University of Global Village (UGV), Barishal

Electrical Machine-I

Content of Theory Course

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Program: B.Sc. in EEE

Basic Course Information

Course Title	Electrical Machine - I
Course Code	EEE 0713-2101
Credits	03
CIE Marks	90
SEE Marks	60
Exam Hours	2 hours (Mid Exam) 3 hours (Semester Final Exam)
Level	3rd Semester
Academic Session	Winter 2025

Continuous Assessment Plan

Quizzes

Altogether 4 quizzes may be taken during the semester, 2 quizzes will be taken for midterm and 2 quizzes will be taken for final term.

Assignments

Altogether 4 assignments may be taken during the semester, 2 assignments will be taken for midterm and 2 assignments will be taken for final term.

Presentation

The students will have to form a group of maximum 3 members. The topic of the presentation will be given to each group and students will have to do the group presentation on the given topic.

Assessment Pattern

CIE – Continuous Internal Evaluation (90 Marks)

Bloom's Category Marks (out of 90)	Mid Exam (45)	Assignment (15)	Quiz (15)	Attendance & External Participation in Curricular/Co-Curricular Activities (15)
Remember	05		05	
Understand	05	05	05	
Apply	10		05	15
Analyze	10			
Evaluate	10			
Create	05	05		

Assessment Pattern

SEE – Semester End Examination (60 Marks)

Bloom's Category	Final Examination
Remember	15
Understand	10
Apply	10
Analyze	10
Evaluate	10
Create	05

Course Learning Outcomes (CLOs)

CLO 01

Explain the aspects of construction, principles of operations and applications of electrical machines

CLO 02

Execute performance analysis of electrical machines.

CLO 03

Design electrical machines subject to specific requirements.

CLO 04

Conduct experiments for analysis of single and three phase electric machine performance.

SYNOPSIS / RATIONALE

This course covers common electrical machines such as DC motors, DC generators and transformers, which find widespread applications in electric power generation, transmission, distribution, and energy conversion. This course will teach the students about construction, working principles, application and design aspects of these electrical machines.

By completing this course, students will:

- Develop a strong theoretical and practical foundation in electrical machines.
- Understand the working principles, construction, and operation of DC machines and transformers.
- Analyze machine characteristics and performance under various loading conditions.
- Prepare for advanced studies in power systems, renewable energy, and industrial automation.

COURSE OBJECTIVES

- To be able to apprise the basic operating principle of Electrical machines like DC motor, DC generator and Transformer etc.
- To demonstrate the performance indicating parameters of electrical machines and learn to manipulate them.
- Equip students to evaluate and design electrical machine systems for optimized efficiency, performance, and reliability in modern engineering applications.

These objectives aim to prepare students for advanced studies and practical roles in electrical engineering, focusing on power systems, automation, and electromechanical energy conversion.

COURSE SUMMARY

Serial No.	Course Content	Hours
1.	Basics of AC/DC, Definition, History, Importance of transformer, Operation, Types, Construction, E.M.F Equation.	**05**
2.	Transformation Ratio, Impedance & Power of Ideal Transformer, Equivalent circuit, losses, Magnetizing current, Transformer ratings Open & sort circuit test, Phasor diagram, voltage regulation, maximum efficiency, All day efficiency.	**15**
3.	Parallel operation, center tap transformer, Types, V-V connection, T-T connection, CT, PT, connection diagram, inrush current etc. Basics of 3-phase transformers, Connection of 3-phase transformers	**15**
4.	Definition, types, Constriction, Essential parts, winding types, EMF equation of DC generator.	**05**

COURSE SUMMARY

Serial No.	Course Content	Hours
5.	Hysteresis loss, Eddy Current loss, cupper loss, magnetic loss, mechanical loss, stray loss, constant loss. Power stage of dc generator, efficiency, condition for maximum efficiency. Demagnetizing, cross-magnetizing effect, separately excited Generator, No-load Curve for Self-excited Generator, Critical Resistance, Critical Speed., Voltage Buildup of a Shunt Generator, Other factors Affecting Voltage Building of a D.C. Generator, External Characteristic, Voltage Regulation, Internal or Total Characteristic, Series Generator, Compound-wound Generator.	**10**
6.	Uses of D.C. Generators Motor Principle, Comparison of generator and motor action, EMF, Condition for maximum power, Torque, Speed. Series, shunt, compound motor, performance curves, losses, efficiency, power stages, Factors controlling motor speed, Rheostatic control method, Electric braking, Stater: Shunt, three-point, four-point, Thyristor controller starters.	**10**

COURSE PLAN MAPPED WITH CLO

Week No.	Topics	Teaching-Learning Strategy	Assessment Strategy	Alignment to CLO
1.	Working Principle of Transformer, Elementary Theory of an Ideal Transformer, Construction of Transformer, Core type Transformer, Shell type Transformer	Lecture, Multimedia, Group Discussion	Feedback, Q&A	CLO 1
2.	Equation of Induced Emf in a Single Phase Transformer, Voltage Transformation Ratio,Transformer on no load, Phasor diagram in no load condition	Lecture, Multimedia, Practical Example	Feedback, Q&A	CLO 1, CLO 2
3.	Transformer on load, Phasor diagram of Transformer on different types of load, Transformer with Winding Resistance but no Magnetic Leakage, Transformer with Resistance and Leakage Reactance	Lecture, Multimedia, Practical Example	Feedback, Q&A Assignment	CLO 1, CLO 2, CLO 3

COURSE PLAN MAPPED WITH CLO

Week No.	Topics	Teaching-Learning Strategy	Assessment Strategy	Alignment to CLO
4.	Equivalent Circuit of Transformer, Open circuit or No-load Test, Separation of Core Losses, Short-Circuit or Impedance Test, Transformer Rating.	Lecture, Multimedia, Group Discussion	Feedback, Q&A Quiz #1	CLO 2, CLO 3
5.	Regulation of a Transformer, Percentage Resistance, Reactance and Impedance,Efficiency of a Transformer, Condition for Maximum Efficiency.	Lecture, Multimedia, Practical Example	Feedback, Q&A	CLO 3
6.	Mathematical problems on Transformer	Practice Problem	Class work	CLO 4
7.	Mathematical problems on Transformer	Practice Problem	Class work	CLO 4

COURSE PLAN MAPPED WITH CLO

Week No.	Topics	Teaching-Learning Strategy	Assessment Strategy	Alignment to CLO
8.	Generator Principle, Simple Loop Generator and EMF Equation of a Simple Loop Generator, Parts of generator.	Lecture, Multimedia, Group Discussion	Feedback, Q&A ,Quiz #2	CLO 1, CLO 2
9.	Iron Loss in Armature, Total loss in a DC Generator, Stray Losses, Constant or Standing Losses,Power Stages, Efficiency equation, Condition for Maximum Efficiency	Lecture, Multimedia, Practical Example	Feedback, Q&A Assignment	CLO 2, CLO 3
10.	Armature Reaction, Demagnetising and Cross magnetising conductors, Compensating Windings, No. of Compensating Windings, Interpoles or Compoles	Lecture, Multimedia, Practical Example	Feedback, Q&A	CLO 2, CLO 3, CLO 4

COURSE PLAN MAPPED WITH CLO

Week No.	Topics	Teaching-Learning Strategy	Assessment Strategy	Alignment to CLO
11.	Paralleling DC Generator, Load Sharing, Procedure for Paralleling DC Generators, Types of DC Generators. Characteristics of Separately excited DC Generator, No load Curve for Self-excited DC Generator	Lecture, Multimedia Group Discussion	Feedback, Q&A Assignment	CLO 3, CLO 4
12.	How to find Critical Resistance R? How to draw O.C.C. at Different speeds? Critical Speed,Voltage Build up of a Shunt Generator, Condition for Build up of a Shunt Generator, Other factors affecting Voltage Building of a DC Generator	Lecture, Multimedia Practical Example	Feedback, Q&A ,Quiz #3	CLO 3, CLO 4
13.	Mathematical Problems on DC Generator	Lecture, Multimedia	Feedback, Q&A	CLO 4

COURSE PLAN MAPPED WITH CLO

Week No.	Topics	Teaching-Learning Strategy	Assessment Strategy	Alignment to CLO
14.	Basic Principle of Motor, Comparison of Generator and Motor Action,Back emf,Conditions for Maximum Power, Armature Torque of a Motor, Shaft Torque, Speed of a DC Motor, Speed Regulation Torque and Speed of a DC Motor	Lecture, Multimedia, Group Discussion	Feedback, Q&A Assignment	CLO 1, CLO 2
15.	Characteristics of Series Motor, Characteristics of Shunt Motor, Compound Motor,Factors Controlling Motor Speed, Speed Control of Shunt Motor, Speed Control of Series Motor	Lecture, Multimedia, Practical Example	Feedback, Q&A	CLO 3, CLO 4
16.	Mathematical Problems on DC Motor	Lecture, Multimedia,	Feedback, Q&A ,Quiz #4	CLO 4
17.	Mathematical Problems on DC Motor	Lecture, Multimedia,	Class work	CLO 4

Study Materials

Reference Books

Performance & Design of AC machines
M.G. Say

Electrical Machinery
P.S. Bhimbra

Electric Machines
Nagrath I J and Kothari D P

Lecture Slides

Corresponding lecture slide will be provided to students within beginning of the course.

Multimedia

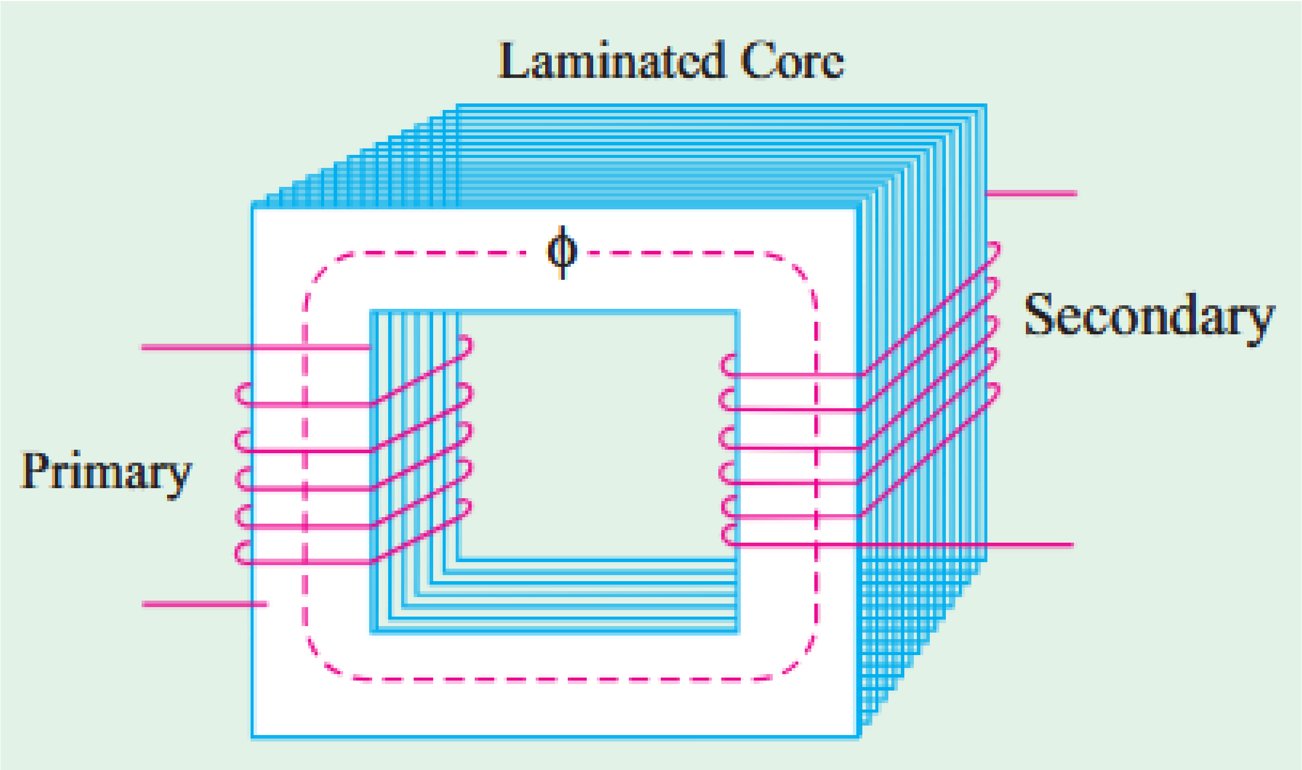
Associated multimedia files/ links will be provided for better understanding

WEEK 01

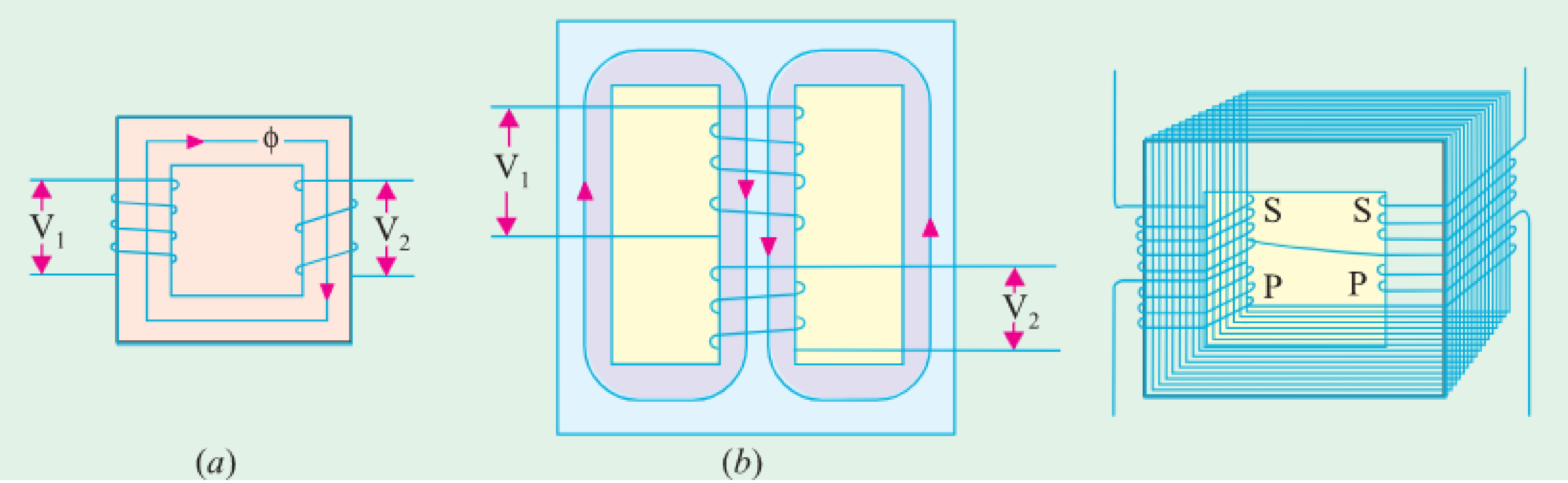
PAGE 18-23

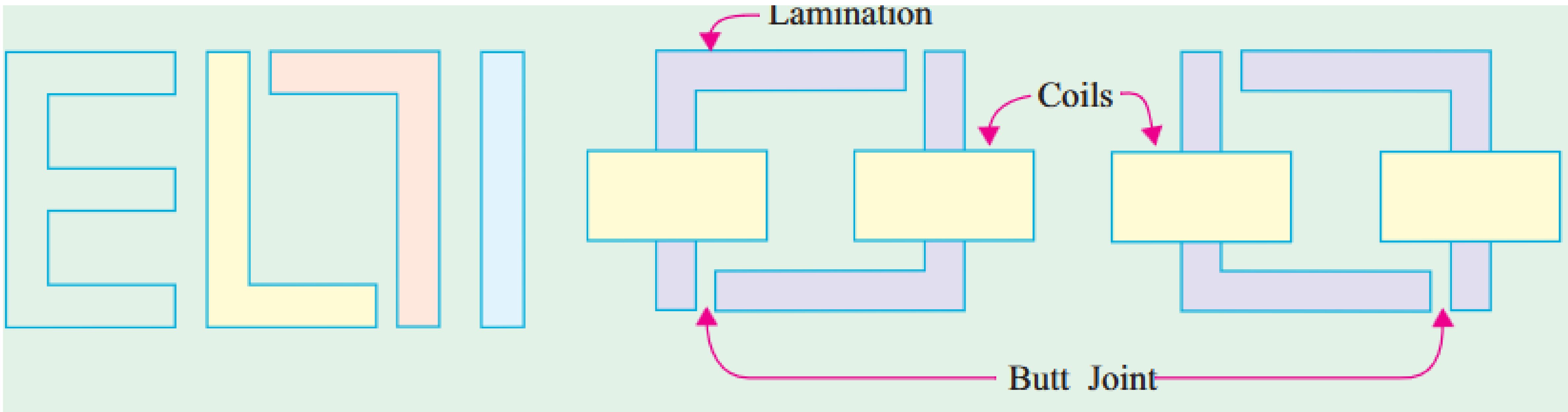
Working Principle of a Transformer

A transformer is a static (or stationary) piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. It can raise or lower the voltage in a circuit but with a corresponding decrease or increase in current. The physical basis of a transformer is mutual induction between two circuits linked by a common magnetic flux. In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance as shown in Figure.

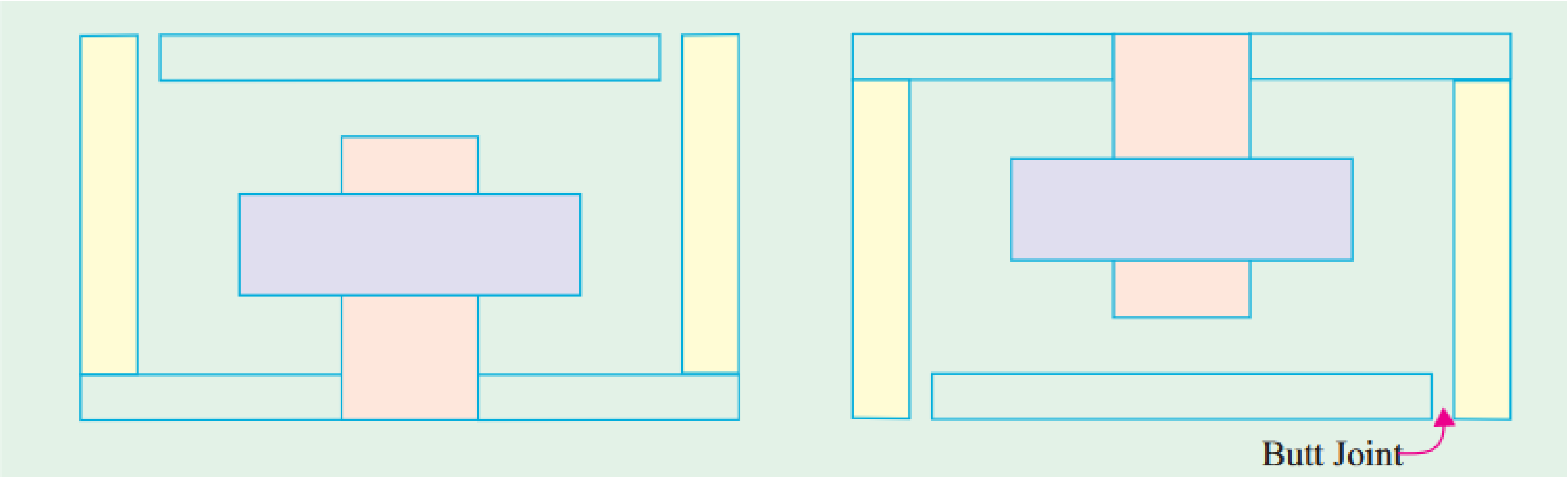


Transformer Construction



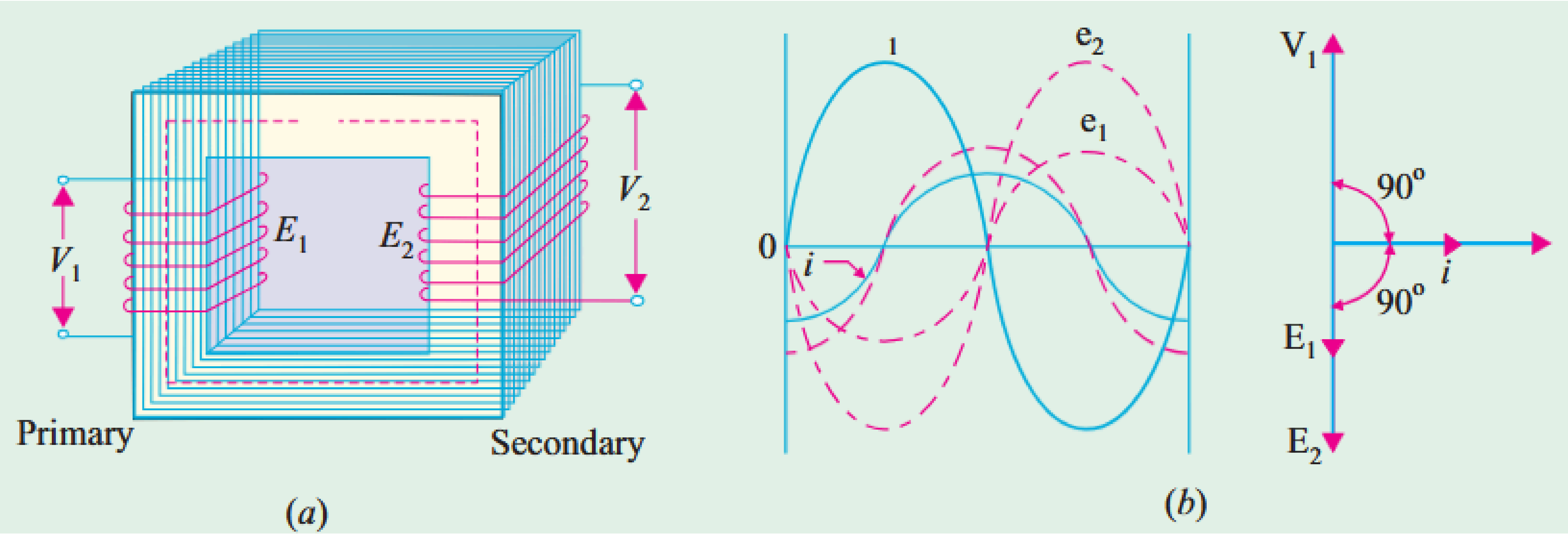


Transformer Construction



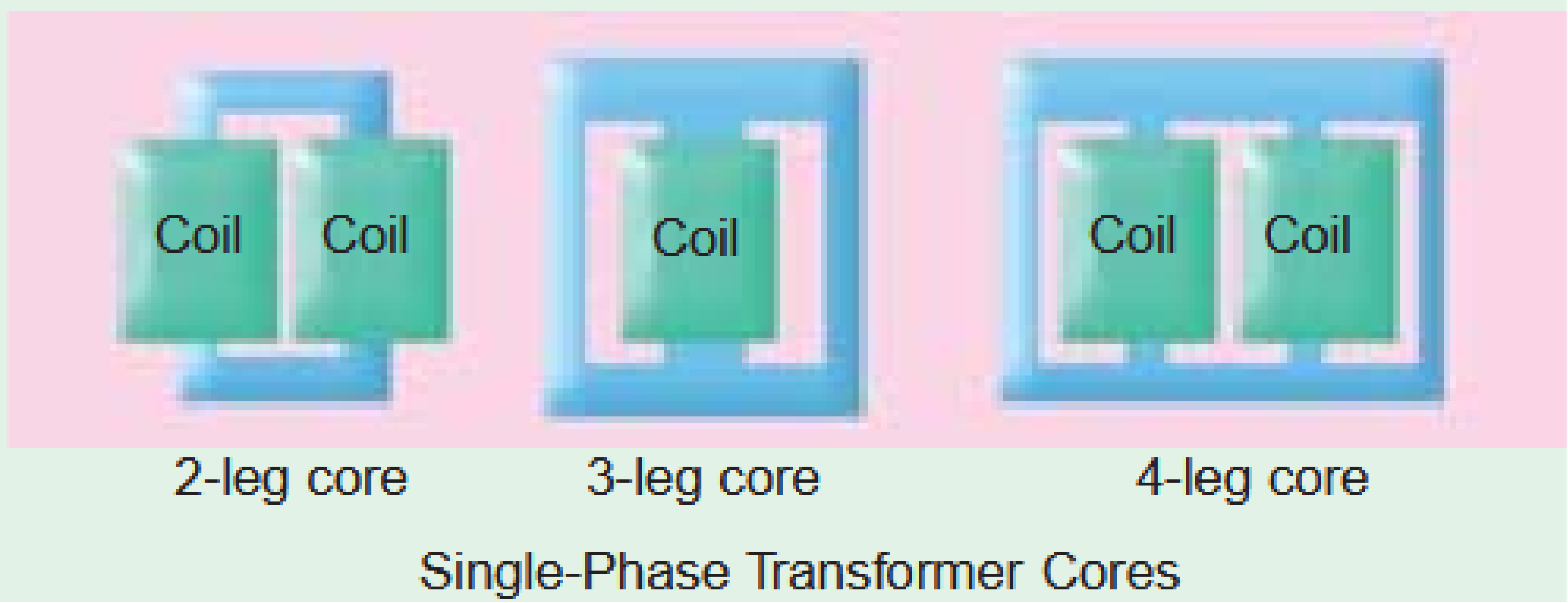
Theory of an Ideal Transformer

An ideal transformer is one which has no losses i.e. its windings have no ohmic resistance, there is no magnetic leakage and hence which has no I2R and core losses. In other words, an ideal transformer consists of two purely inductive coils wound on a loss-free core. It may, however, be noted that it is impossible to realize such a transformer in practice, yet for convenience, we will start with such a trans-former and step by step approach an actual transformer.

