3) Impedance taking rated quantities as the base values on the two sides respectively.

11 a) What do you mean by efficiency of a transformer? Derive the condition for the maximum efficiency of a single phase transformer.

b) In a 25 KVA transformer, the iron loss and full load copper loss are 250 W and 400 W respectively. Calculate the efficiency of the transformer at:

1) Half full-load and unity pf. 2) ¾th full-load at 0.8 pf lagging

12 a) Explain voltage regulation of a transformer. Explain how the nature of load affects voltage regulation.

b) The readings of a direct loading list on a single phase transformer are:

| Primary Side | | | | Secondary Side | |
|---|---|---|---|---|---|
| | V1 (v) | I1(A) | W1(w) | V2(v) | I2(A) |

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| | | | | | |
|---|---|---|---|---|---|
| (1) No-Load condition | 220 | 1.5 | 60 | 110 | 0 |
| (2) Full-load condition with resistive load | 220 | 15.07 | 3,375 | 104.5 | 30 |

Find the full load efficiency and regulation of the Transformer.

13 a) Calculate the efficiencies at half full-load and full load of 50 KVA, single phase transformer for pf of 1) unity 2) 0.8. The full load copper loss is 500 w.

b) A 5 KVA, 440/220 V, 50 Hz single phase transformer has primary winding resistance, and reactance as 0.25 Ω and 0.75 Ω respectively. The resistance ad reactance of secondary winding are 0.06 Ω and 0.25 Ω respectively. Calculate the percentage regulation of the transformer on full-load at a pf of 1) 0.8 lagging 2) 0.8 leading 3) unity

14a) Explain all-day efficiency of a 1 Φ transformer.

b) A single phase transformer has its maximum efficiency of 0.975 at 25 KVA and unity pf. During the day, it is loaded as follows:

| | |
|---|---|
| 8 hrs: | 15 KVA at 0.8 pf lag |
| 4 hrs: | 25 KVA at unity pf |
| 2 hrs: | 28 KVA at 0.9 pf |
| 10 hrs: | 0 KVA |

Determine its all day efficiency.

15) Explain the effects of variation of frequency and supply voltage on Iron losses.

## UNIT-II

### Essay Questions

1) a) Explain in detail the O.C and S.C tests on a single phase transformer, and their use to find regulation and efficiency of the transformer.

b) The wattmeter in the O.C. test on a transformer reads iron losses, while it reads copper losses in the S.C. test. Why?

2) O.C and S.C tests on a 5 KVA, 200/40v, 50 Hz a phase transformer gave the following results.

| | | | | |
|---|---|---|---|---|
| OC Test: | 200v | 1A | 100w | (on LV Side) |
| SC Test: | 15v | 10A | 25w | (with 200v winding short-circuited) |

1) Draw the equivalent circuits referred to primary and secondary sides
2) Calculate the approximate regulation of the transformer at full load 0.8pf lag and lead

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3) a) How can you predetermine efficiency and regulation for a given single phase transformer at any load without carrying out a load test?

b) How can you predetermine the load at which two losses i.e. iron losses and copper losses are equal? How can you estimate the efficiency at any load?

c) A 11000/230v, 150 KVA, 1 – phase, 50Hz transformer has a core loss of 1.4 KW and a full load copper loss of 1.6 KW. Determine

1) The KVA load for maximum efficiency and the value of maximum efficiency at unity pf?

2) The efficiency at half full-load, 0.8pf leading.

4) a) A100KVA, single phase transformer when working at UPF has an efficiency of 90% both at full load and half load determine the efficiency when it operates at UPF.

b) A 300 KVA single phase transformer is designed to have a resistance of 1.5% and its maximum efficiency at a load of 173.2KVA. Find its efficiency when supplying full load at 0.8 power factor lagging at normal voltage and frequency.

5) Describe a test for separation of iron losses in a transformer?

6) a) Describe the conditions required for the parallel operation of two single phase transformers.

b) Describe the process of load sharing by two single phase transformers, when connected in parallel with equal voltage ratios and also unequal voltage ratios

7 a) Explain the operation of an auto transformer with a neat sketch and deduce the saving of copper in auto transformer compared with a 2 winding transformer of the same rating?

b) A 5KVA, 2300/230 V two winding transformer is reconnected as a 2530/2300 V auto transformer and excited by a 2530V source. The transformer is loaded to the maximum extent that the rated currents of the windings are not exceeded. Calculate

i) Currents in different sections of the auto transformer

ii) KVA output

iii) VA transferred inductively and conductively from input to output

iv) Saving in copper as compared to a 2530/2300V two winding transformer for same output.