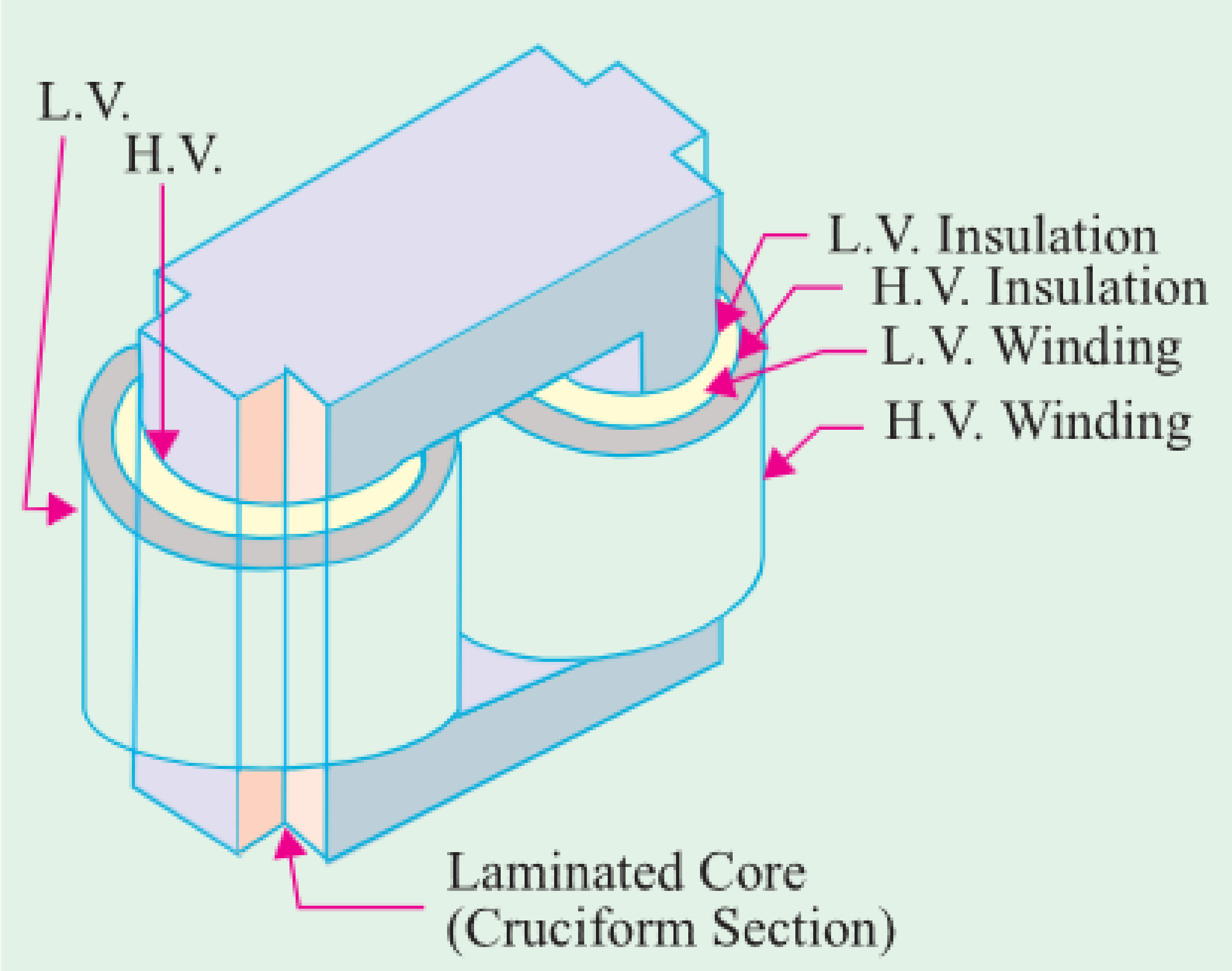


Core-type Transformer

The coils used are form-wound and are of the cylindrical type. The general form of these coils may be circular or oval or rectangular. In small size core-type transformers, a simple rectangular core is used with cylindrical coils which are either circular or rectangular in form. But for large-size core-type transformers, round

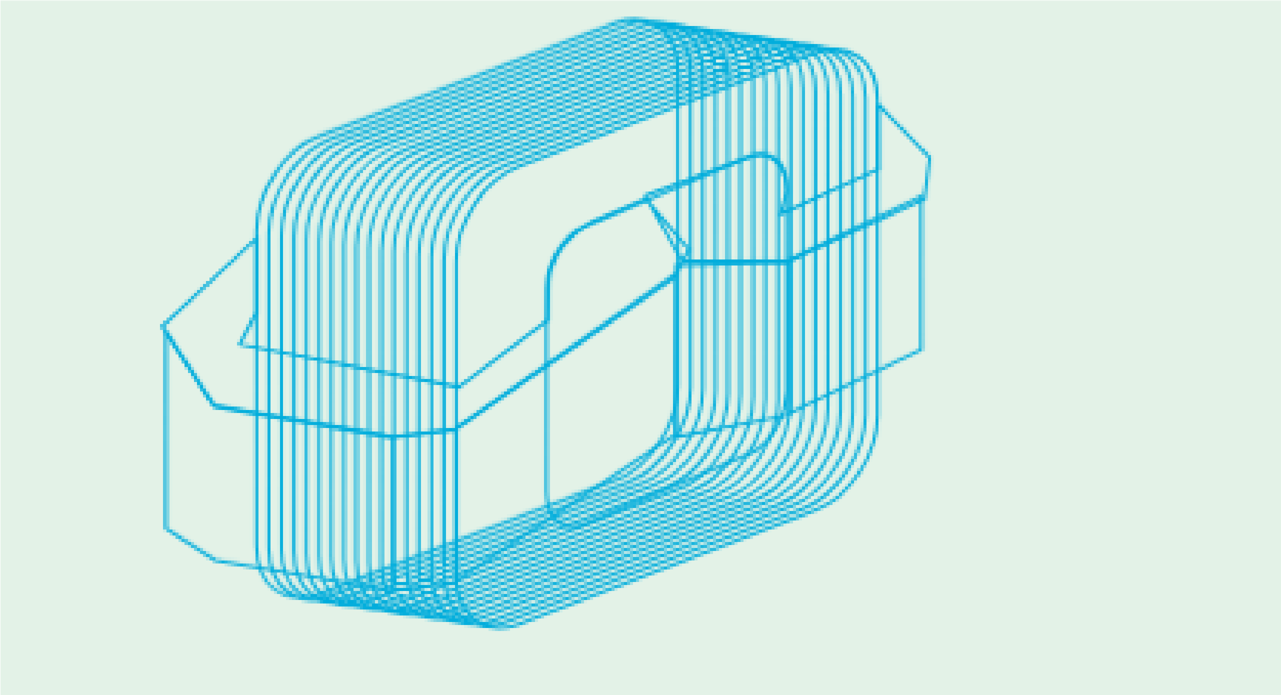


or circular cylindrical coils are used which are so wound as to fit over a cruciform core section as shown in Fig. The circular cylindrical coils are used in most of the core-type transformers because of their mechanical strength. Such cylindrical coils are wound in helical layers with the different layers insulated from each other by paper, cloth, micarta board or cooling ducts.

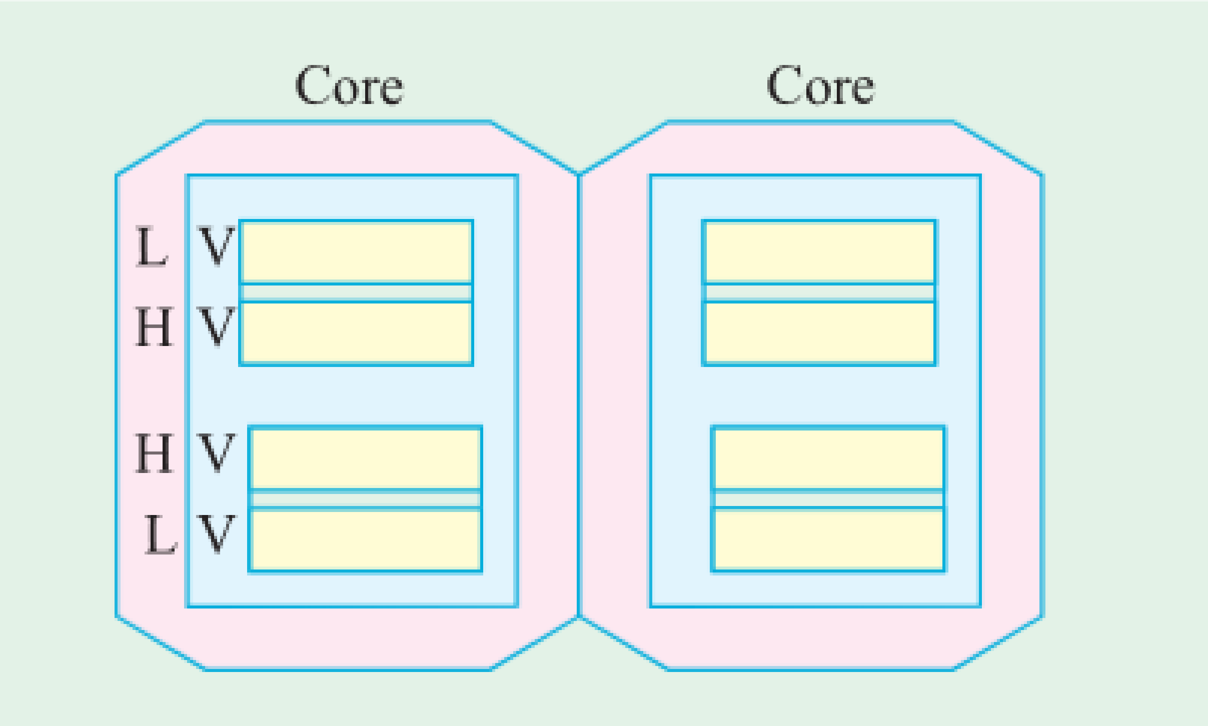


Shell-type Transformer

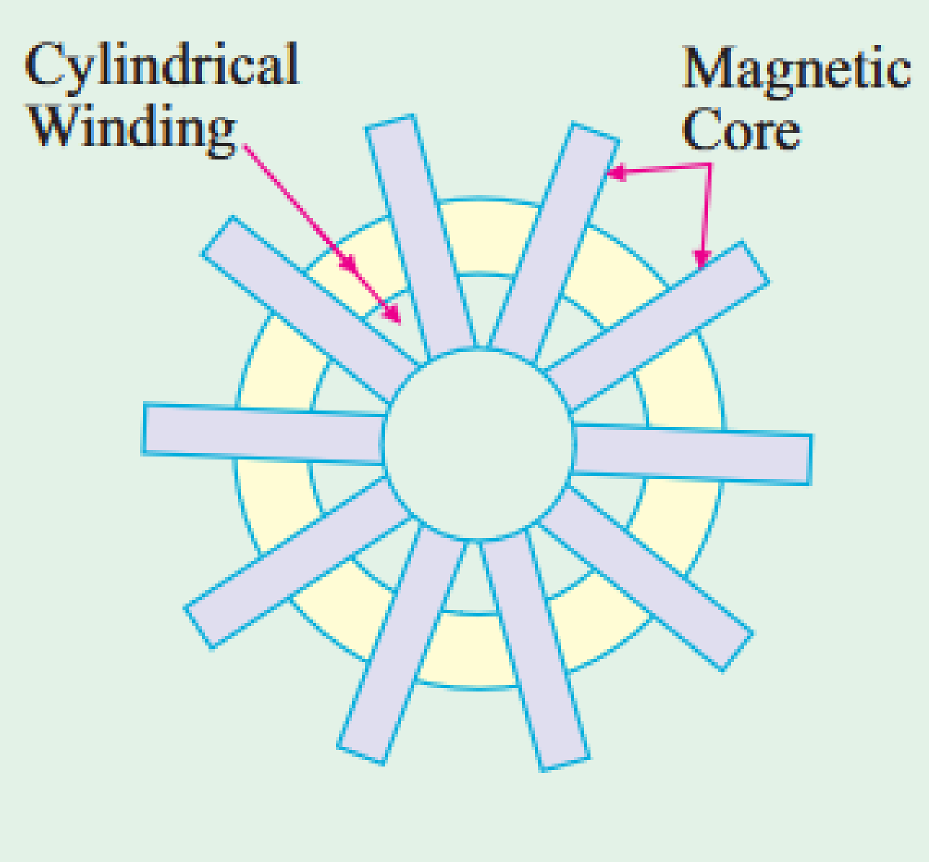
In these case also, the coils are form-would but are multi-layer disc type usually wound in the form of pancakes. The different layers of such multi-layer discs are insulated from each other by paper. The complete winding consists of stacked discs with insulation space between the coils–the spaces forming horizontal cooling and insulating ducts.



(*a*)



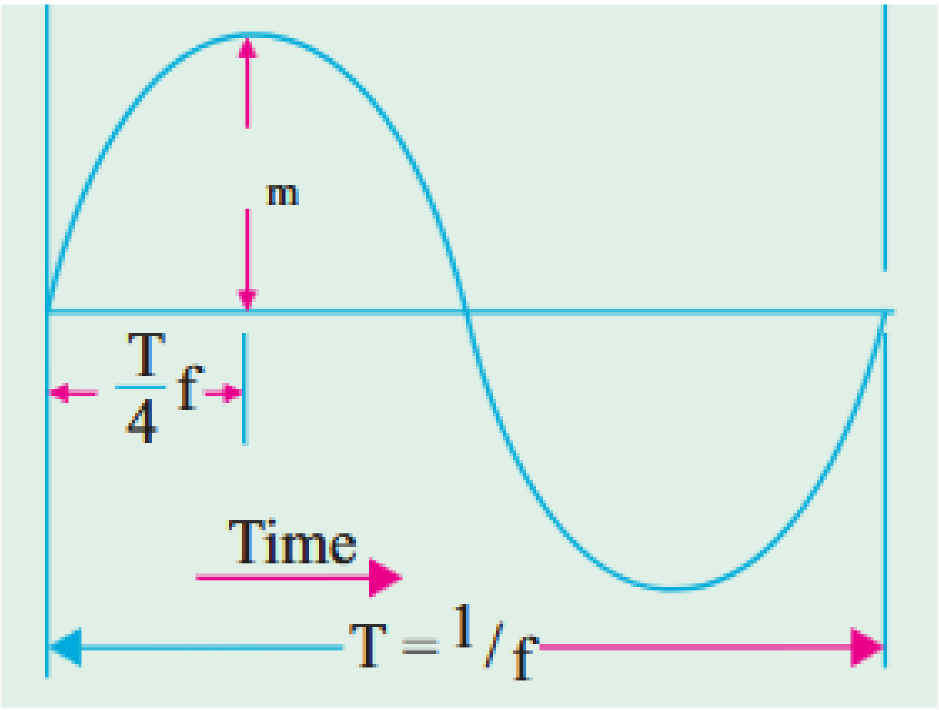
(*b*)



WEEK 02

PAGE 25-29

EMF Equation of a Transformer



Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

Φ_m = Maximum flux in core in webers

$= B_m \times A$

f = Frequency of a.c. input in Hz

As shown in Fig. flux increases from its zero value to maximum value Φ_m in one quarter of the cycle *i.e.* in $1/4f$ second.

$$\therefore \quad \text{Average rate of change of flux} = \frac{\Phi_m}{1/4f}$$

$$= 4f\Phi_m \text{ Wb/s or volt}$$

Now, rate of change of flux per turn means induced e.m.f. in volts.

$$\therefore \quad \text{Average e.m.f./turn} = 4f\Phi_m \text{ volt}$$

If flux Φ varies *sinusoidally*, then r.m.s. value of induced e.m.f. is obtained by multiplying the average value with form factor.

$$\text{Form factor} = \frac{\text{r.m.s. value}}{\text{average value}} = 1.11$$

$$\therefore \quad \text{r.m.s. value of e.m.f./turn} = 1.11 \times 4f\Phi_m = 4.44f\Phi_m \text{ volt}$$

Now, r.m.s. value of the induced e.m.f. in the whole of primary winding

$$= (\text{induced e.m.f/turn}) \times \text{No. of primary turns}$$

$$E_1 = 4.44fN_1\Phi_m = 4.44fN_1B_mA \quad \text{...}(i)$$

EMF Equation of a Transformer

Similarly, r.m.s. value of the e.m.f. induced in secondary is,

$$E_2 = 4.44 f N_2 \Phi_m = 4.44 f N_2 B_m A \qquad ...(ii)$$

It is seen from (*i*) and (*ii*) that $E_1/N_1 = E_2/N_2 = 4.44 f \Phi_m$. It means that e.m.f./turn is the *same* in both the primary and secondary windings.

In an ideal transformer on no-load, $V_1 = E_1$ and $E_2 = V_2$ where V_2 is the terminal voltage

Voltage Transformation Ratio (K)

From equations (*i*) and (*ii*), we get

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

This constant K is known as voltage transformation atio.

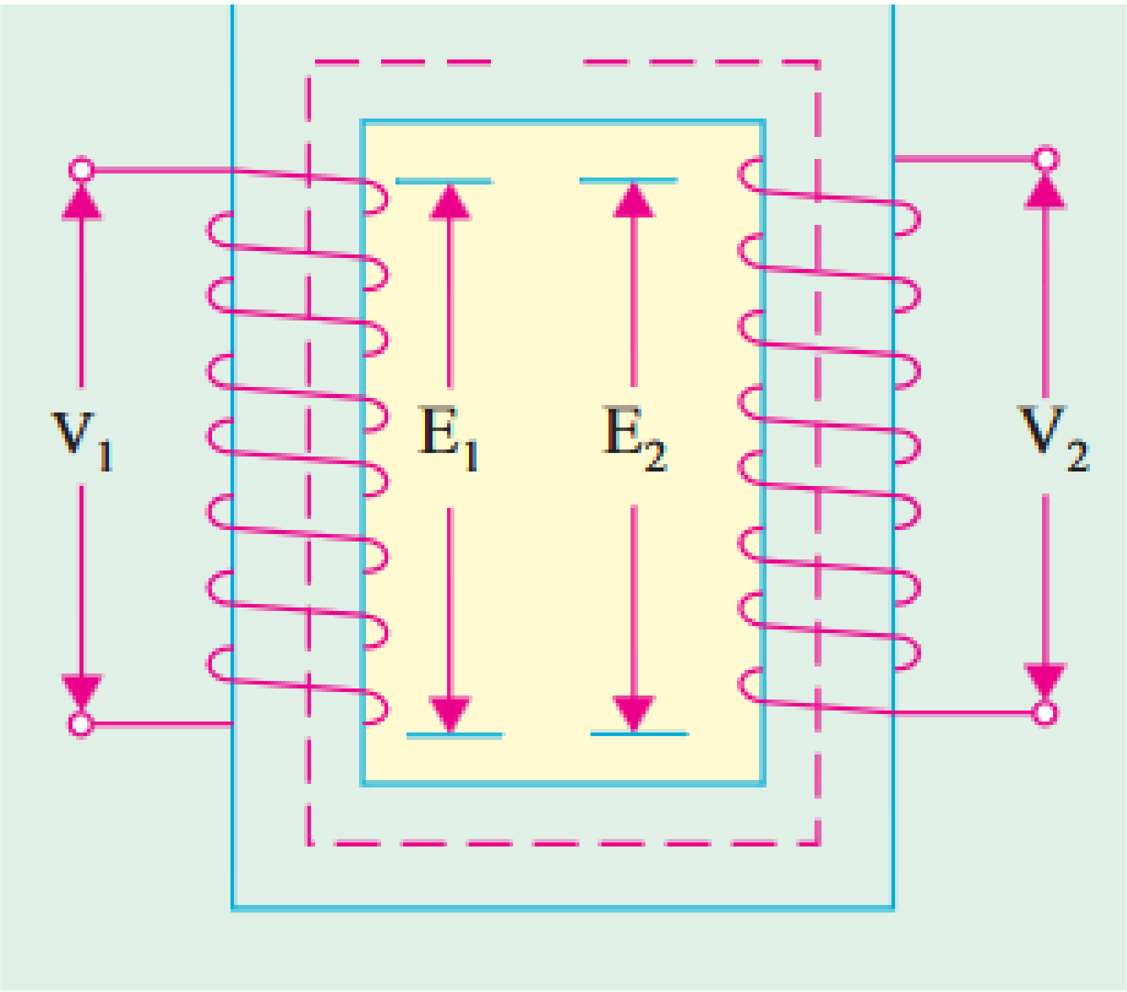
(*i*) If $N_2 > N_1$ *i.e.* $K > 1$, then transformer is called ***step-up*** ransformer.

(*ii*) If $N_2 < N_1$ *i.e.* $K < 1$, then transformer is known as ***tep-down*** transformer.

Again, for an *ideal* transformer, input VA = output VA.

$$V_1 I_1 = V_2 I_2 \text{ or } \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$$

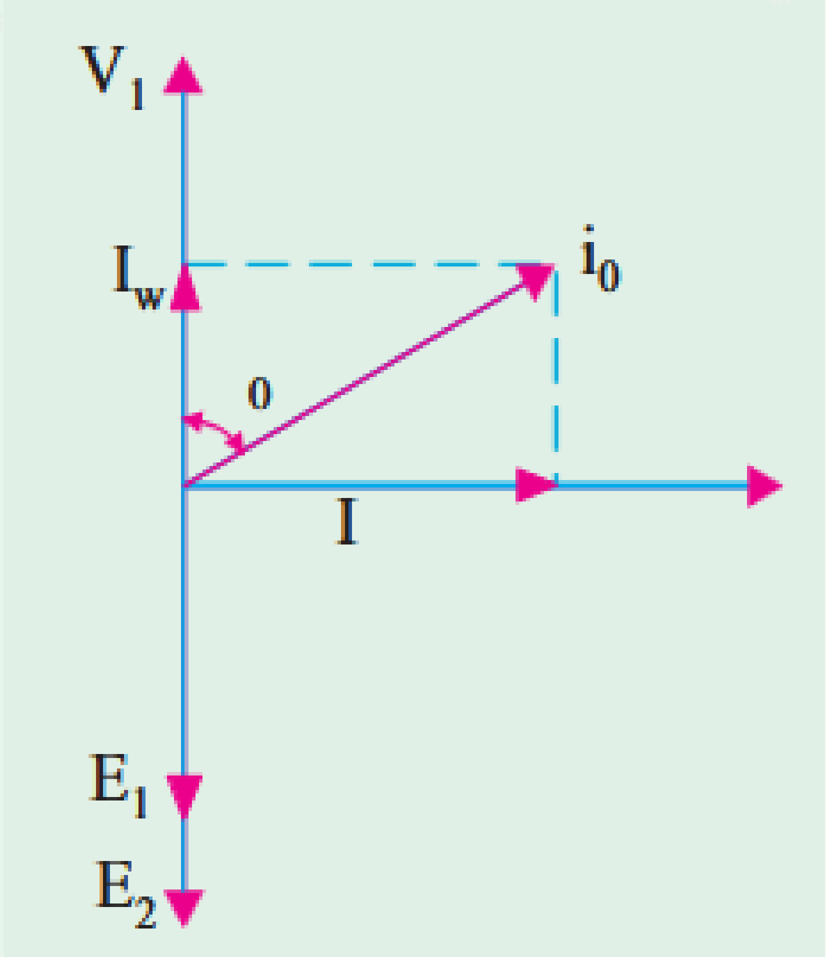
Hence, currents are in the inverse ratio of the (voltage) transformation ratio.



Transformer on No-load

Even when the transformer is on no-load, the primary input current is not wholly reactive. The primary input current under no-load conditions has to supply *(i)* iron losses in the core *i.e.* hysteresis loss and eddy current loss and *(ii)* a very small amount of copper loss in primary (there being no Cu loss in secondary as it is open). Hence, the no-load primary input current I_0 is not at 90° behind V_1 but lags it by an angle $\phi_0 < 90°$. No-load input power

$$W_0 = V_1 I_0 \cos \phi_0$$



where $\cos \phi_0$ is primary power factor under no-load conditions. No-load condition of an actual transformer is shown vectorially in Fig.

As seen from Fig. primary current I_0 has two components :

(i) One in phase with V_1. This is known as ***active*** or ***working*** or ***iron*** loss component I_w because it mainly supplies the iron loss plus small quantity of primary Cu loss.

$$I_w = I_0 \cos \phi_0$$

(ii) The other component is in quadrature with V_1 and is known as ***magnetising*** component I_μ because its function is to sustain the alternating flux in the core. It is wattless.

$$I_\mu = I_0 \sin \phi_0$$

Transformer on No-load

Obviously, I_0 is the vector sum of I_w and I_μ, hence $I_0 = (I_\mu^2 + I_\omega^2)$.

The following points should be noted carefully :

1. The no-load primary current I_0 is very small as compared to the full-load primary current. It is about 1 per cent of the full-load current.

2. Owing to the fact that the permeability of the core varies with the instantaneous value of the exciting current, the wave of the exciting or magnetising current is not truly sinusoidal. As such it should not be represented by a vector because only sinusoidally varying quantities are represented by rotating vectors. But, in practice, it makes no appreciable difference.

3. As I_0 is very small, the no-load primary Cu loss is negligibly small which means ***that no-load primary input is practically equal to the iron loss in the transformer***.

4. As it is principally the core-loss which is responsible for shift in the current vector, angle ϕ_0 is known as ***hysteresis angle of advance***.

WEEK 03

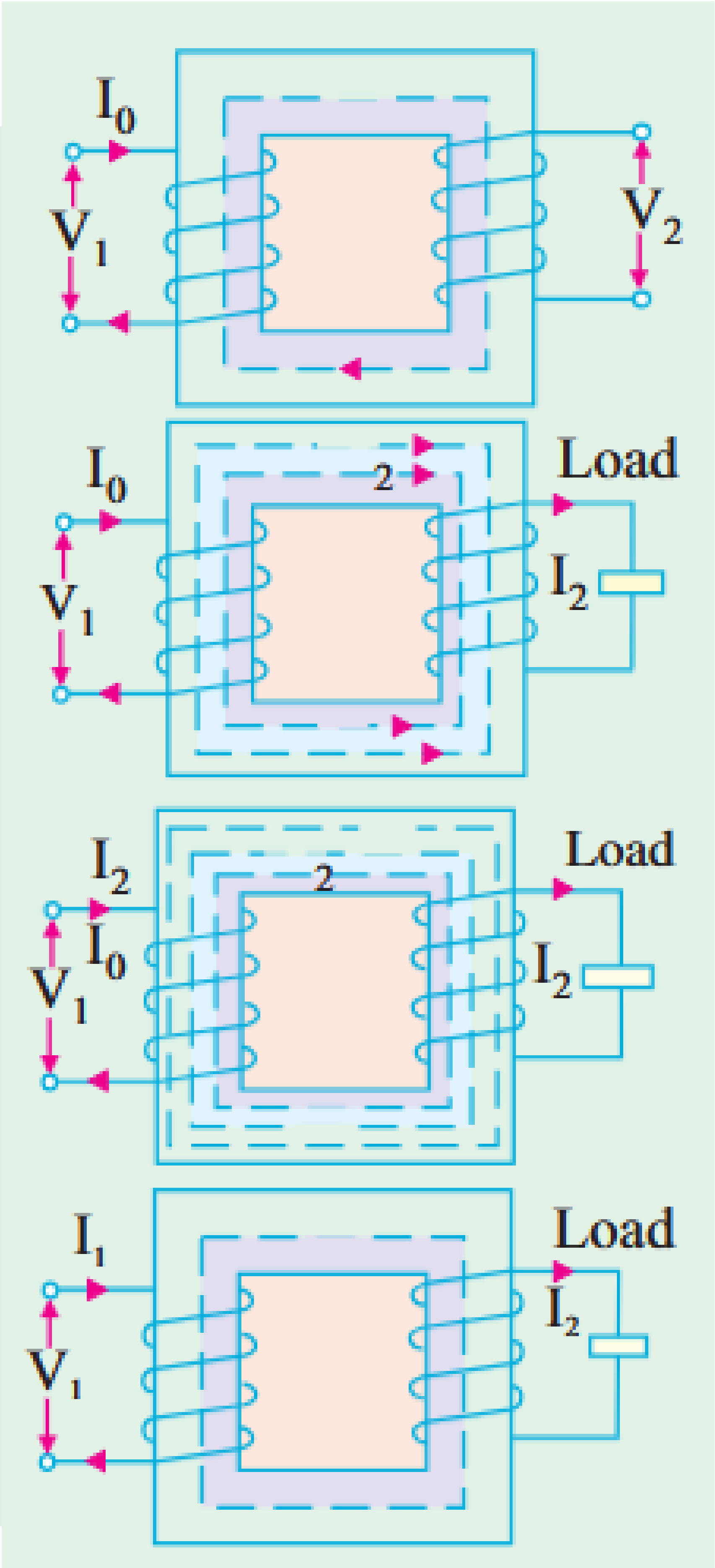
PAGE 31-42

Transformer on load

When the secondary is loaded, the secondary current I_2 is set up. The magnitude and phase of I_2 with respect to V_2 is determined by the characteristics of the load. Current I_2 is in phase with V_2 if load is non-inductive, it lags if load is inductive and it leads if load is capacitive.

The secondary current sets up its own m.m.f. ($=N_2I_2$) and hence its own flux Φ_2 which is in opposition to the main primary flux Φ which is due to I_0. The secondary ampere-turns $N_2\ I_2$ are known as ***demagnetising*** amp-turns. The opposing secondary flux Φ_2 weakens the primary flux Φ momentarily, hence primary back e.m.f. E_1 tends to be reduced. For a moment V_1 gains the upper hand over E_1 and hence causes more current to flow in primary.

Let the additional primary current be I_2'. It is known as ***load component of primary current***. This current is antiphase with I_2'. The additional primary m.m.f. $N_1\ I_2$ sets up its own flux Φ_2' which is in opposition to Φ_2 (but is in the same direction as Φ) and is equal to it in magnitude. Hence, the two cancel each other out. So, we find that the magnetic effects of secondary current I_2 are immediately neutralized by the additional primary current I_2' which is brought into existence exactly at the same instant as I_2. The whole process is illustrated in Fig.

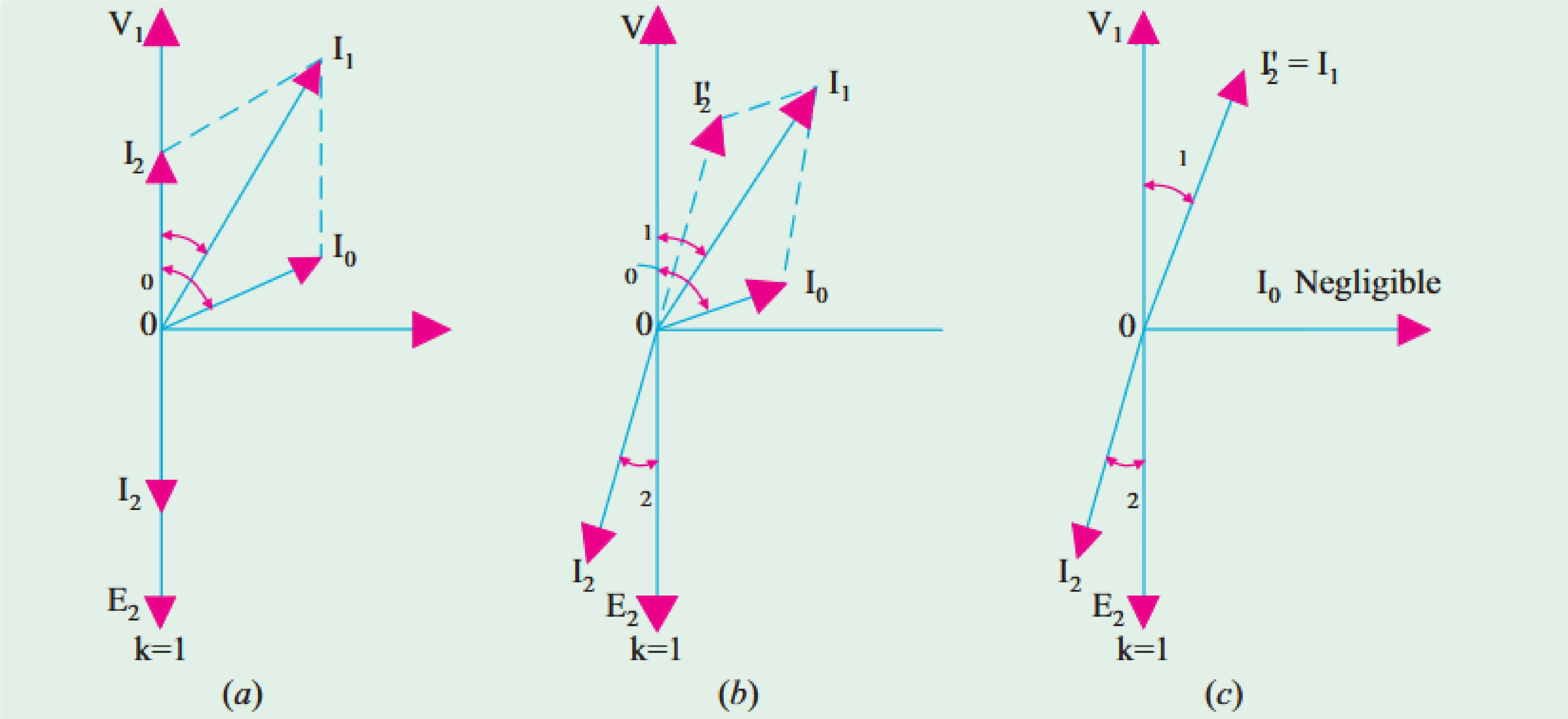


Transformer on load

Hence, whatever the load conditions, ***the net flux passing through the core is approximately the same as at no-load***. An important deduction is that due to the constancy of core flux at all loads, ***the core loss is also practically the same under all load conditions***.

As $\Phi_2 = \Phi_2'$ $\therefore$ $N_2 I_2 = N_1 I_2'$ $\therefore$ $I_2' = \frac{N_2}{N_1} \times I_2 = K I_2$

Hence, when transformer is on load, the primary winding has two currents in it; one is I_0 and the other is I_2' which is anti-phase with I_2 and K times in magnitude. ***The total primary current is the vector sum of I_0 and I_2'***.



Transformer with Winding Resistance but No Magnetic Leakage

An ideal transformer was supposed to possess no resistance, but in an actual transformer, there is always present some resistance of the primary and secondary windings. Due to this resistance, there is some voltage drop in the two windings. The result is that :

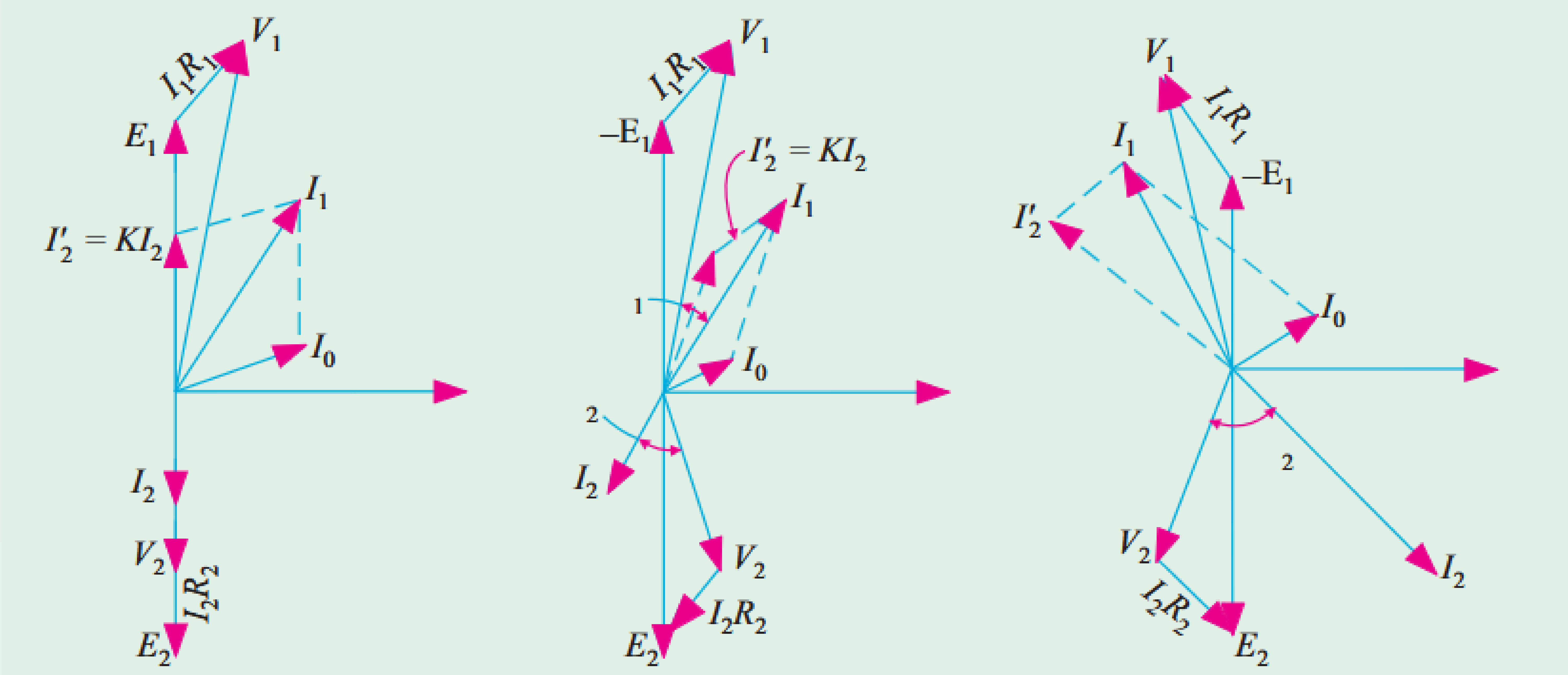
(*i*) The secondary terminal voltage V_2 is vectorially less than the secondary induced e.m.f. E_2 by an amount $I_2 R_2$ where R_2 is the resistance of the secondary winding. Hence, V_2 is equal to the vector difference of E_2 and resistive voltage drop $I_2 R_2$.

$$\therefore \quad V_2 = E_2 - I_2 R_2 \quad \text{...vector difference}$$

(*ii*) Similarly, primary induced e.m.f. E_1 is equal to the vector difference of V_1 and $I_1 R_1$ where R_1 is the resistance of the primary winding.

$$E_1 = V_1 - I_1 R_1 \quad \text{...vector difference}$$

Transformer with Winding Resistance but No Magnetic Leakage



(a) (b) (c)

Equivalent Resistance

The copper loss in secondary is $I_2^2 R_2$. This loss is supplied by primary which takes a current of I_1. Hence if R_2' is the ***equivalent resistance in primary which would have caused the same loss*** as R_2 in secondary, then

$$I_1^2 R_2' = I_2^2 R_2 \text{ or } R_2' = (I_2/I_1)^2 R_2$$

Now, if ***we neglect no-load current*** I_0, then $I_2/I_1 = I/K^*$. Hence, $R_2' = R_2/K^2$

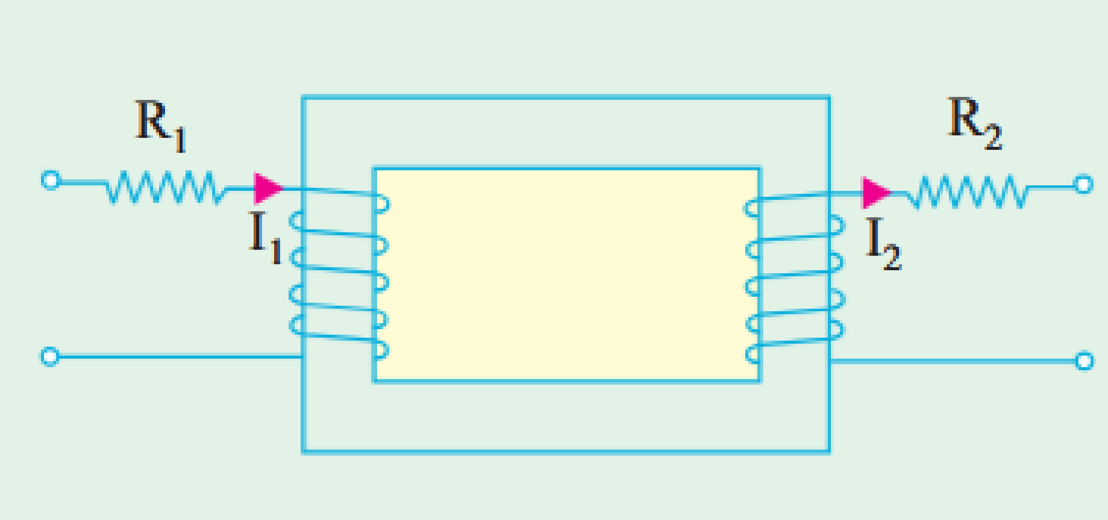
Similarly, equivalent primary resistance as referred to secondary is $R_1' = K^2 R_1$

In Fig. secondary resistance has been transferred to primary side leaving secondary circuit resistanceless. The resistance $R_1 + R_2' = R_1 + R_2/K^2$ is known as the ***equivalent*** or ***effective resistance of the transformer as referred to primary*** and may be designated as R_{01}.

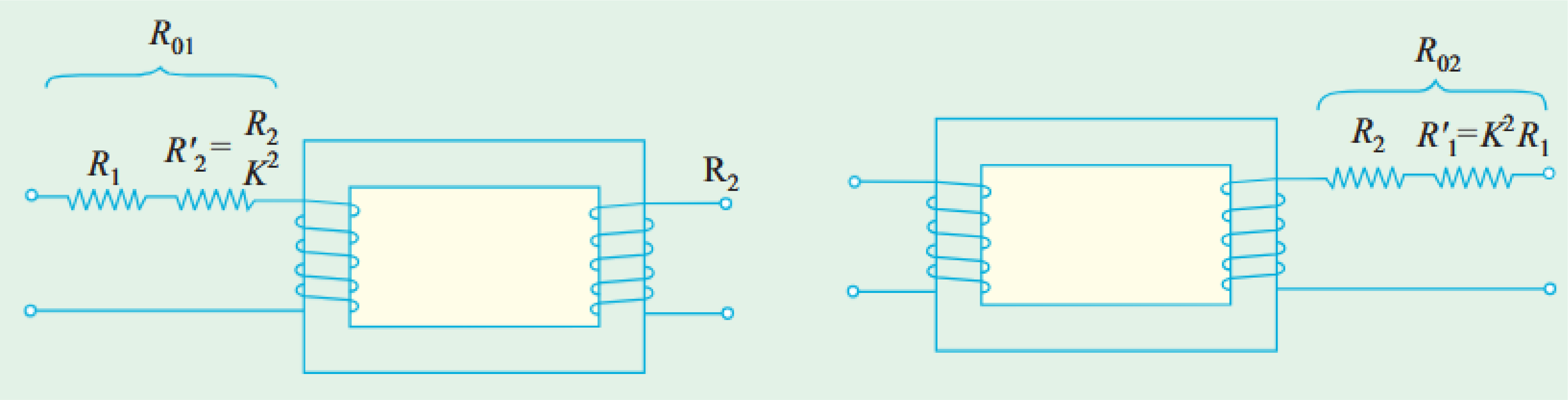
$$\therefore \quad R_{01} = R_1 + R_2' = R_1 + R_2/K^2$$

Similarly, the ***equivalent resistance of the transformer as referred to secondary is***

$$R_{02} = R_2 + R_1' = R_2 + K^2 R_1.$$



Equivalent Resistance



It is to be noted that

1. a resistance of R_1 in primary is equivalent to K^2R_1 in secondary. Hence, it is called ***equivalent resistance as referred to secondary*** *i.e.* R_1.

2. a resistance of R_2 in secondary is equivalent to R_2/K^2 in primary. Hence, it is called the ***equivalent secondary resistance as referred to primary*** *i.e.* R_2'.

3. Total or effective resistance of the transformer as referred to primary is

$$R_{01} = \text{primary resistance + equivalent secondary resistance as referred to primary}$$
$$= R_1 + R_2' = R_1 + R_2/K^2$$

4. Similarly, total transformer resistance as referred to secondary is,

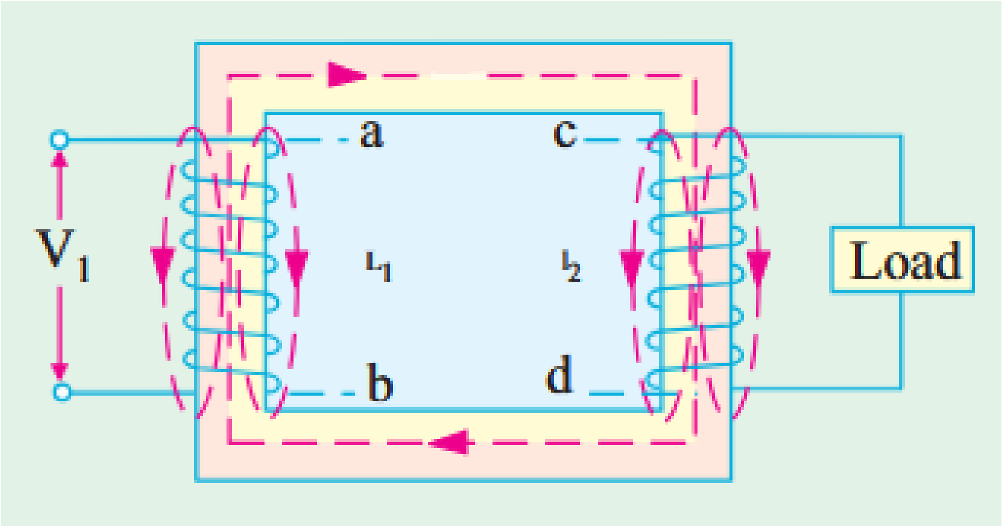
$$R_{02} = \text{secondary resistance + equivalent primary resistance as referred to secondary}$$
$$= R_2 + R_1' = R_2 + K^2R_1$$

Magnetic Leakage

Magnetic leakage in a transformer refers to the phenomenon where a portion of the magnetic flux generated by the primary winding does not link with the secondary winding but instead passes through the air or other paths outside the transformer core. This unlinked magnetic flux is termed leakage flux.