## *UNIT – III*

### Essay Questions

1) a) Explain different types of three phase connections.
b) Explain the construction of 3 phase transformer.

2) a) Explain Scott connection of transformer
b) 2 transformers are used in Scott connection to supply a 440V, 33KVA, balanced 2 phase load from a balanced 3 phase supply of 3300 V. Calculate

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i) The voltage and current rating of each coil

ii) The KVA rating of the main and teaser transformers.

3) Explain the applications and also the equivalent circuit of 3 winding transformers.

4) Explain the cause and characteristics of switching transients produced in transformer.

5) Explain with neat sketch the different arrangements of transformer taps and their applications

## UNIT-IV

### Essay Questions

1) a) Explain the principle of operation and working of polyphase induction motor.

b) Explain the terms: rotor emf ,rotor frequency, rotor reactance ,rotor current and power factor of a 3 phase induction motor and how they vary from stand still to the normal running condition of the motor?

2) a) A 4 pole, 3phase induction motor operates from a supply whose frequency is 50 Hz, calculate:

i) Speed at which the magnetic field of the stator is rotating

ii) Speed of the rotor when the slip is 0.04

iii) Frequency of the rotor currents when slip is 0.03

iv) Frequency of rotor currents at stand still.

3) The star connected rotor of an induction motor has a stand still impedance of (0.4+j4)Ω/phase and the rheostat impedance per phase is (6+j2)Ω. The motor has an induced emf of 80V between slip rings at stand still when connected to its normal supply voltage. Find rotor current

a) At stand still with rheostat in the circuit

b) When slip rings are short circuited and the motor is running with a slip of 3%

4) A 3 phase slip ring induction motor with star connected rotor has an induced emf 120V between slip rings at stand still with normal voltage applied to the stator. The rotor winding has a resistance per phase of 0.3 Ω and stand still leakage reactance per phase of 1.5Ω.Calculate

i) Rotor current per phase when running at 4% slip with slip rings short circuited

ii) Slip and rotor current per phase when the rotor is developing maximum torque

5) a) Derive the equation connecting rotor input and rotor copper loss and mechanical power developed in a 3 phase induction motor?

b) The power supplied to a 3 phase induction motor is 40 KW, and the corresponding stator copper losses are 1.5KW. Calculate the total mechanical power developed and the rotor copper loss when the slip is 0.04

6 a) Derive the equation for full load torque, maximum torque and starting torque in an induction motor in terms of the applied voltage and motor parameters? Distinguish between gross torque and shaft torque?

b) Derive the relation between full load toque and maximum torque in a 3 phase induction motor?

7) a) Explain with a neat sketch the typical torque slip characteristics of a 3 phase induction motor

b) A3 phase induction motor operating at rated voltage is driving its full load whose torque is independent of speed .If the line voltage drops to 90% of the rated value estimate the increase in rotor copper loss making suitable assumption.

8) a) Explain the constructions and characteristics of double cage and deep bar induction rotors with their applications.

b) The outer and inner cages of a double cage induction, motor have impedances equal to (0.04+j0.1) and (0.01+j0.4) ohm per phase respectively. Find the ratio of torques due to two cages a) At starting b) when running with slip 0.04.Neglect stator impedance.

9. a) Draw and explain the approximate equivalent of a double cage 3 phase induction motor

b) Explain the terms crawling and cogging as required to 3 phase induction motor

## *UNIT - V*

### Essay Questions

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1) a) Explain the construction of the circle diagram of a 3 phase induction motor

b) Draw the circle diagram for a 3.73 KW, 200V, 4 poles, 50Hz, and 3 phase star connected induction motor from the following data:

No-load: line voltage =200V, line current=5A, total input =350W
Blocked rotor: line voltage=100V, line current =26 A, total input=1700W
Estimate from the diagram for full load condition, the line current =5A,total input 1700W

Estimate from the diagram for full load condition, the line current, power factor and also the maximum torque in terms of full load torque .The rotor copper loss at stand still is half the total copper loss.

2) a) Explain no load and blocked rotor tests.

b) In a no load test on a 3 phase induction motor took 10 A and 450W with a line voltage of 110V.If stator resistance is 0.05 ohm/phase and friction and windage losses amount to 135W.Calculate the exciting conductance and substance per phase

3) Explain with sketch the types of starters used with squirrel cage induction motor and also slip ring induction motor?

4) a)Describe different methods by which speed control of induction motor is achieved ., i.e., the control from stator side as well as control from rotor side.

b) The rotor of 4 poles, 50 Hz, slip ring induction motor runs at 1440 rpm at full load. Calculate the external resistance per phase, which must be added to lower the speed to 1320 rpm, the torque being same as before.