Causes of Magnetic Leakage:

- Imperfect coupling between windings: The primary and secondary windings are not perfectly aligned or coupled magnetically.
- Core material limitations: The magnetic permeability of the core might not be ideal, leading to some flux leakage.
- Design constraints: Certain designs prioritize other factors (e.g., cooling or insulation) over tighter coupling, increasing leakage flux.



Magnetic Leakage

Effects of Magnetic Leakage:

- Voltage drop: Leakage flux reduces the efficiency of energy transfer, leading to voltage drops in the windings.
- Impedance increase: Leakage inductance (due to leakage flux) increases the transformer's impedance, affecting performance, especially under load.
- Reduced efficiency: Since not all the magnetic flux contributes to energy transfer, the transformer operates less efficiently.

In some cases, magnetic leakage is deliberately increased (e.g., in arc welding transformers) to limit current and stabilize performance. However, in general power transformers, minimizing magnetic leakage is desirable to ensure efficient operation.

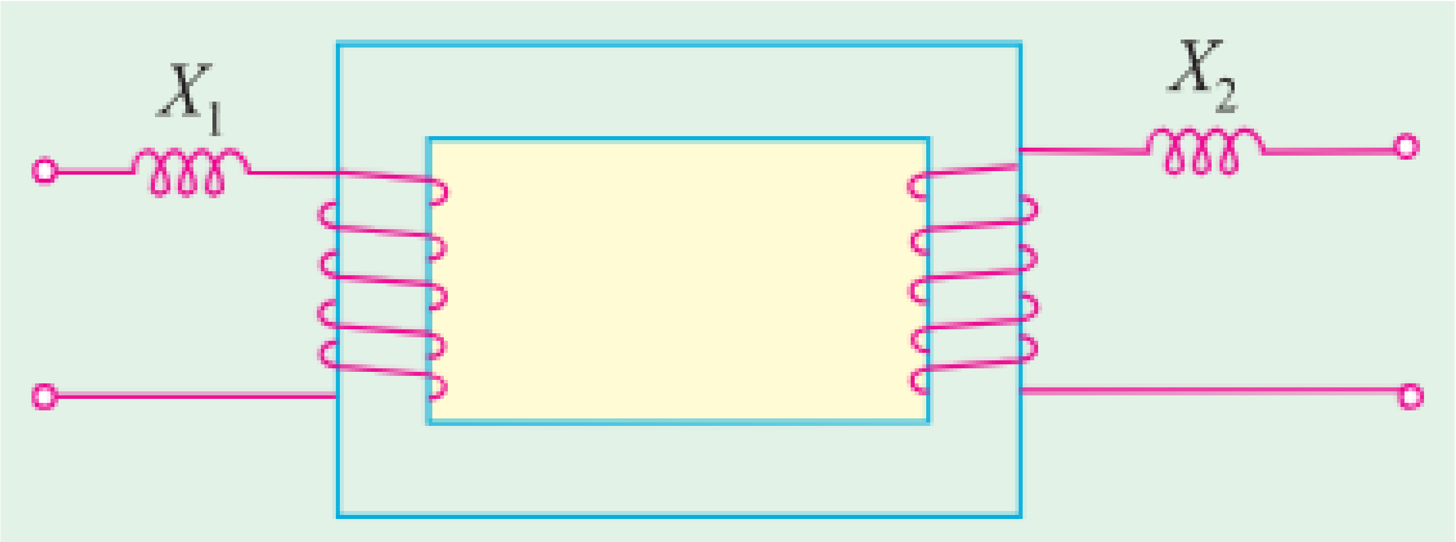
Magnetic Leakage

Following few points should be kept in mind :

1. The leakage flux links one or the other winding but ***not both***, hence it in no way contributes to the transfer of energy from the primary to the secondary winding.

2. The primary voltage V_1 will have to supply reactive drop I_1X_1 in addition to I_1R_1. Similarly E_2 will have to supply $I_2 R_2$ and $I_2 X_2$.

3. In an actual transformer, the primary and secondary windings are not placed on separate legs or limbs as shown in Fig. because due to their being widely separated, large primary and secondary leakage fluxes would result. These leakage fluxes are minimised by sectionalizing and interleaving the primary and secondary windings as in Fig



Transformer with Resistance and Leakage Reactance

In Fig. the primary and secondary windings of a transformer with reactances taken out of the windings are shown. The primary impedance is given by

$$Z_1 = \sqrt{(R_1^2 + X_1^2)}$$

Similarly, secondary impedance is given by

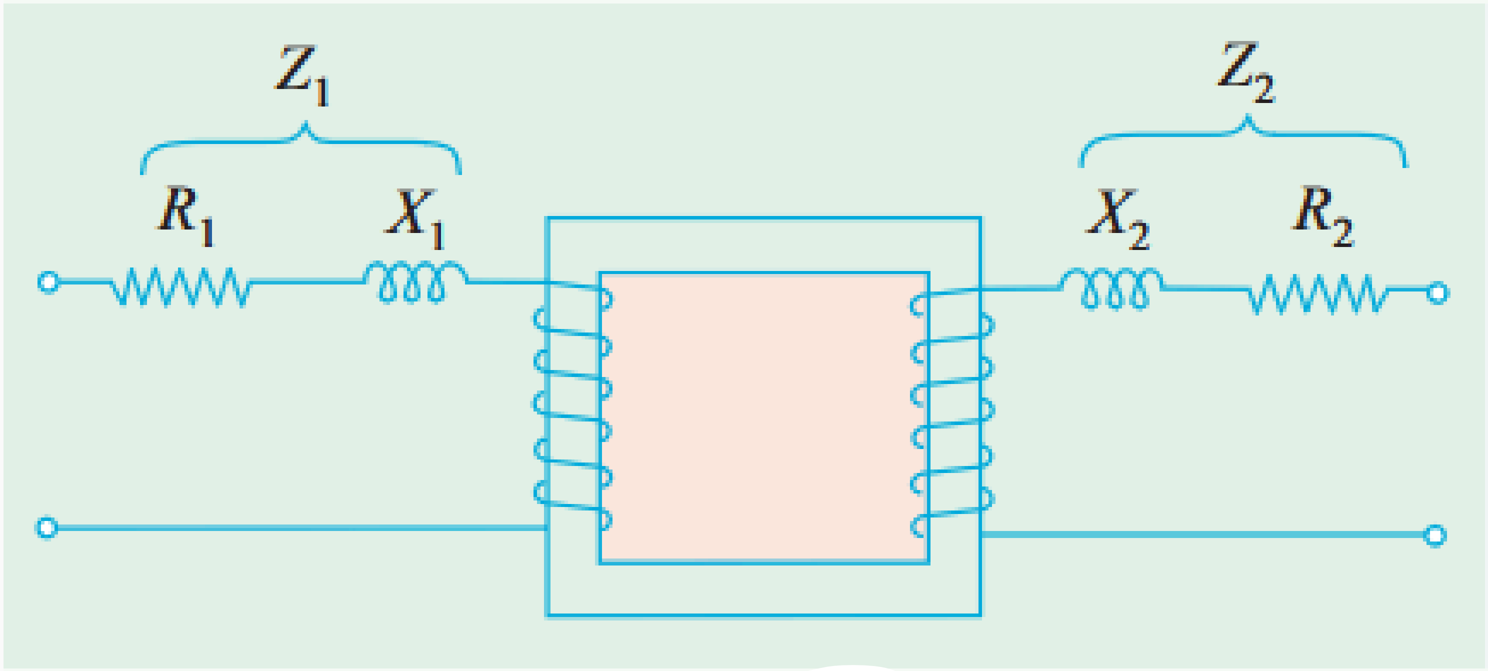
$$Z_2 = \sqrt{(R_2^2 + X_2^2)}$$

The resistance and leakage reactance of each winding is responsible for some voltage drop in each winding. In primary, the leakage reactance drop is I_1X_1 (usually 1 or 2% of V_1). Hence

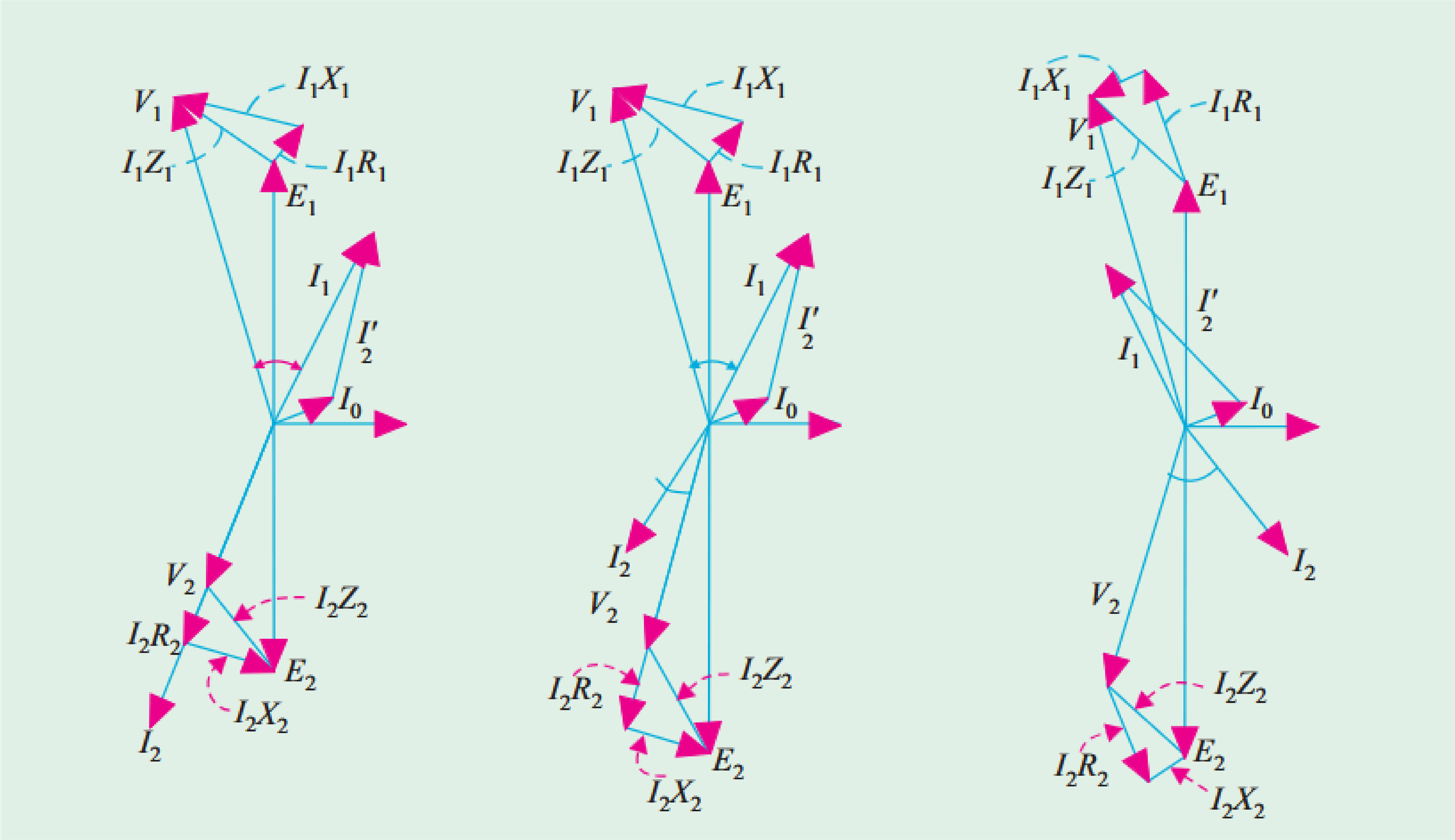
$$\mathbf{V_1} = \mathbf{E_1} + \mathbf{I_1}(R_1 + jX_1) = \mathbf{E_1} + \mathbf{I_1}\mathbf{Z_1}$$

Similarly, there are I_2R_2 and I_2X_2 drops in secondary which combine with V_2 to give E_2.

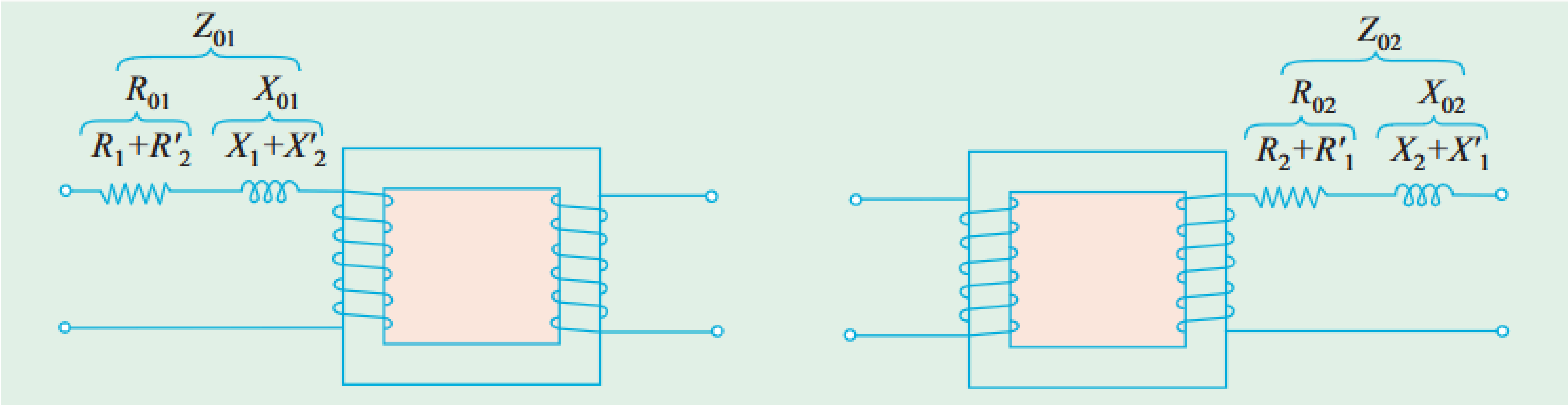
$$\mathbf{E_2} = \mathbf{V_2} + \mathbf{I_2}(R_2 + jX_2) = \mathbf{V_2} + \mathbf{I_2}\mathbf{Z_2}$$



Transformer with Resistance and Leakage Reactance



Transformer with Resistance and Leakage Reactance



It is obvious that total impedance of the transformer as referred to primary is given by

$$Z_{01} = \sqrt{(R_{01}^2 + X_{01}^2)} \quad (a)$$

and

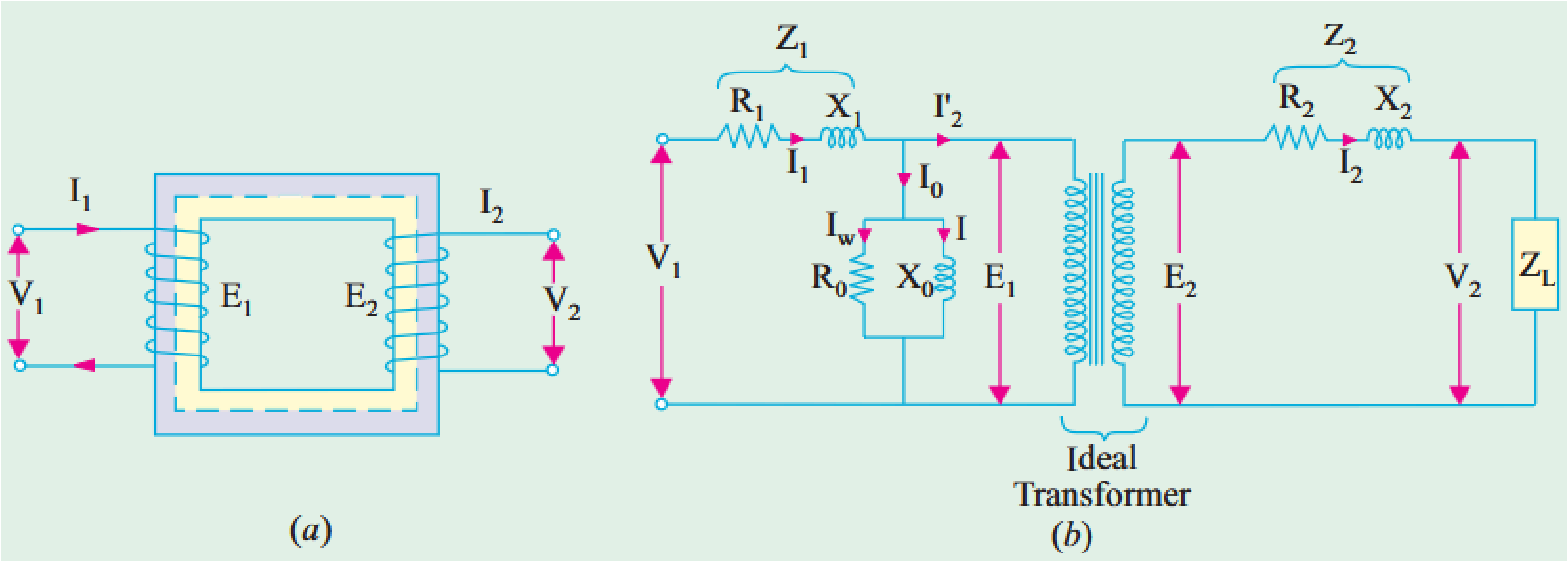
$$Z_{02} = \sqrt{(R_{02}^2 + X_{02}^2)} \quad (b)$$

WEEK 04

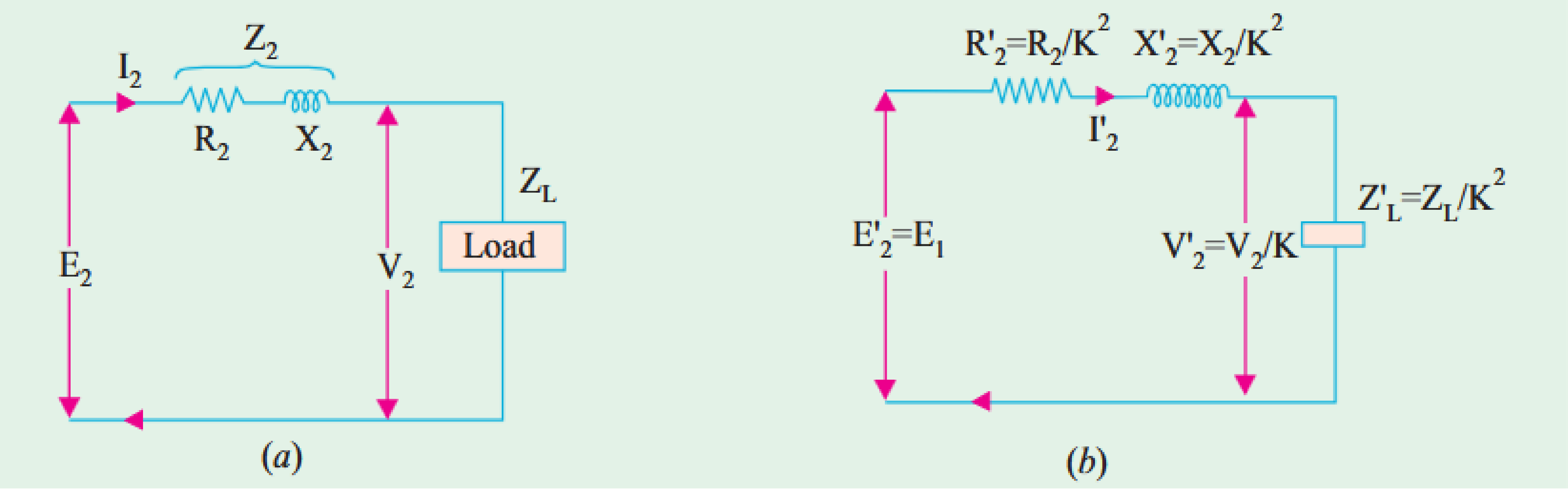
PAGE 44–48

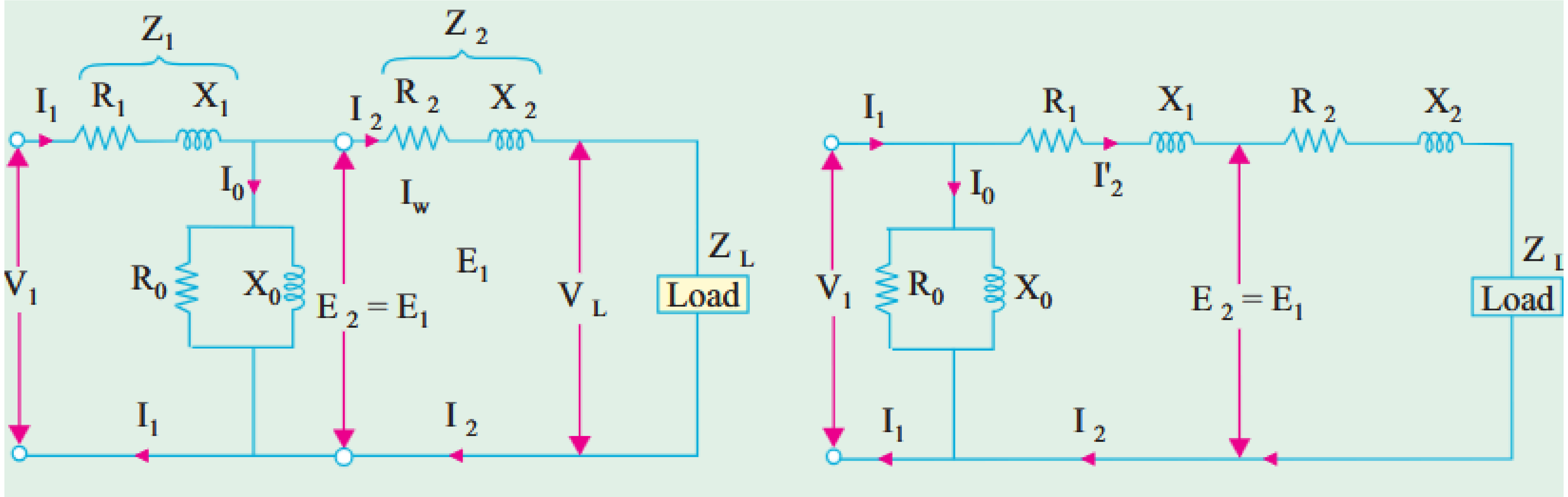
Equivalent Circuit of Transformer

The equivalent circuit of a transformer is a simplified representation that models the behavior of an actual transformer, considering its various electrical characteristics like losses, leakage flux, and impedance. It allows engineers to analyze the transformer under different conditions using standard circuit analysis techniques.