5) Explain the working of a Scharge motor with a neat sketch.

6) Explain the principle of working and characteristics of an induction generator.

# 20.Tutorial Problems:

1 a) A 3000/200 V, 50 Hz, single-phase transformer has a net cross-sectional area of 150 $cm^2$ for the core. If the number of turns on the low voltage winding is 80, determine the number of turns on the high voltage winding, and the maximum value of flux density in the core.

b) A 4,600/230 V, 60 Hz, step down transformer has core dimensions of 76.2 mm x 111.8 mm. A maximum flux density of 0.930 tesla is to be used. Calculate the following assuming 9% loss of area due to stacking factor of laminations:

i) primary turns required I) Turns per Volt

iii) Secondary turns required and iv)is it actual transformation ratio

2) a) A 600 KVA, single phase transformer has an efficiency of 92% both at full load and half load at unity power factor. Determine the efficiency at 60% of full load at 0.8 power factor lag?

b) The maximum efficiency of a 100 KVA, single phase transformer is 98% and occurs at 80 KVA and UPF .If the leakage impedance of the transformer is 5%, find the voltage regulation of the transformer at rated KVA &at 0.8 power factor lagging?

3) Two similar 250 KVA, single phase transformers gave the following results when tested by the back-to-back method:

Mains wattmeter $W_1$=5.0 KW

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Primary series circuit wattmeter, $W_2$=7.5 KW at full load.

Find out the individual transformer efficiencies at 75% of full load and 0.8 pf lead

4) a) A 4 KVA, 200/400 V, 50Hz, single phase transformer gave the following test results:

No-load test: 200 V, 0.7 A, 60 w (LV side)
S.C test: 9 V, 6 A, 21.6 w (HV side)

Find the efficiency, and voltage regulation of the transformer on full-load at 0.9 pf lagging.

b) The O.C. and S.C test results of a 50 KVA, 3,300/400 V, 50Hz, single phase transformer are:

OC Test: 3,300 V, 4 A, 425 w
SC Test: 150v, 16A, 500w (Hv side)

Calculate the efficiency and regulation of the transformer on full-load and 0.8 pf lagging.

5. a) Two 100KVA, single phase transformers are to be operated in parallel. Transformer A has an internal impedance of 0.005+j0.04 pu. How they will share the following loads and what will be their operating power factors?

a) 180KW at 0.9 power factor lagging
b) 200KW at unity power factor

b) Two single phase transformers A&B of equal voltage ratios running in parallel supply a load of 1000A at 0.8 power factor lag. The equivalent impedance of the two transformers are 2+j3 Ω and 2.5+j5 Ω respectively. Calculate the current supplied by each transformer and the ratio of KW outputs of the transformers?

6. a) Two single phase transformers A&B are joined in parallel to the same load. Determine the current delivered by each transformer given that the open circuit emf is 6600V for A and 6400V for B.The load impedance is 8+j6Ω.

b) Two single phase transformers one of 100KVA and the other of 50KVA are connected in parallel to the same bus bars on the 1000V and 950V respectively. The transformer resistances are 2 and 2.5 percent respectively and their reactance's 8 and 6 percent respectively. Calculate no load circulating current in the secondaries.

7.A 6600/400/110V, star/star/mesh, 3 phase transformer has a magnetizing current of 5.5A and balanced 3 phase loads of 100KVA at 0.8 lagging power factor on the secondary and 200KVA at 0.5 leading power factor on tertiary. Neglect losses. Find the primary current, KVA and power factor.

8) a) A 4 pole 50 Hz, 7.46 KW motor operating at rated voltage and frequency has a starting torque of 160% and a maximum torque of 200% of full load torque. Determine I)full load speed ii)speed at the maximum torque.

b) A 50 Hz, 8 pole induction motor has a full load slip of 2% .The rotor resistance is 0.001Ohm per phase and it's stand still reactance is 0.005Ohm/phase find the ratio of max to full load torque and the speed at which max torque appears.

9) a) A 18.65KW, 4 pole, 50Hz,3 phase induction motor has friction and wind age losses of 2.5% of the Output and it's full load slip is 4%.Calculate rotor copper loss, rotor input, output torque, gross torque.

b) A 20HP, 4 pole, 50Hz, 3 phase induction motor has friction and windage losses of 5% of the Output and it's full load slip is 4%. Calculate rotor copper loss, rotor input, output torque, and gross torque

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10) a) For a 3 phase slip ring induction motor ,the maximum torque is 2.5 times the full load torque and the starting torque at full applied voltage is 1.5 times the full load torque. Determine the percentage reduction in rotor circuit resistance needed to get a full load slip of 3%. Neglect stator impedance.

b) A 20HP, 4 pole, 50Hz, 3 phase induction motor develops a maximum torque of 162.8 Nm at 1365 rpm .The resistance of the star connected rotor is 0.2 ohm/phase. Calculate the value of resistance that must be inserted in series with each rotor phase to produce a starting torque equal to half the maximum torque.