Equivalent Circuit of Transformer



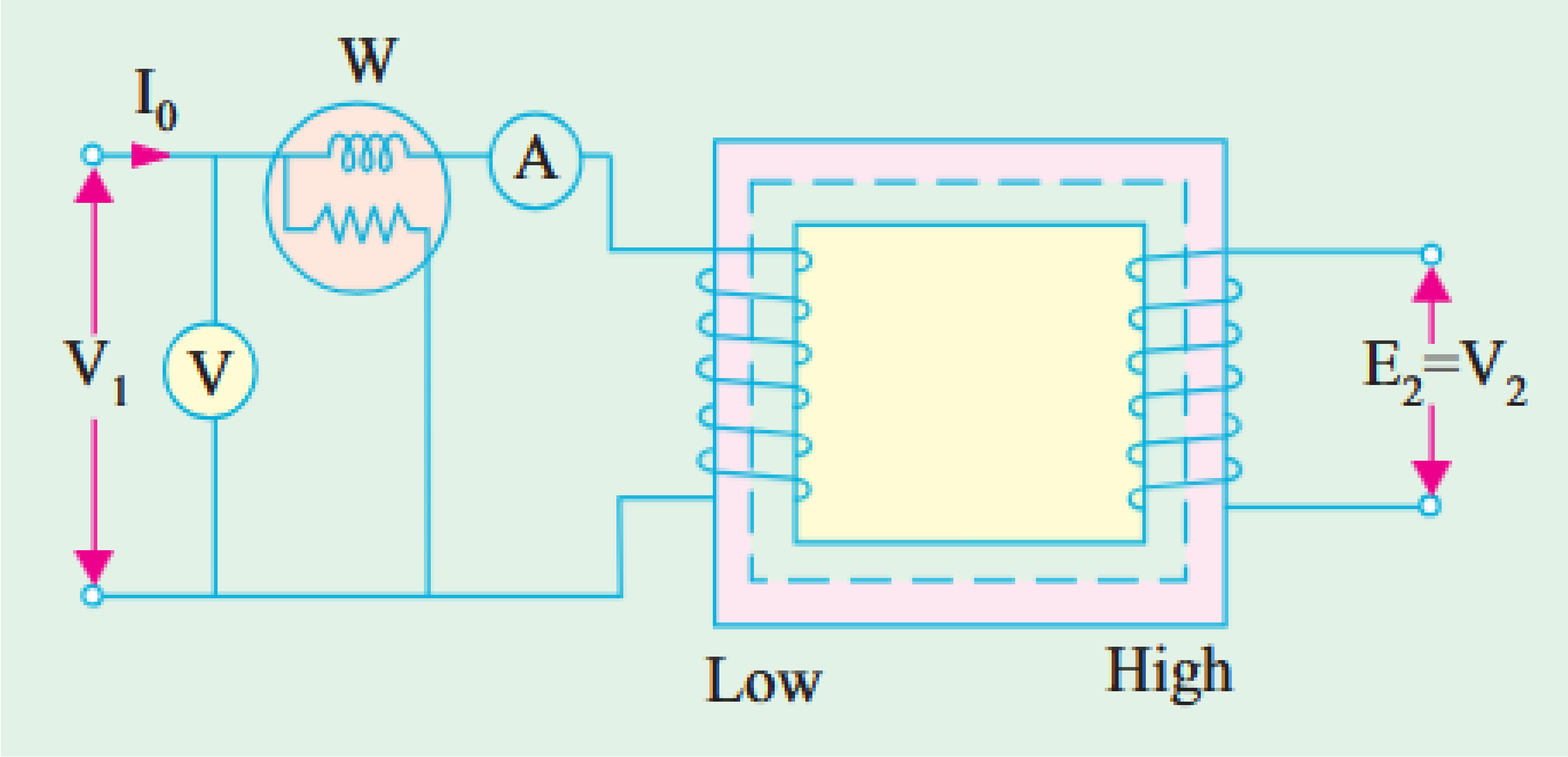


Transformer Tests (No-Load Test)

The Open-Circuit Test (No-Load Test) is a standard method used to determine the core losses (iron losses) and magnetizing current of a transformer under no-load conditions. This test is performed on the primary winding of the transformer, while the secondary winding is left open.

Objectives:

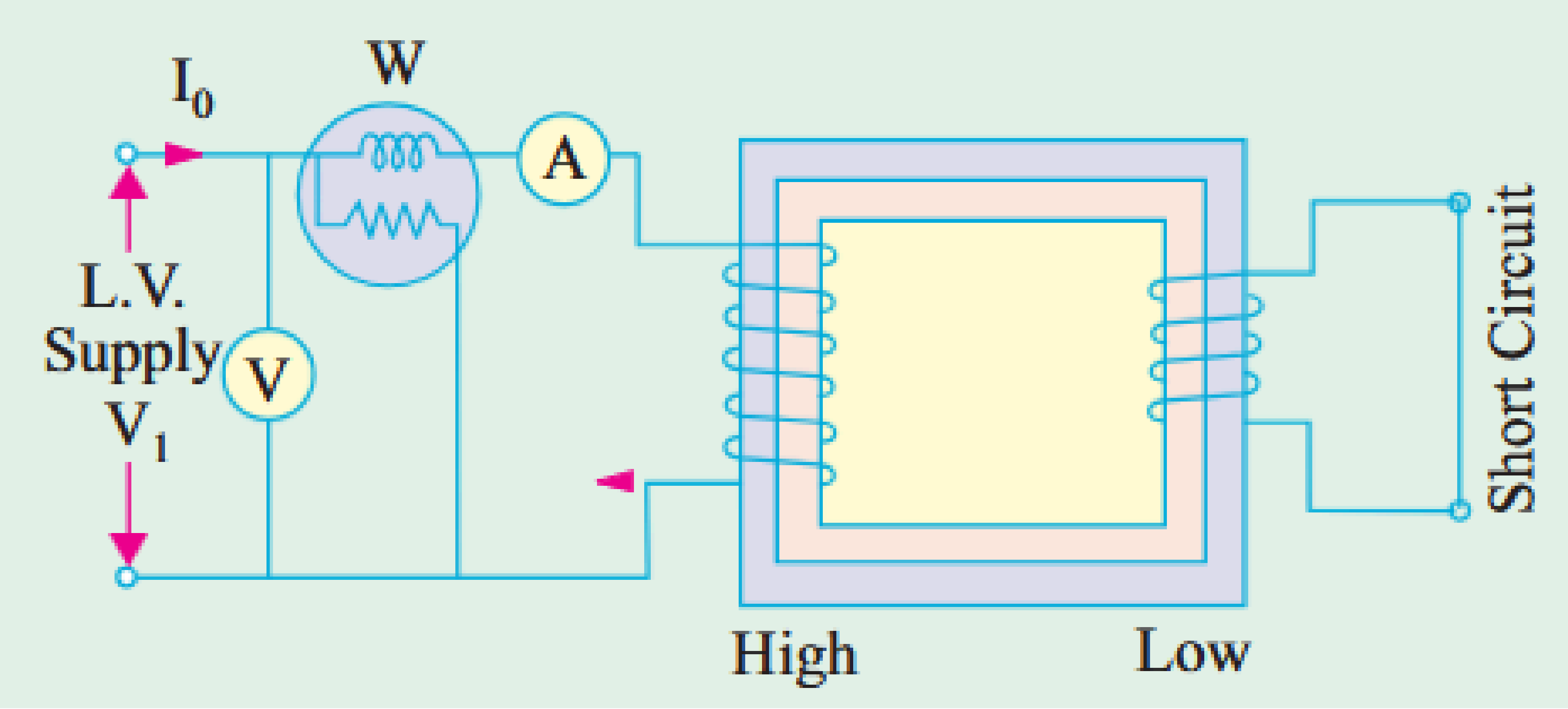
- Measure the core losses (hysteresis and eddy current losses).
- Determine the magnetizing reactance (Xm) and core loss resistance (Rc).
- Estimate the no-load current (I0) and its components.



Short-Circuit or Impedance Test

This is an economical method for determining the following :

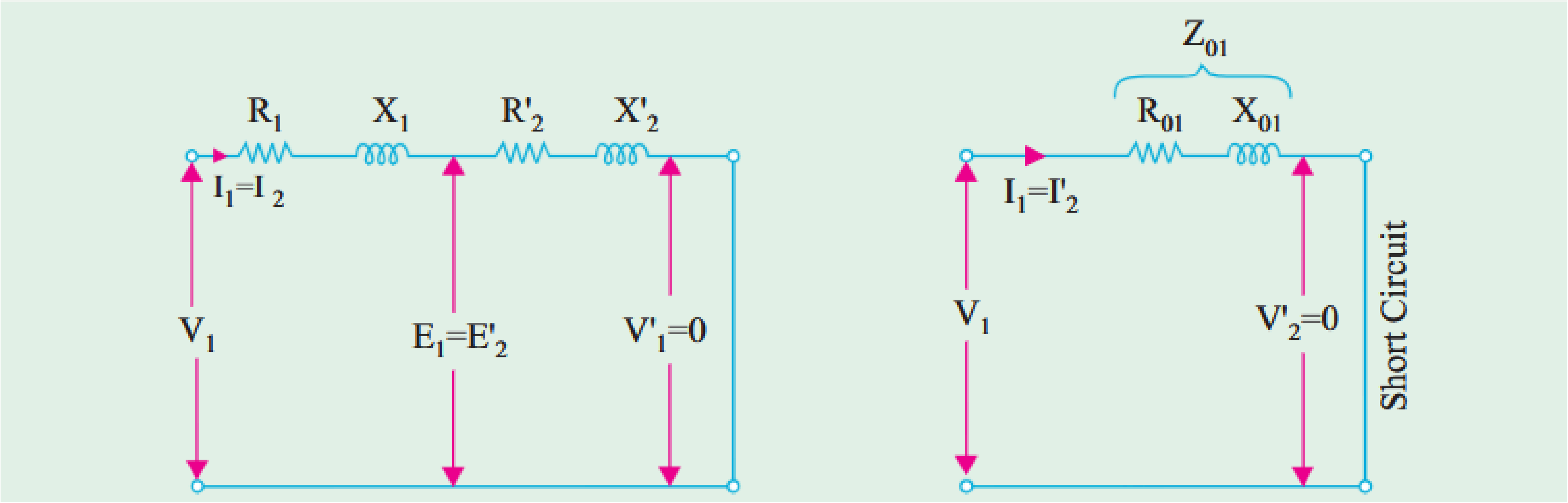
(i) Equivalent impedance ($\mathbf{Z}_{01}$ or $\mathbf{Z}_{02}$), leakage reactance (X_{01} or X_{02}) and total resistance (R_{01} or R_{02}) of the transformer as referred to the winding in which the measuring instruments are placed.



(ii) Cu loss at full load (and at any desired load). This loss is used in calculating the efficiency of the transformer.

(iii) Knowing Z_{01} or Z_{02}, the total voltage drop in the transformer as referred to primary or secondary can be calculated and hence regulation of the transformer determined.

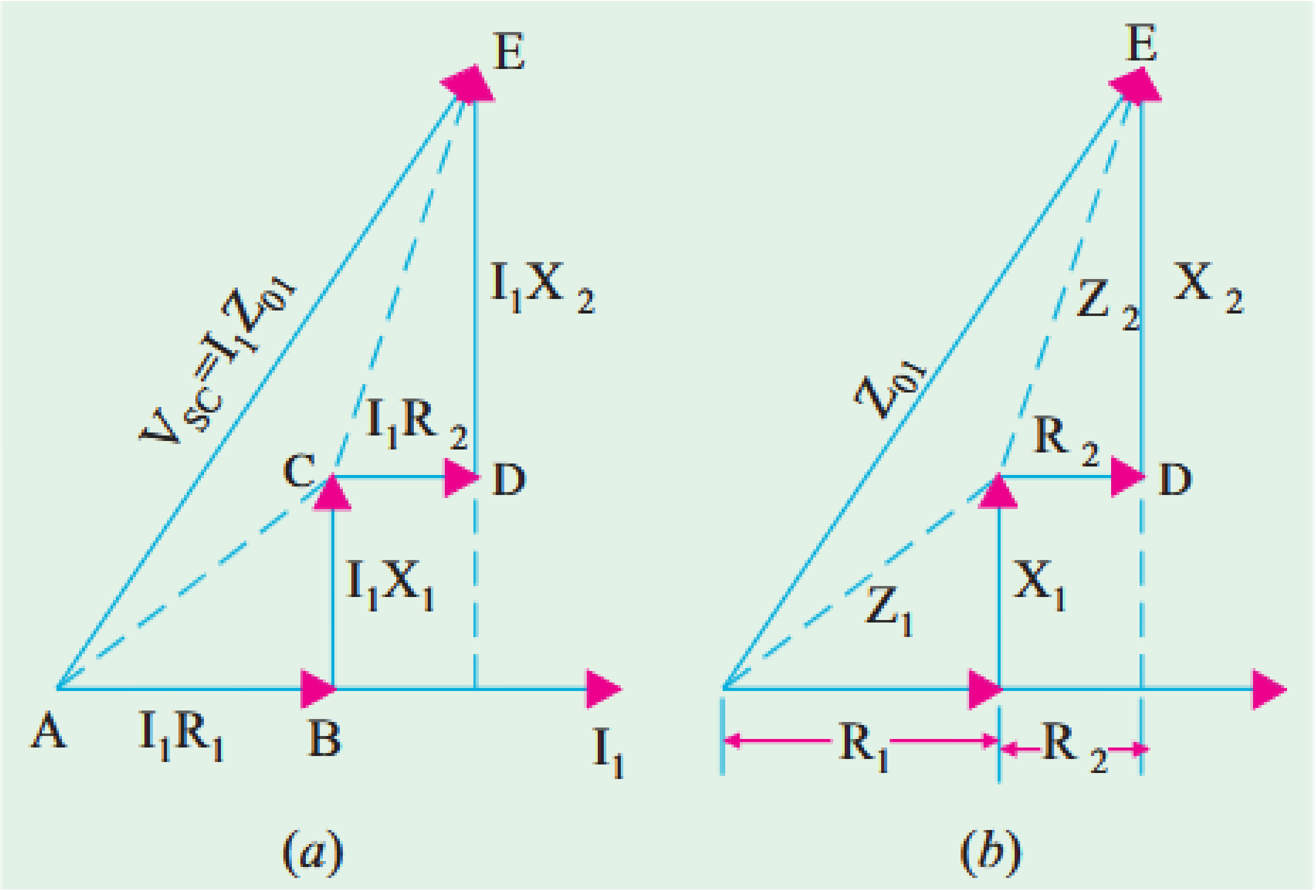
Short-Circuit or Impedance Test



Also $\quad W = I_1^2 R_{01}$

$\therefore \quad R_{01} = W/I_1$

$\therefore \quad X_{01} = \sqrt{\left(Z_{01}^2 - R_{01}^2\right)}$



WEEK 05

PAGE 50-53

Regulation of a Transformer

1. When a transformer is loaded with a ***constant primary voltage***, the secondary voltage decreases* because of its internal resistance and leakage reactance.

Let $\quad {}_0V_2 \;=\;$ secondary terminal voltage at *no-load*.

$\quad = E_2 = EK_1 = KV_1$ because at no-load the impedance drop is negligible.

$V_2 \;=\;$ secondary terminal voltage on *full-load*.

The change in secondary terminal voltage from no-load to full-load is $= {}_0V_2 - V_2$. This change divided by ${}_0V_2$ is known as regulation 'down'. If this change is divided by V_2, *i.e.*, full-load secondary terminal voltage, then it is called regulation 'up'.

$$\therefore \quad \%\ \text{regn 'down'} = \frac{{}_0V_2 - V_2}{{}_0V_2} \times 100 \quad \text{and } \%\ \text{regn 'up'} = \frac{{}_0V_2 - V_2}{V_2} \times 100$$

(2) The regulation may also be explained in terms of primary values.

In Fig. (*a*) the approximate equivalent circuit of a transformer is shown and in Fig. (*b*), (*c*) and (*d*) the vector diagrams corresponding to different power factors are shown.

The secondary ***no-load*** terminal voltage as referred to primary is $E_2' = E_2/K = E_1 = V_1$ and if the secondary full-load voltage as referred to primary is $V_2' (= V_2/K)$ then

$$\%\ \text{regn} = \frac{V_1 - V_2'}{V_1} \times 100$$

Regulation of a Transformer

(3) In the above definitions of regulation, ***primary voltage was supposed to be kept constant*** and the changes in secondary terminal voltage were considered.

As the transformer is loaded, the secondary terminal voltage falls (for a lagging p.f.). Hence, to keep the output voltage constant, the primary voltage must be increased. The rise in primary voltage required to maintain rated output voltage from no-load to full-load at a given power factor expressed as percentage of rated primary voltage gives the regulation of the transformer.

Suppose primary voltage has to be raised from its rated value V_1 to V_1', then

$$\%\ \text{regn.} = \frac{V_1' - V_1}{V_1} \times 100$$

Efficiency of a Transformer

As is the case with other types of electrical machines, the efficiency of a transformer at a particular load and power factor is defined as the output divided by the input–the two being measured in the same units (either watts or kilowatts).

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

But a transformer being a highly efficient piece of equipment, has very small loss, hence it is impractical to try to measure transformer, efficiency by measuring input and output. These quantities are nearly of the same size. A better method is to determine the losses and then to calculate the efficiency from ;

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{losses}} = \frac{\text{Output}}{\text{Output} + \text{Cu loss} + \text{iron loss}}$$

or

$$\eta = \frac{\text{Input} - \text{Losses}}{\text{Input}} = 1 - \frac{\text{losses}}{\text{Input}}$$

It may be noted here that efficiency is based on power output in watts and not in volt-amperes, although losses are proportional to VA. Hence, at any volt-ampere load, the efficiency depends on power factor, being maximum at a power factor of unity.

Efficiency can be computed by determining core loss from no-load or open-circuit test and Cu loss from the short-circuit test.

Condition for Maximum Efficiency

$$\text{Cu loss} = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02} = W_{cu}$$

$$\text{Iron loss} = \text{Hysteresis loss} + \text{Eddy current loss} = W_h + W_e = W_i$$

Considering primary side,

$$\text{Primary input} = V_1 I_1 \cos\phi_1$$

$$\eta = \frac{V_1 I_1 \cos\phi_1 - \text{losses}}{V_1 I_1 \cos\phi_1} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$

$$= 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

Differentiating both sides with respect to I_1, we get

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} + \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

For η to be maximum, $\frac{d\eta}{dI_1} = 0$. Hence, the above equation becomes

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1} \quad \text{or} \quad W_i = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02}$$

or **Cu loss = Iron loss**

WEEK 06-07

PAGE 55

Mathematical Problems on Transformer

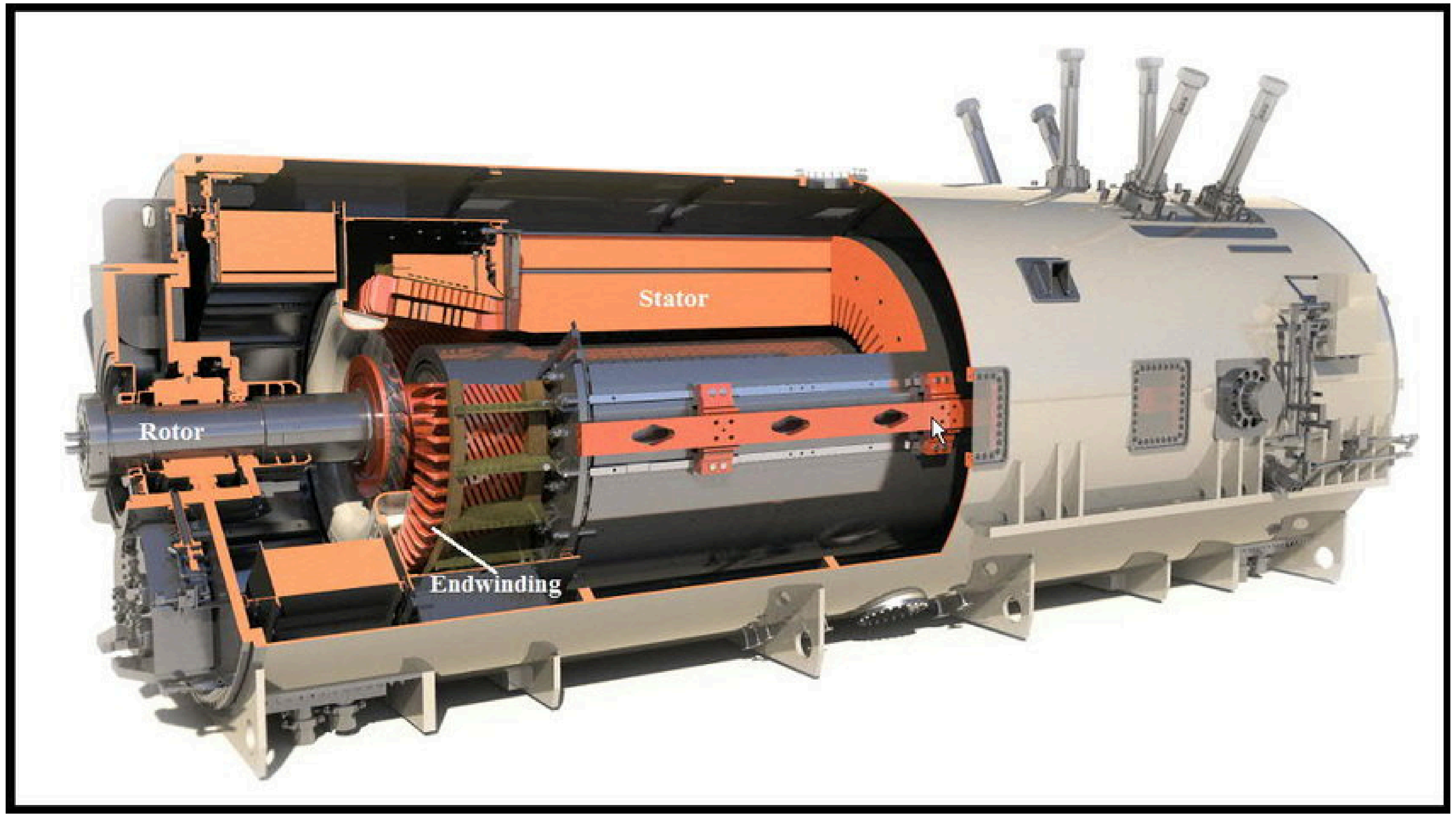
Mathematical problems related to transformers will be practiced and solved during classroom sessions. Problems from the prescribed reference book will be addressed, and additional practice materials will be provided to enhance understanding and proficiency.

WEEK 08

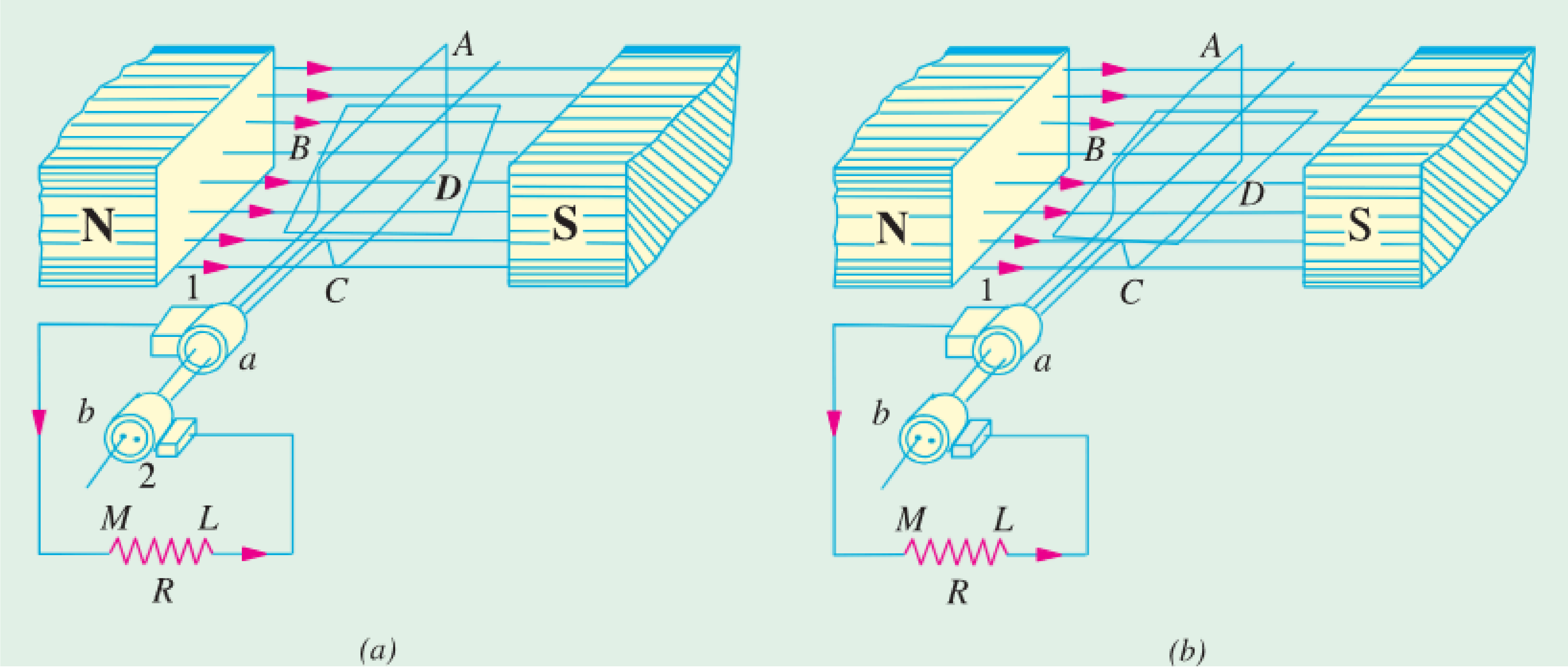
PAGE 57 - 68

Principle of a Generator

The working principle of a generator is based on Faraday's Law of Electromagnetic Induction, which states:
"When a conductor moves in a magnetic field, or the magnetic field around a stationary conductor changes, an electromotive force (EMF) is induced in the conductor."



Simple Loop Generator(Construction)

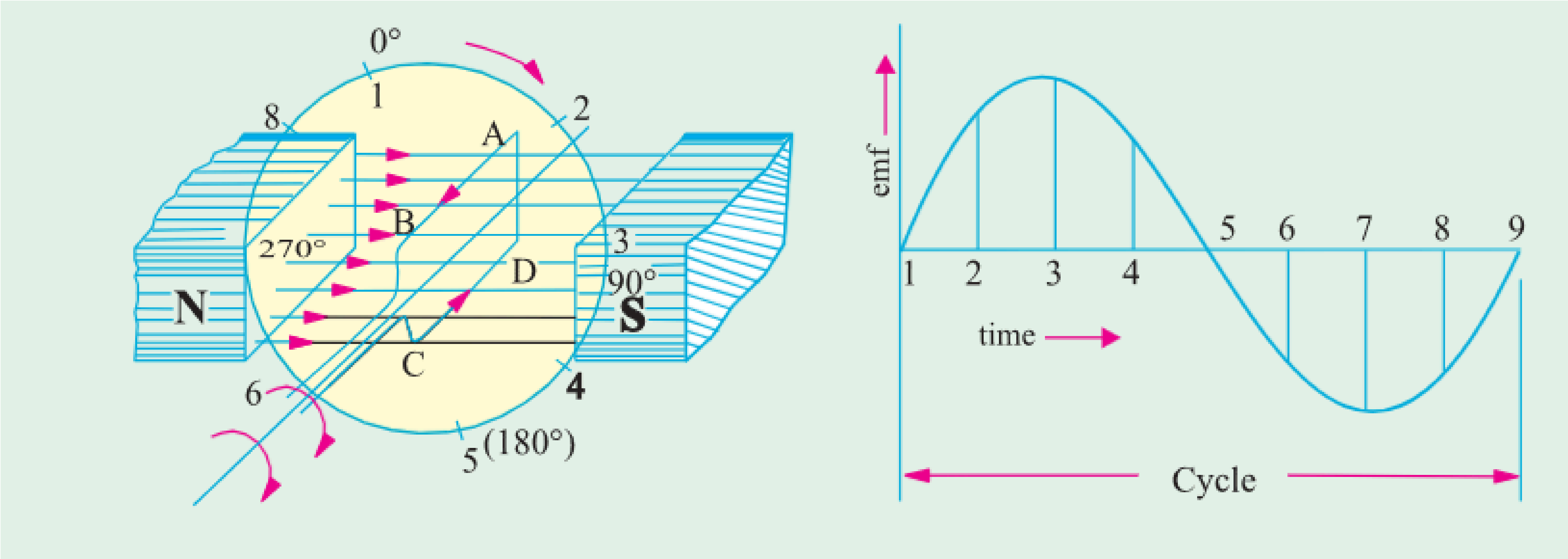


Simple Loop Generator(Working)

The working of a simple loop generator is based on Faraday's Law of Electromagnetic Induction, which states that an electromotive force (EMF) is induced in a conductor when it moves through a magnetic field. In a simple loop generator, a rectangular conductor loop (armature) is placed within a uniform magnetic field provided by permanent magnets or electromagnets. This loop is rotated mechanically, causing it to cut through the magnetic field lines. As the loop rotates, the magnetic flux linked with it changes continuously, inducing an EMF.

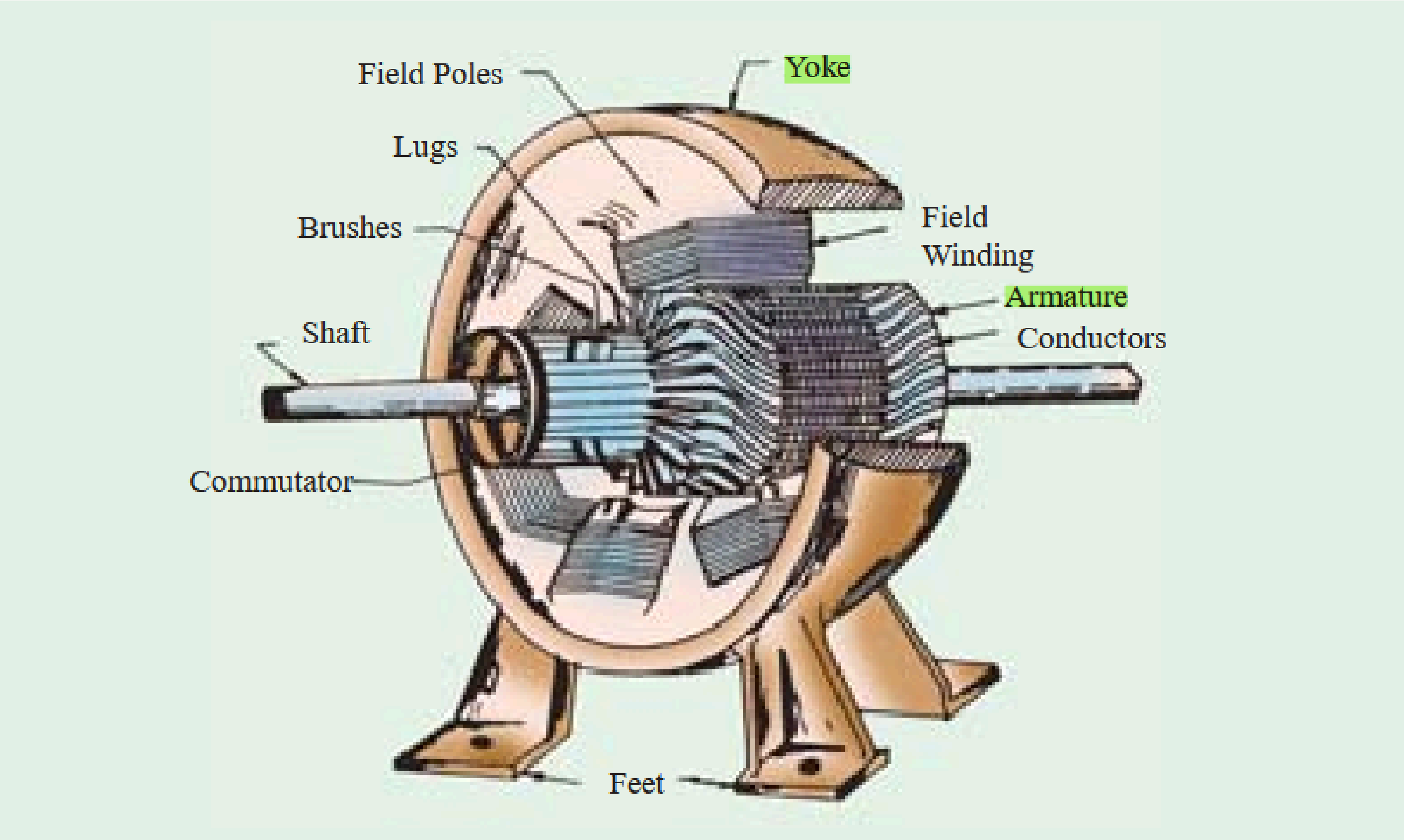
During rotation, when the loop is perpendicular to the magnetic field, the rate of flux cutting is maximum, resulting in the peak EMF. Conversely, when the loop is parallel to the magnetic field, no flux is cut, and the EMF is zero. This periodic change in the magnitude and direction of the induced EMF produces an alternating current (AC) if the loop is connected to an external circuit via slip rings and brushes. Thus, the simple loop generator converts mechanical energy into electrical energy effectively.

Simple Loop Generator(Working)



Parts of Generator

1. Magnetic Frame or Yoke
2. Pole-Cores and Pole-Shoes
3. Pole Coils or Field Coils
4. Armature Core
5. Armature Windings or Conductors
6. Commutator
7. Brushes and Bearings



Yoke

The outer frame or yoke serves double purpose :

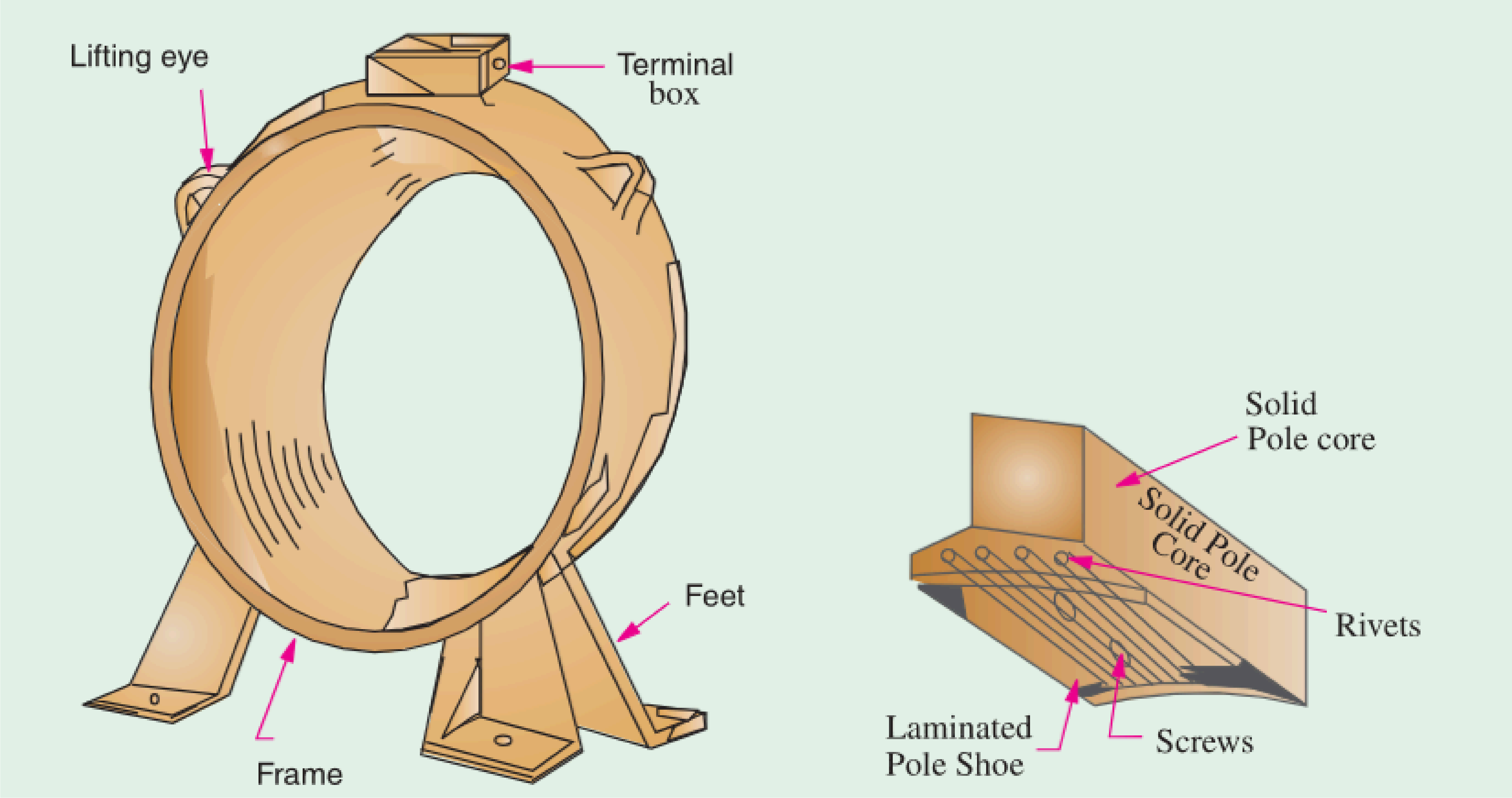
(*i*) It provides mechanical support for the poles and acts as a protecting cover for the whole machine and

(*ii*) It carries the magnetic flux produced by the poles.

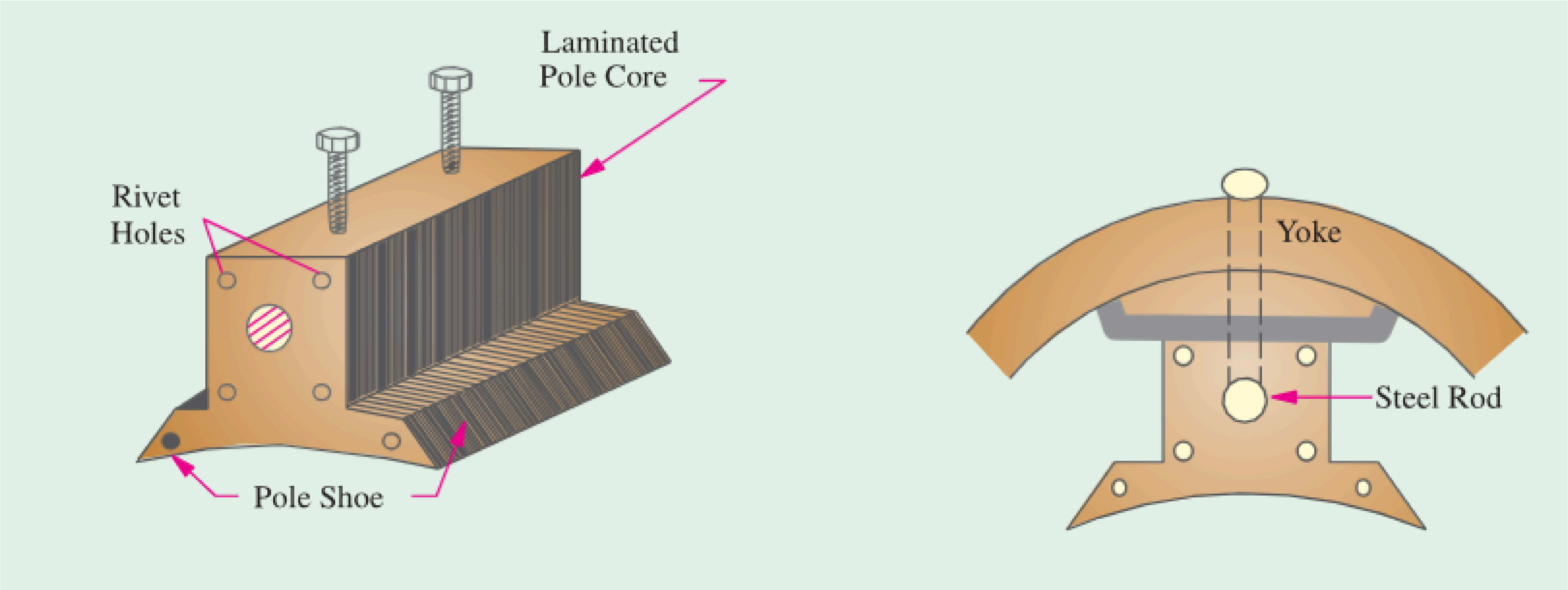
Yoke

In small generators where cheapness rather than weight is the main consideration, yokes are made of cast iron. But for large machines usually cast steel or rolled steel is employed. The modern process of forming the yoke consists of rolling a steel slab round a cylindrical mandrel and then welding it at the bottom. The feet and the terminal box etc. are welded to the frame afterwards. Such yokes possess sufficient mechanical strength and have high permeability.

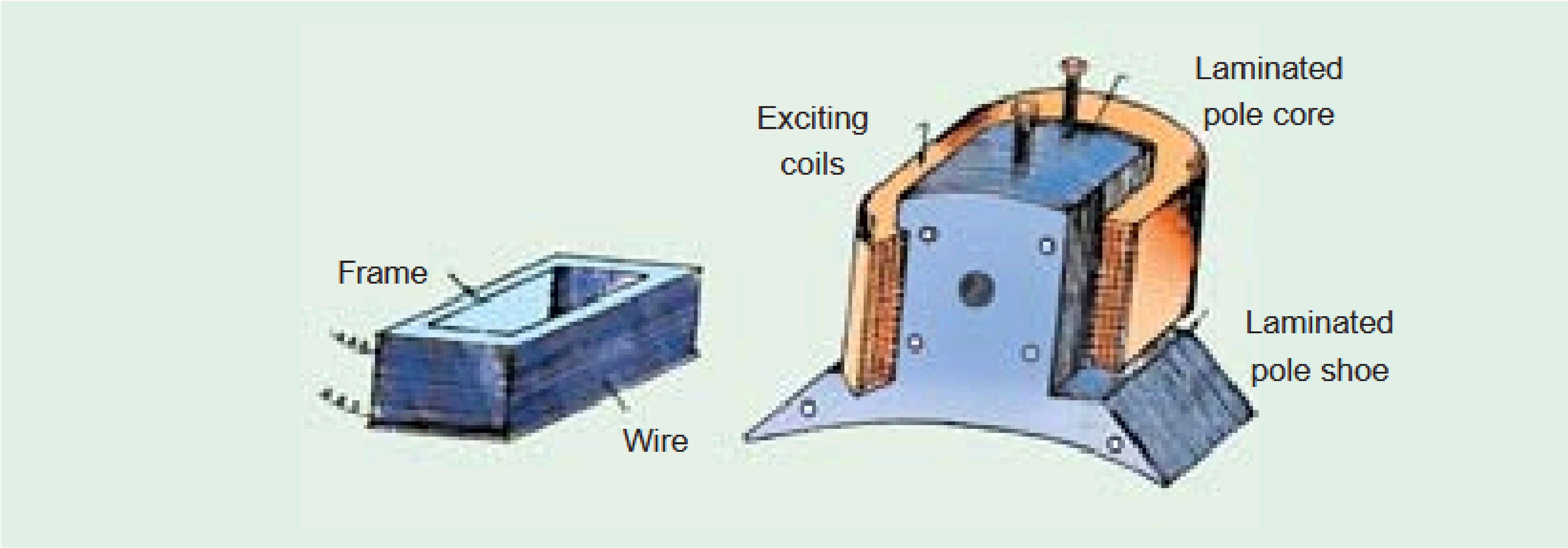
Pole Cores and Pole Shoes.

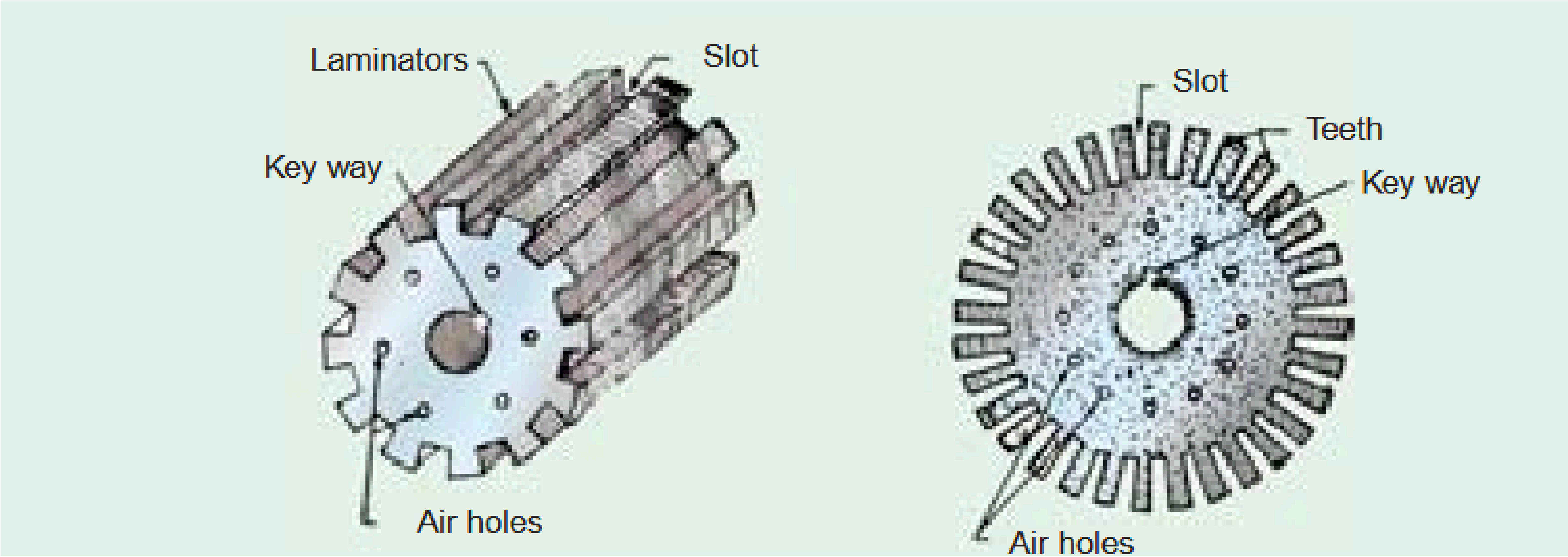


Pole Cores and Pole Shoes.