11)A 440V, 4 pole, 50Hz, 3 phase star connected induction motor has a full load speed of 1425 rpm .The rotor has an impedance of 0.4+j4 ohm /phase and rotor /stator turn ratio of 0.8. Calculate I)full load developed torque ii) rotor current and rotor copper loss at full load iii)full load power output if windage and friction losses amount to 500W.iv)Maximum torque and the speed at which it occurs v)full voltage starting current vi) starting torque.

12) The rotor resistance and stand still reactance of a 3 phase induction motor are respectively 0.015 ohm and 0.09 ohm per phase .At normal voltage full load slip is 3%. Estimate the percentage reduction in stator voltage to develop full load torque at half full load speed. Also calculate the power factor.

13) Construct the circle diagram for a 5.6KW, 400V, 3 phase 50Hz,and slip ring induction motor from the following data:

No load ratings: 400V, 6A,cosΦ=0.087
Short circuit test: 100V, 12A, 720 W
The ratio of primary to secondary turns=2.6 ohm
Resistance of stator per phase is 0.67 ohm and of the rotor is 0.185 ohm. Calculate

- i) Full load current ii) Full load slip iii) Full load power factor
- iv) Ratio of maximum torque to full load torque
- v) Maximum power

14) a) Find the percentage tapping required on an auto transformer for a squirrel cage induction motor to start the motor against ¼ of full load torque .The short circuit current on normal voltage is 4 times the full load current and full load slip is 3%?

b) A 20 hp (14,92 KW), 400 V, 950 rpm, 3 phase, 50 Hz, 6 pole cage motor with 400V applied takes 6 times full load current at stand still and develops 1.8 times the full load torque. The full load current is 30 A

- i) What voltage must be applied to produce full load torque at starting?
- ii) What current will this voltage produce?
- iii) If the voltage is obtained by an autotransformer what will be the line current?
- iv) If the starting current is limited to full load current by an autotransformer what will be the starting torque as a percentage of full load torque? Ignore the magnetizing current and stator impedance drop.

15) Construct the circle diagram of a 7.46 KW, 200V, 50Hz 3 phase slip ring induction motor with a star connected stator and rotor, a winding ratio of unity, a stator resistance of 0.38 ohm/phase and a rotor resistance of 0.24 ohm per phase, the following are test readings:

No-load 200V, 7.7 A, cosΦ=0.195

Short circuit: 100V, 47.6 A, cosΦ=0.454 Find the i) Starting torque ii) Maximum torque ii) Maximum power factor iv) Slip for maximum torque v) Maximum output.

16) Calculate the steps in a 5 step rotor resistance starter for a 3 phase induction motor. The slip at the maximum starting current is 2% with slip ring short circuited and the resistance per rotor phase is 0.02 oh

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17)a) A squirrel cage induction motor when started by means of a star/delta starter takes 180% of full load line current and develops 35% of full load torque at starting. Calculate the starting torque and current in terms of full load values, if an autotransformer with 75% tapping were employed.

b) A 10 hp motor when started at normal voltage with a star /delta switch in star position is found to take an initial current of 1.7 times the full load current and give initial starting torque of 35% of full load torque. Explain what happens when the motor started under the following conditions.

i) With an auto transformer giving 60% of normal voltage

ii) With resistance in series with the stator reducing the voltage to 60% of the normal.

Calculate in each case the value of starting current and torque in terms of the corresponding quantities at full load.

# 21.Known Gaps:

# 22.Discussion Topics:

1. Materials used for the construction of Transformer
2.Types of Transformers and their Applications
3. Poly Phase Transformers and their applications in power systems
4. Poly Phase Induction Motors and their applications
5. Elimination of Cogging and Crawling in Induction Motors
6. Applications of Induction Generators in Present Power Generation Schemes.

# 23.References,Journals,Websites & E – Links:

# 24.Quality Measurement Sheets:

# 25.Student List:

# 26.Groupwise Student List for Discussion Topics:

## Group -1:

## Group -2:

## Group -3:

## Group -4:

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**Group -5:**

**Group -6:**

**Group -7:**

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