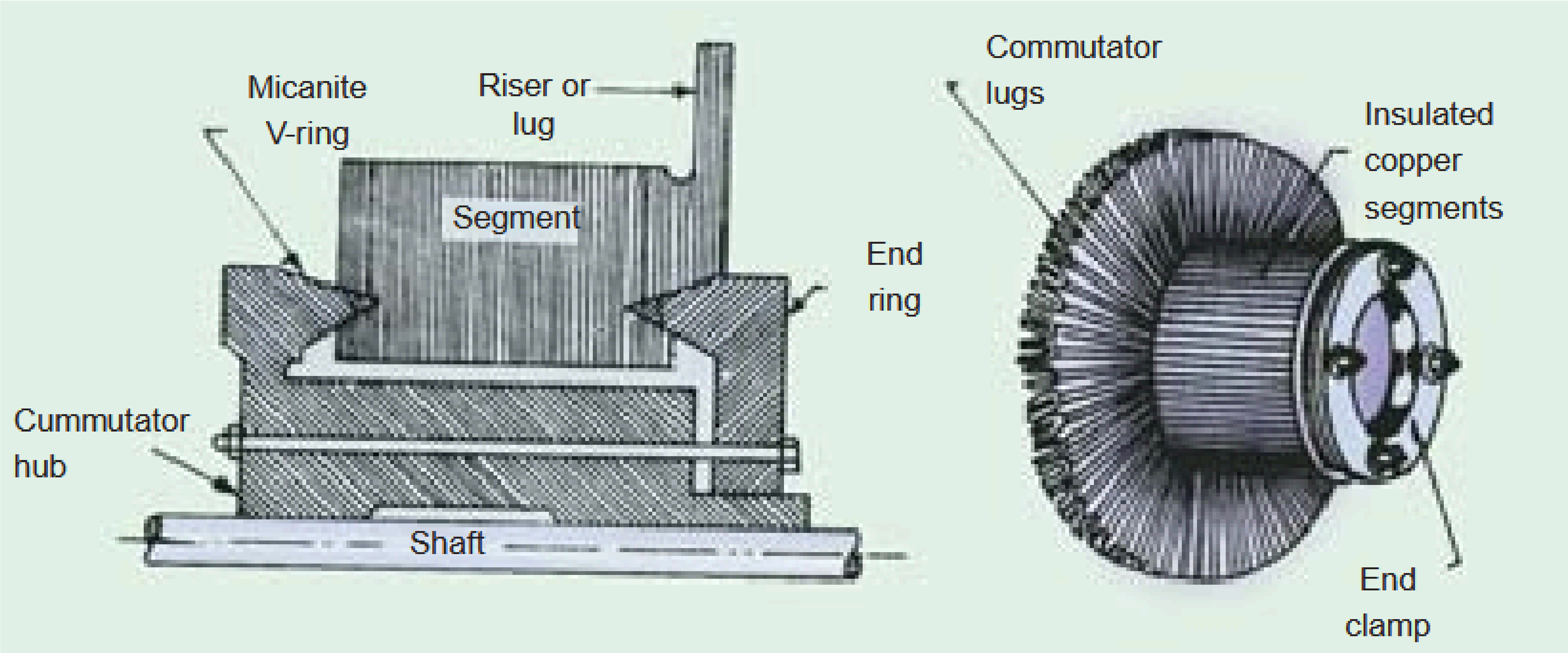


Armature Core





Commutator



Micanite
V-ring
Riser or
lug
Segment
End
ring
Cummutator
hub
Shaft
Commutator
lugs
Insulated
copper
segments
End
clamp

Brushes and Bearings

Bearing

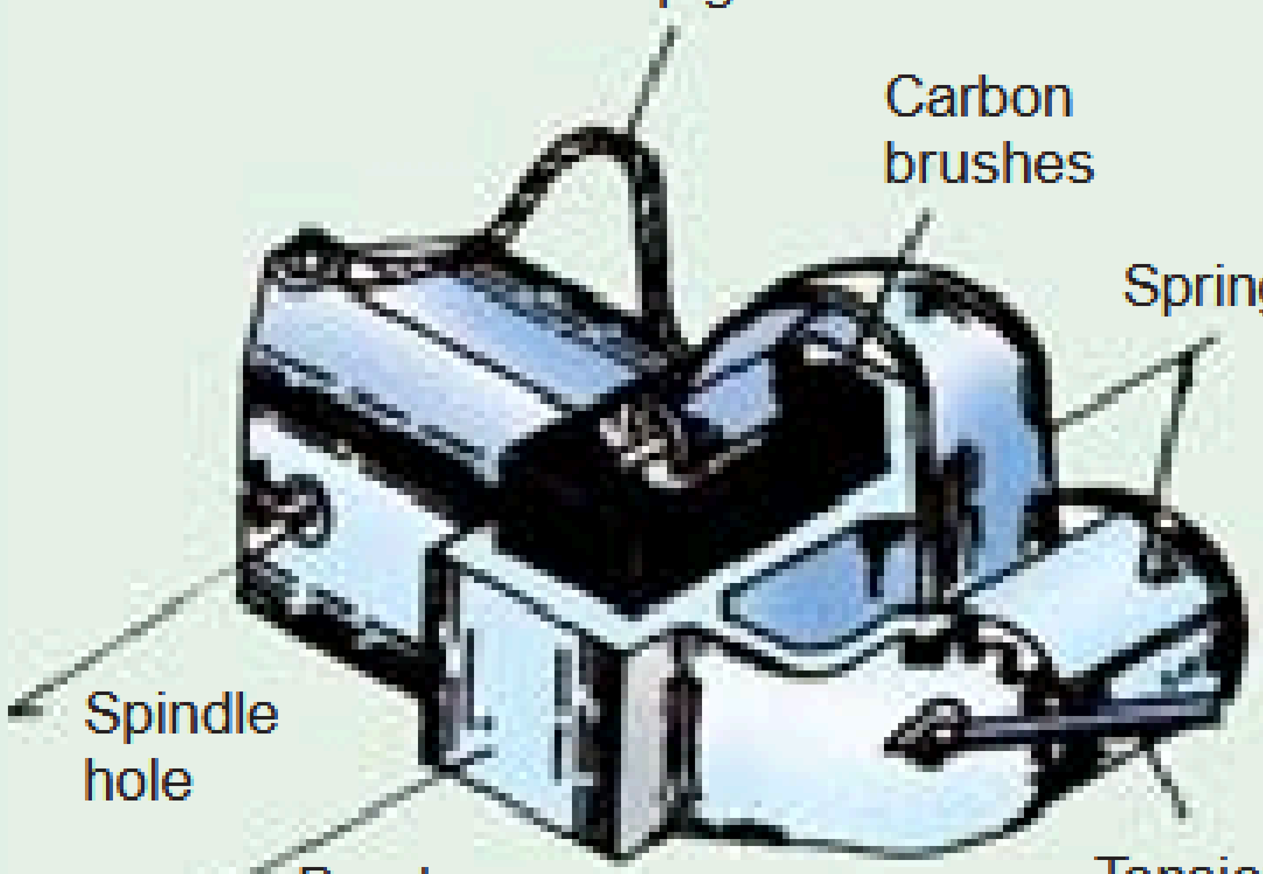


Fig. 26.20

Armature Windings

The armature winding of a DC generator is a critical component responsible for generating electrical power through electromagnetic induction. It consists of a series of conductive wires (usually copper) wound on the slots of an armature core, which rotates within a magnetic field. The armature winding is where the electromotive force (EMF) is induced when the armature cuts through the magnetic flux. There are two primary types of armature windings in a DC generator: lap winding and wave winding.

WEEK 09

PAGE 70 - 78

E.M.F Equation of a Generator

Let Φ = flux/pole in weber

Z = total number of armature conductors

= No. of slots × No. of conductors/slot

P = No. of generator poles

A = No. of parallel paths in armature

N = armature rotation in revolutions per minute (r.p.m.)

E = e.m.f. induced in any parallel path in armature

Generated e.m.f. E_g = e.m.f. generated in any one of the parallel paths *i.e.* E.

Average e.m.f. generated/conductor $= \dfrac{d\Phi}{dt}$ volt $(\because n = 1)$

Now, flux cut/conductor in one revolution $d\Phi = \Phi P$ Wb

No. of revolutions/second $= N/60$ $\quad\therefore\quad$ Time for one revolution, $dt = 60/N$ second

Hence, according to Faraday's Laws of Electromagnetic Induction,

E.M.F. generated/conductor $= \dfrac{d\Phi}{dt} = \dfrac{\Phi P N}{60}$ volt

E.M.F Equation of a Generator

For a simplex wave-wound generator

No. of parallel paths = 2

No. of conductors (in series) in one path = $Z/2$

$$\therefore \quad \text{E.M.F. generated/path} = \frac{\Phi PN}{60} \times \frac{Z}{2} = \frac{\Phi ZPN}{120} \text{ volt}$$

For a simplex lap-wound generator

No. of parallel paths = P

No. of conductors (in series) in one path = Z/P

$$\therefore \quad \text{E.M.F. generated/path} = \frac{\Phi PN}{60} \times \frac{Z}{P} = \frac{\Phi ZN}{60} \text{ volt}$$

In general generated e.m.f. $E_g = \dfrac{\Phi ZN}{60} \times \left(\dfrac{P}{A}\right)$ volt

where A = 2-for simplex wave-winding

= P-for simplex lap-winding

Also, $$E_g = \frac{1}{2\pi} \cdot \left(\frac{2\pi N}{60}\right) \Phi Z \left(\frac{P}{A}\right) = \frac{\omega \Phi Z}{2\pi}\left(\frac{P}{A}\right) \text{ volt} - \omega \text{ in rad/s}$$

For a given d.c. machine, Z, P and A are constant. Hence, putting $K_a = ZP/A$, we get

$$E_g = K_a \Phi N \text{ volts—where } N \text{ is in r.p.s.}$$

Iron Loss in Armature

Due to the rotation of the iron core of the armature in the magnetic flux of the field poles, there are some losses taking place continuously in the core and are known as Iron Losses or Core Losses. Iron losses consist of **(*i*) Hysteresis** loss and **(*ii*) Eddy Current** loss.

(*i*) Hysteresis Loss (W_h)

This loss is due to the reversal of magnetisation of the armature core. Every portion of the rotating core passes under *N* and *S* pole alternately, thereby attaining *S* and *N* polarity respectively. The core undergoes one complete cycle of magnetic reversal after passing under one *pair* of poles. If *P* is the number of poles and *N*, the armature speed in r.p.m., then frequency of magnetic reversals is $f = PN/120$.

The loss depends upon the volume and grade of iron, maximum value of flux density B_{max} and frequency of magnetic reversals. For normal flux densities (*i.e.* upto 1.5 Wb/m^2), hysteresis loss is given by **Steinmetz** formula. According to this formula,

$$W_h = \eta B_{max}^{1.6} f V \text{ watts}$$

where V = volume of the core in m^3

η = Steinmetz hysteresis coefficient.

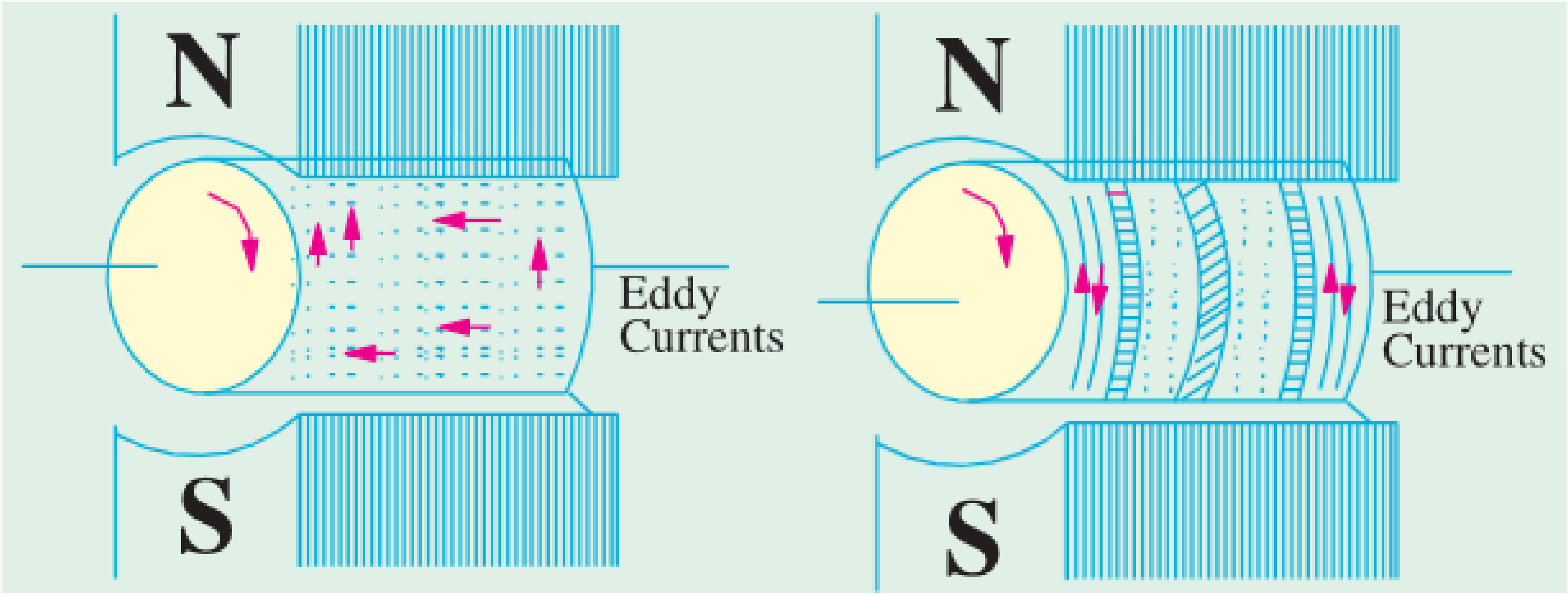
Iron Loss in Armature

Value of η for :

Good dynamo sheet steel = 502 J/m^3, Silicon steel = 191 J/m^2, Hard Cast steel = 7040 J/m^3, Cast steel = 750 – 3000 J/m^3 and Cast iron = 2700 – 4000 J/m^3.

(ii) Eddy Current Loss (W_e)

When the armature core rotates, it also cuts the magnetic flux. Hence, an e.m.f. is induced in the body of the core according to the laws of electromagnetic induction. This e.m.f. though small, sets up large current in the body of the core due to its small resistance. This current is known as eddy current. The power loss due to the flow of this current is known as eddy current loss. This loss would be considerable if solid iron core were used. In order to reduce this loss and the consequent heating of the core to a small value, the core is built up of thin laminations, which are stacked and then riveted at right angles to the path of the eddy currents. These



Total Loss in a D.C Generator

The various losses occurring in a generator can be sub-divided as follows :

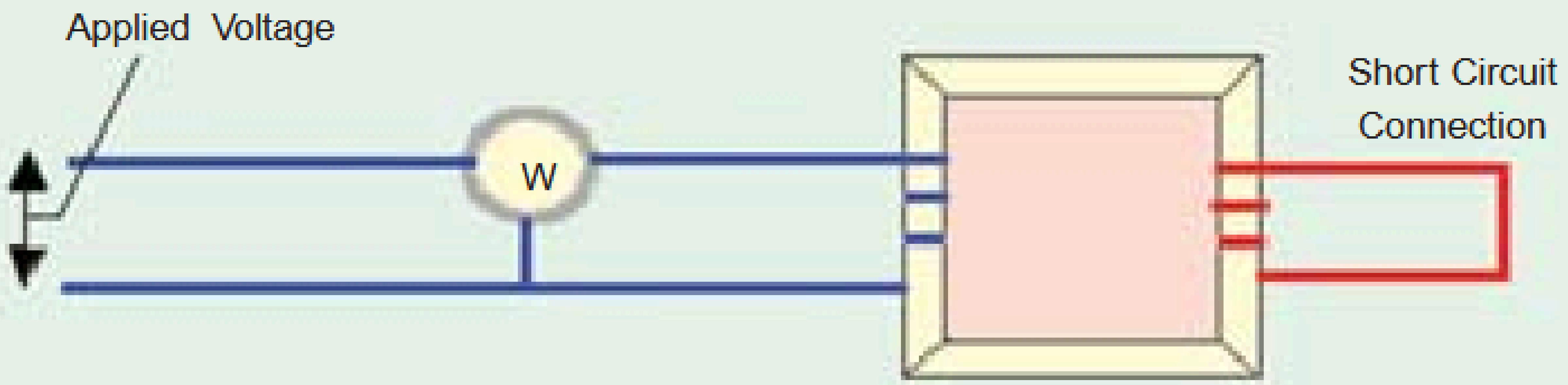
(*a*) Copper Losses

(*i*) Armature copper loss = $I_a^2 R_a$

[**Note :** $E_g I_a$ is the power output from armature.]

where R_a = resistance of armature and interpoles and series field winding etc.

This loss is about 30 to 40% of full-load losses.



Short Circuit Connections for Copper Loss Test

Total Loss in a D.C Generator

(*ii*) Field copper loss. In the case of shunt generators, it is practically constant and $I_{sh}^2 R_{sh}$ (or VI_{sh}). In the case of series generator, it is $= I_{se}^2 R_{se}$ where R_{se} is resistance of the series field winding.

This loss is about 20 to 30% of F.L. losses.

(*iii*) The loss due to brush contact resistance. It is usually included in the armature copper loss.

(*b*) **Magnetic Losses** (also known as iron or core losses),

(*i*) hysteresis loss, $W_h \propto B_{max}^{1.6} f$ and (*ii*) eddy current loss, $W_e \propto B_{max}^2 f^2$

These losses are practically constant for shunt and compound-wound generators, because in their case, field current is approximately constant.

Both these losses total up to about 20 to 30% of F.L. losses.

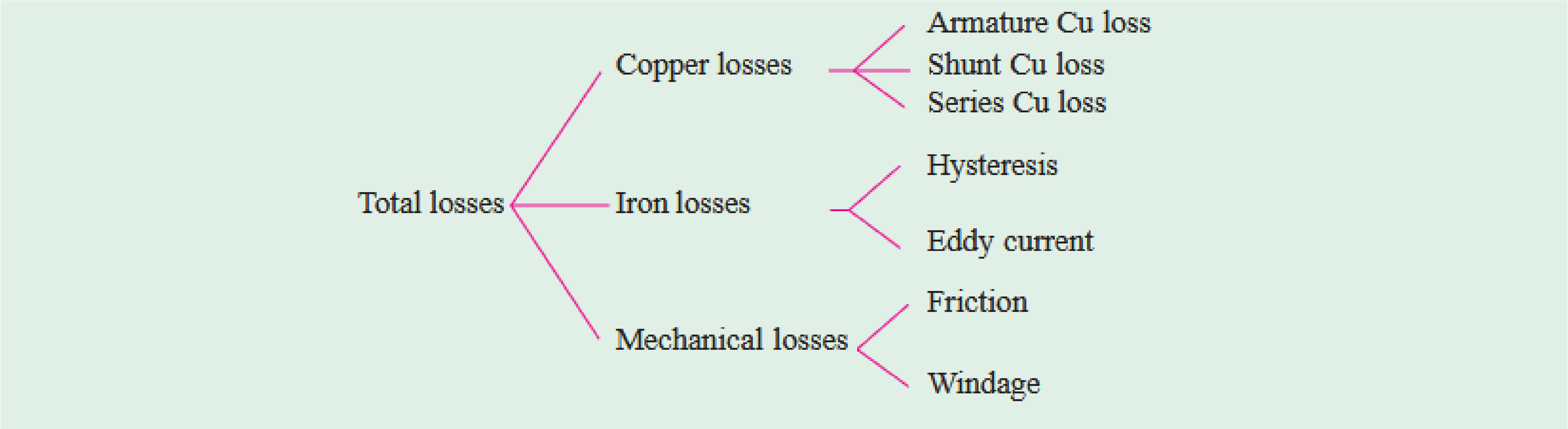
(*c*) **Mechanical Losses.** These consist of :

(*i*) friction loss at bearings and commutator.

(*ii*) air-friction or windage loss of rotating armature.

Total Loss in a D.C Generator

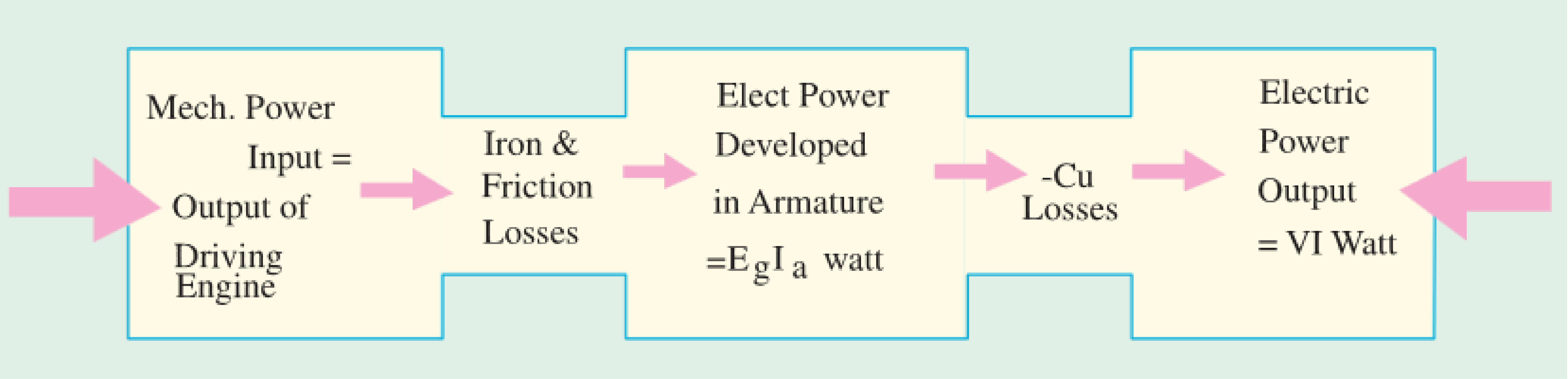
The total losses in a d.c. generator are summarized below :



Usually, magnetic and mechanical losses are collectively known as ***Stray Losses***. These are also known as rotational losses for obvious reasons.

Power Stages

Various power stages in the case of a d.c. generator are shown below :



Following are the three generator efficiencies :

1. **Mechanical Efficiency**

$$\eta_m = \frac{B}{A} = \frac{\text{total watts generated in armature}}{\text{mechanical power supplied}} = \frac{E_g I_a}{\text{output of driving engine}}$$

2. **Electrical Efficiency**

$$\eta_e = \frac{C}{B} = \frac{\text{watts available in load circuit}}{\text{total watts generated}} = \frac{VI}{E_g I_a}$$

3. **Overall or Commercial Efficiency**

$$\eta_c = \frac{C}{A} = \frac{\text{watts available in load circuit}}{\text{mechanical power supplied}}$$

It is obvious that overall efficiency $\eta_c = \eta_m \times \eta_e$. For good generators, its value may be as high as 95%.

Condition for Maximum Efficiency

Generator output = VI

Generator input = output + losses

$$= VI + I_a^2 R_a + W_c = VI + (I + I_{sh})^2 R_a + W_c \qquad (\because I_a = I + I_{sh})$$

However, if I_{sh} is negligible as compared to load current, then $I_a = I$ (approx.)

$$\therefore \qquad \eta = \frac{\text{output}}{\text{input}} = \frac{VI}{VI + I_a^2 R_a + W_c} = \frac{VI}{VI + I^2 R_a + W_c} \qquad (\because I_a = I)$$

$$= \frac{1}{1 + \left(\frac{IR_a}{V} + \frac{W_c}{VI}\right)}$$

Now, efficiency is maximum when denominator is minimum *i.e.* when

$$\frac{d}{dI}\left(\frac{IR_a}{V} + \frac{W_c}{VI}\right) = 0 \text{ or } \frac{R_a}{V} - \frac{W_c}{VI^2} = \quad \text{or} \quad I^2 R_a = W_c$$

Hence, generator efficiency is maximum when

Variable loss = constant loss.

WEEK 10

PAGE 80 - 83

Armature Reaction and Related Concepts in DC Generators

Armature Reaction refers to the effect of the magnetic field produced by the armature current on the main field flux in a DC generator. This interaction distorts the main field, causing a shift in the neutral plane (the plane where no EMF is induced) and leading to problems such as sparking at the brushes, reduced efficiency, and uneven magnetic flux distribution. The distortion can be classified into two components: demagnetizing and cross-magnetizing effects.

Demagnetizing Conductors:
These are the armature conductors that produce a magnetic field opposing the main field flux.
This opposition reduces the overall magnetic flux, decreasing the generator's voltage output.

Cross-Magnetizing Conductors:
These are the conductors that produce a magnetic field perpendicular to the main field.
This causes flux distortion, leading to a shift in the neutral plane, which can result in sparking at the brushes.

Compensating Windings

To mitigate the adverse effects of armature reaction, compensating windings are used. These windings are embedded in the pole faces and carry current proportional to the armature current. The magnetic field generated by the compensating windings neutralizes the armature reaction in the pole arc region, ensuring a uniform magnetic field and improving the commutation process.

Number of Compensating Windings:

The number of compensating winding turns per pole can be calculated as:

$$N_c = \frac{I_a}{I_c} \cdot Z$$

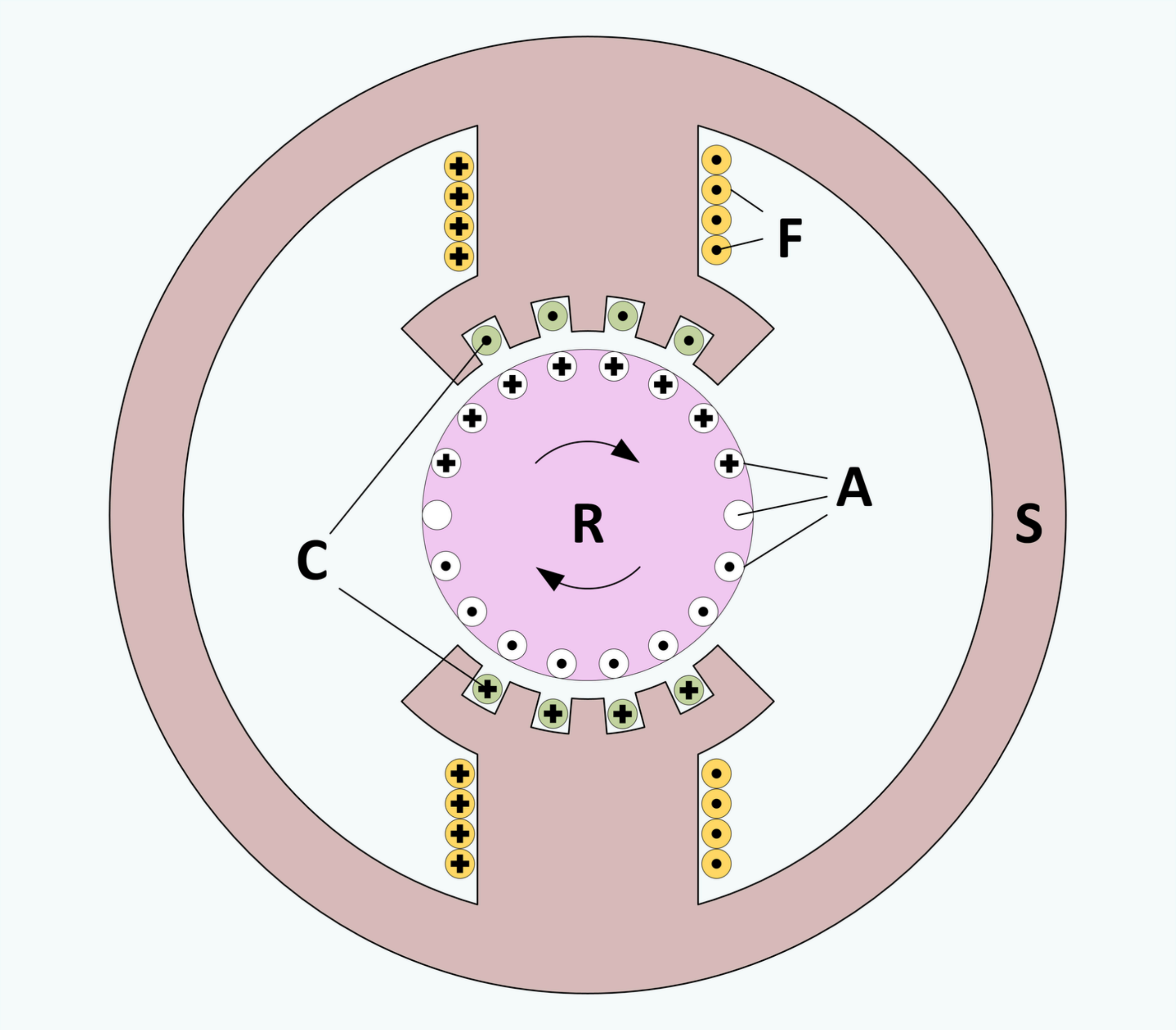
Where:

Nc: Number of compensating winding turns per pole

Ia: Armature current

Ic: Current per turn in compensating windings

Z: Total number of armature conductors per pole



Interpoles (or Compoles)

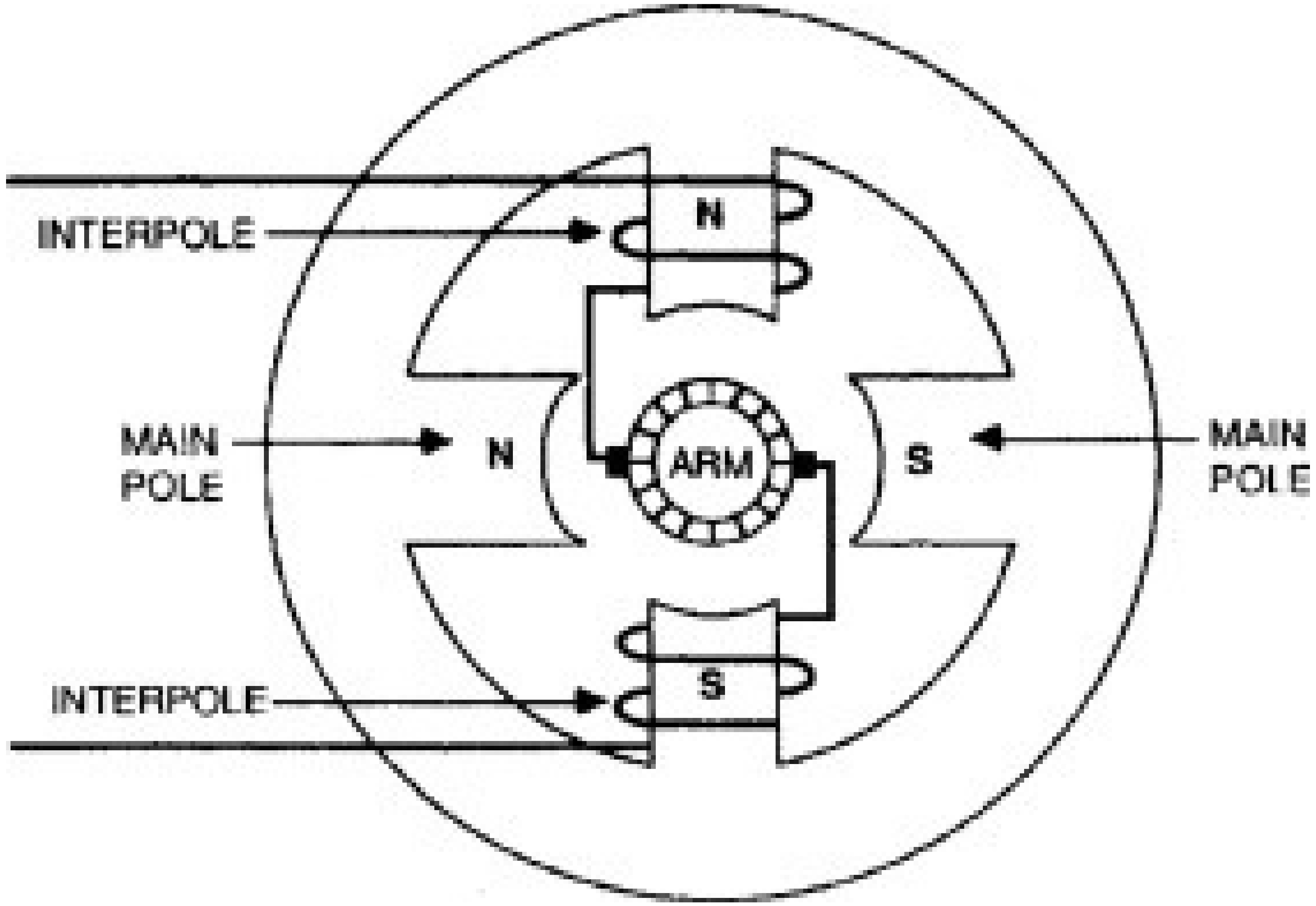
Interpoles are small auxiliary poles placed between the main poles of a DC machine. These poles are connected in series with the armature winding and carry the armature current. The primary functions of interpoles are:

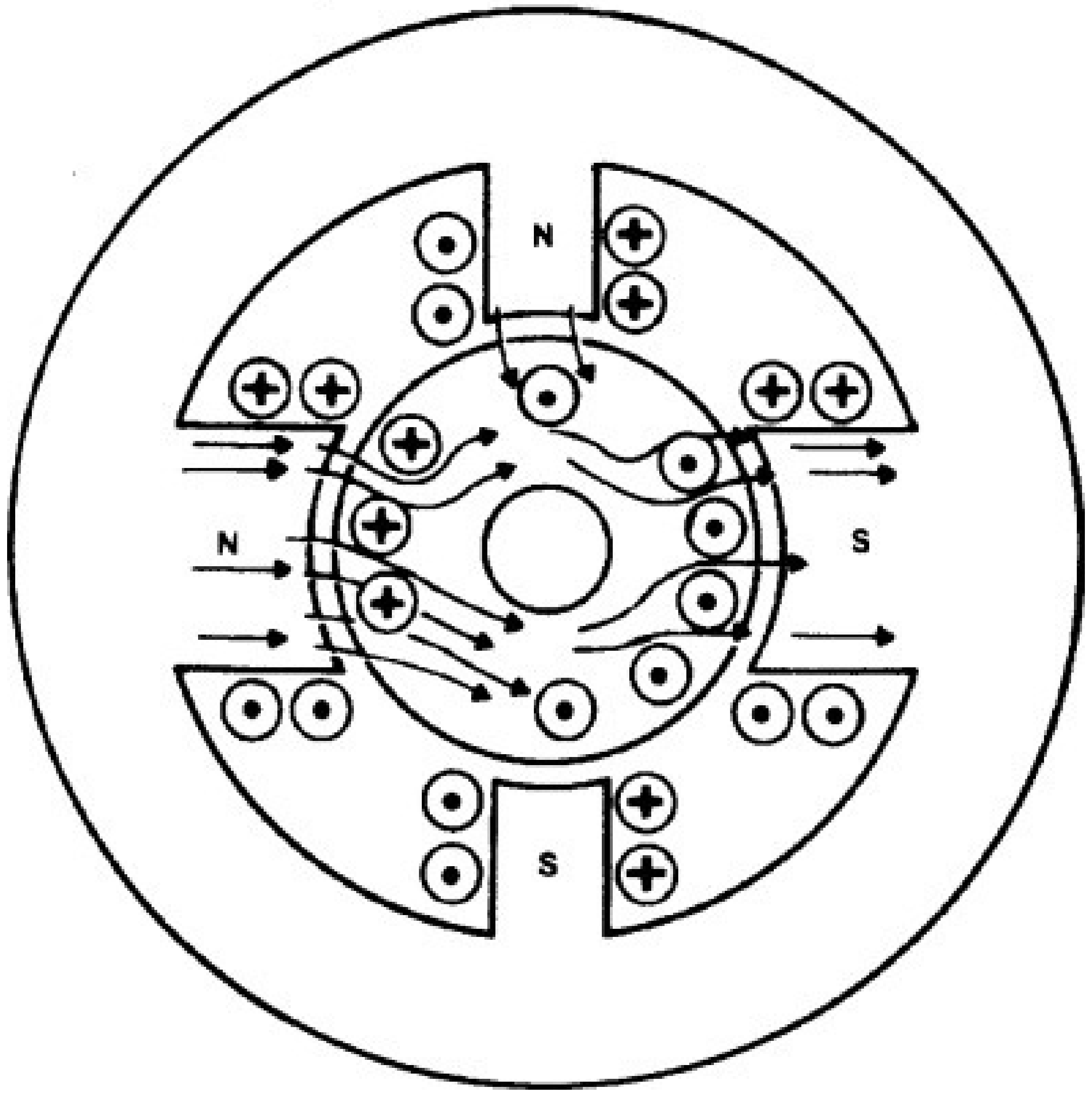
Neutralize Armature Reaction: They generate a flux that counteracts the cross-magnetizing effect in the commutator zone.

Aid in Commutation: By inducing a small voltage in the commutator coils, interpoles reduce sparking and improve the smoothness of the commutation process.

Interpoles are essential for maintaining the performance and efficiency of DC generators under varying load conditions. Their combined use with compensating windings ensures stable operation and prevents issues caused by armature reaction.

Interpoles (or Compoles)





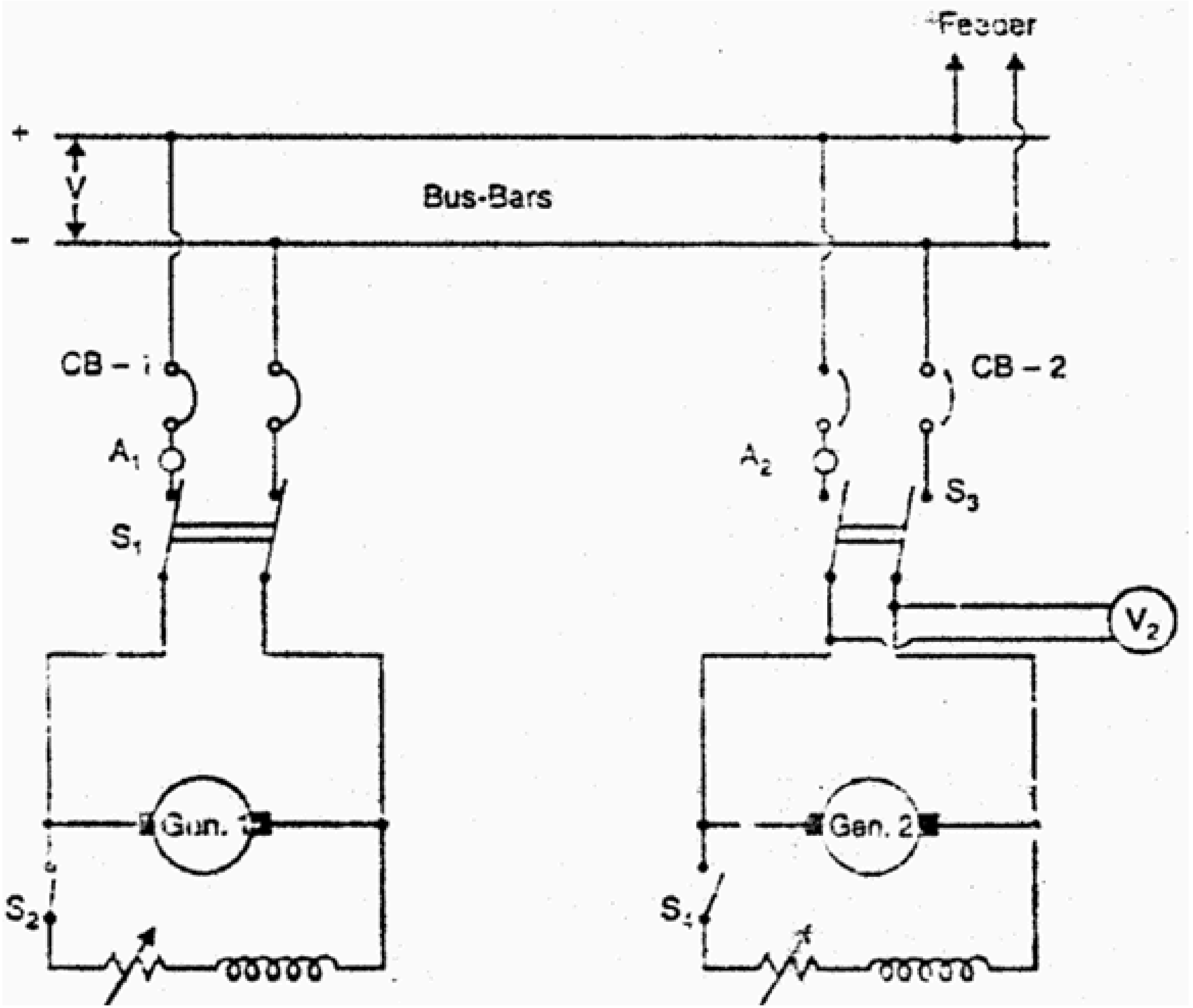
WEEK 11

PAGE 85 - 94

Paralleling DC Generators

In a d.c. power plant, power is usually supplied from several generators of small ratings connected in parallel instead of from one large generator. This is due to the following reasons: (i) Continuity of service If a single large generator is used in the power plant, then in case of its breakdown, the whole plant will be shut down. However, if power is supplied from a number of small units operating in parallel, then in case of failure of one unit, the continuity of supply can be maintained by other healthy units. (ii) Efficiency Generators run most efficiently when loaded to their rated capacity. Electric power costs less per kWh when the generator producing it is efficiently loaded. Therefore, when load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded. (iii) Maintenance and repair Generators generally require routine-maintenance and repair. Therefore, if generators are operated in parallel, the routine or emergency operations can be performed by isolating the affected generator while load is being supplied by other units. This leads to both safety and economy. (iv) Increasing plant capacity In the modern world of increasing population, the use of electricity is continuously increasing. When added capacity is required, the new unit can be simply paralleled with the old units. (v) Non-availability of single large unit In many situations, a single unit of desired large capacity may not be available. In that case a number of smaller units can be operated in parallel to meet the load requirement. Generally a single large unit is more expensive

Connecting Shunt Generators in Parallel



Connecting Shunt Generators in Parallel

(i) The prime mover of generator 2 is brought up to the rated speed. Now switch S4 in the field circuit of the generator 2 is closed.

(ii) The prime mover of generator 2 is brought up to the rated speed. Now switch S4 in the field circuit of the generator 2 is closed. Next circuit breaker CB-2 is closed and the excitation of generator 2 is adjusted till it generates voltage equal to the bus-bars voltage. This is indicated by voltmeter V2.

(iii) Now the generator 2 is ready to be paralleled with generator 1. The main switch S3, is closed, thus putting generator 2 in parallel with generator 1. Note that generator 2 is not supplying any load because its generated e.m.f. is equal to bus-bars voltage. The generator is said to be “floating” (i.e., not supplying any load) on the bus-bars.

(iv) If generator 2 is to deliver any current, then its generated voltage E should be greater than the bus-bars voltage V. In that case, current supplied by it is $I = (E - V)/R_a$ where R_a is the resistance of the armature circuit. By increasing the field current (and hence induced e.m.f. E), the generator 2 can be made to supply proper amount of load.

Types of D.C. Generators

The magnetic field in a d.c. generator is normally produced by electromagnets rather than permanent magnets. Generators are generally classified according to their methods of field excitation.

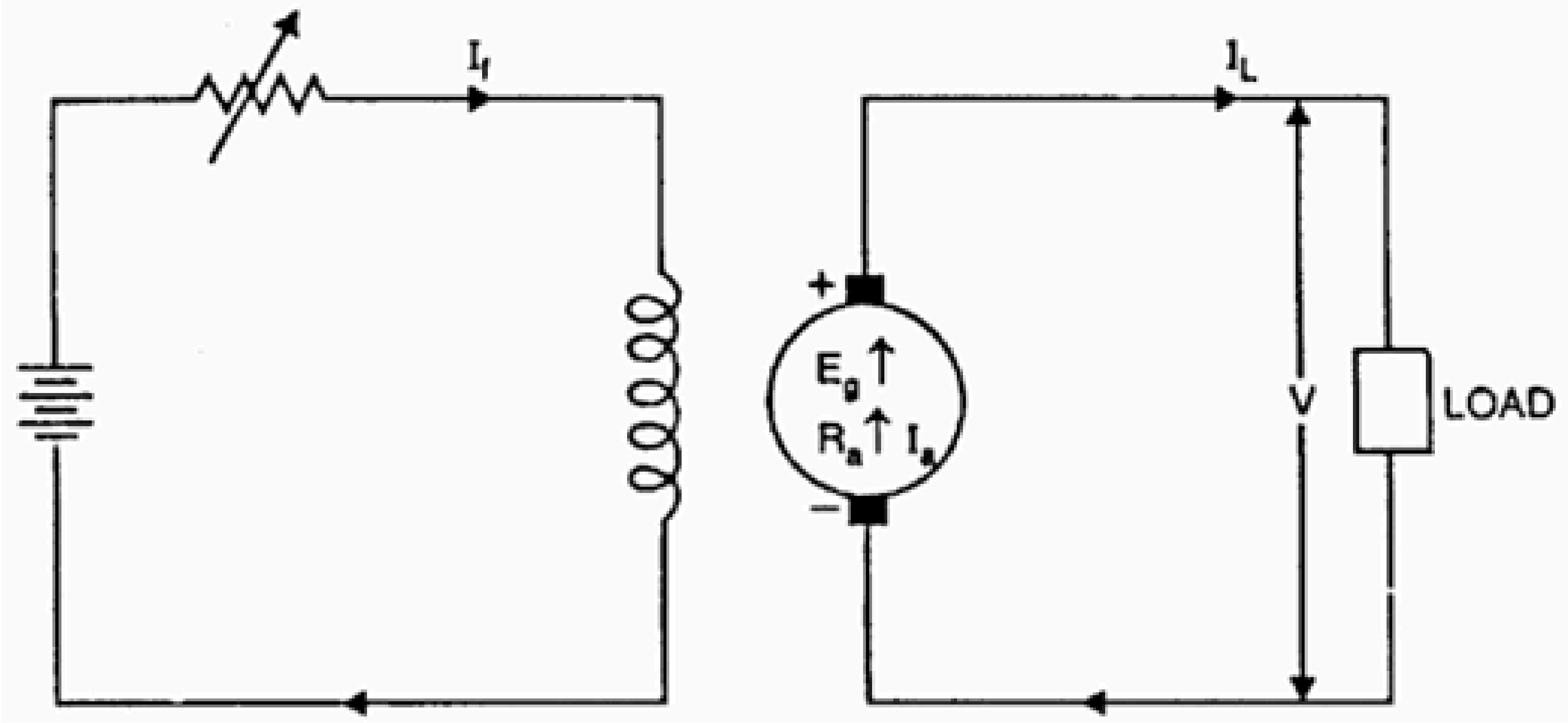
On this basis, d.c. generators are divided into the following two classes:

(i) Separately excited d.c. generators
(ii) Self-excited d.c. generators

The behaviour of a d.c. generator on load depends upon the method of field excitation adopted.

Separately Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator. Fig. shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current (E_g = Pϕ ZN/60 A). The greater the speed and field current, greater is the generated e.m.f. It may be noted that separately excited d.c. generators are rarely used in practice. The d.c. generators are normally of self-excited type.



Separately Excited D.C. Generators

Armature current, $I_a = I_L$
Terminal voltage, $V = E_g - I_a R_a$
Electric power developed = $E_g I_a$
Power delivered to load = $E_g I_a - I_a^2 R_a = I_a \left(E_g - I_a R_a\right) = VI_a$

Self-Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

(i) Series generator;
(ii) Shunt generator;
(iii) Compound generator

Series Generator

In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load. Fig. shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., as boosters.

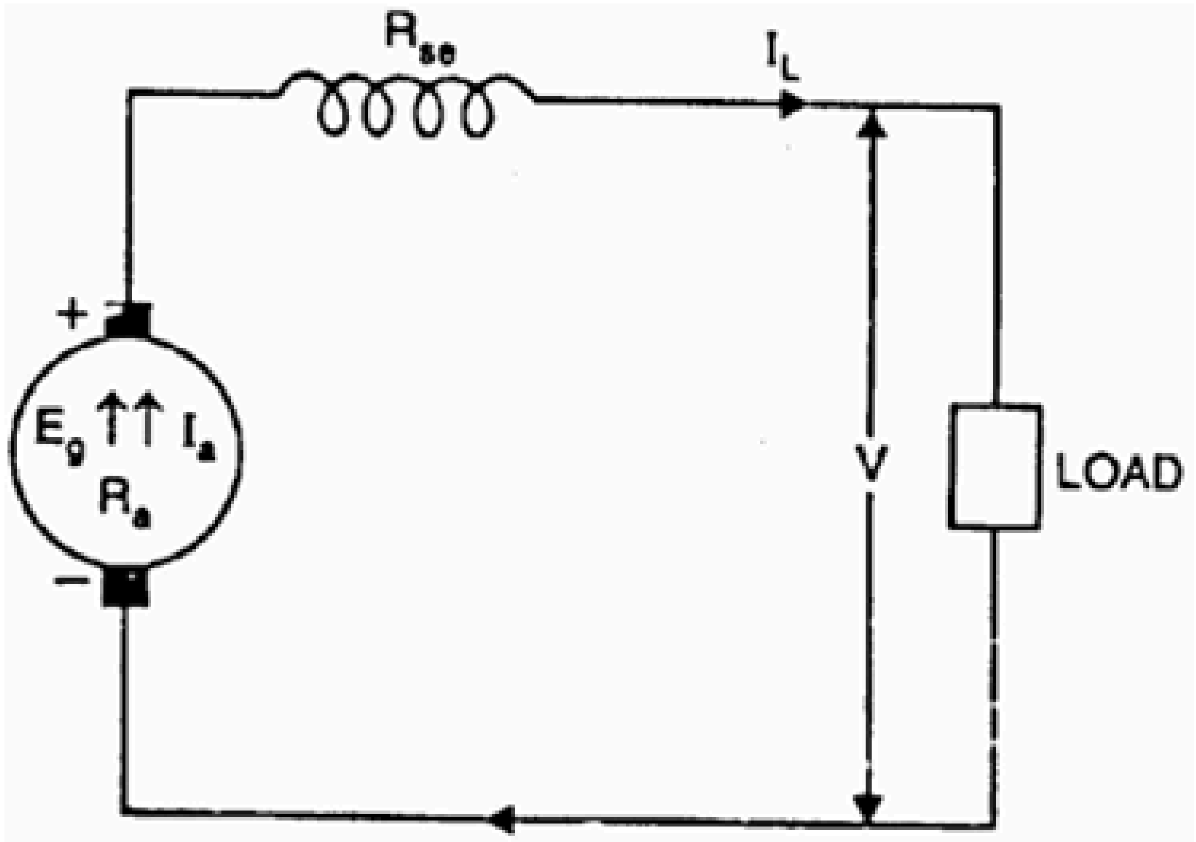
Armature current, $I_a = I_{se} = I_L = I(\text{say})$

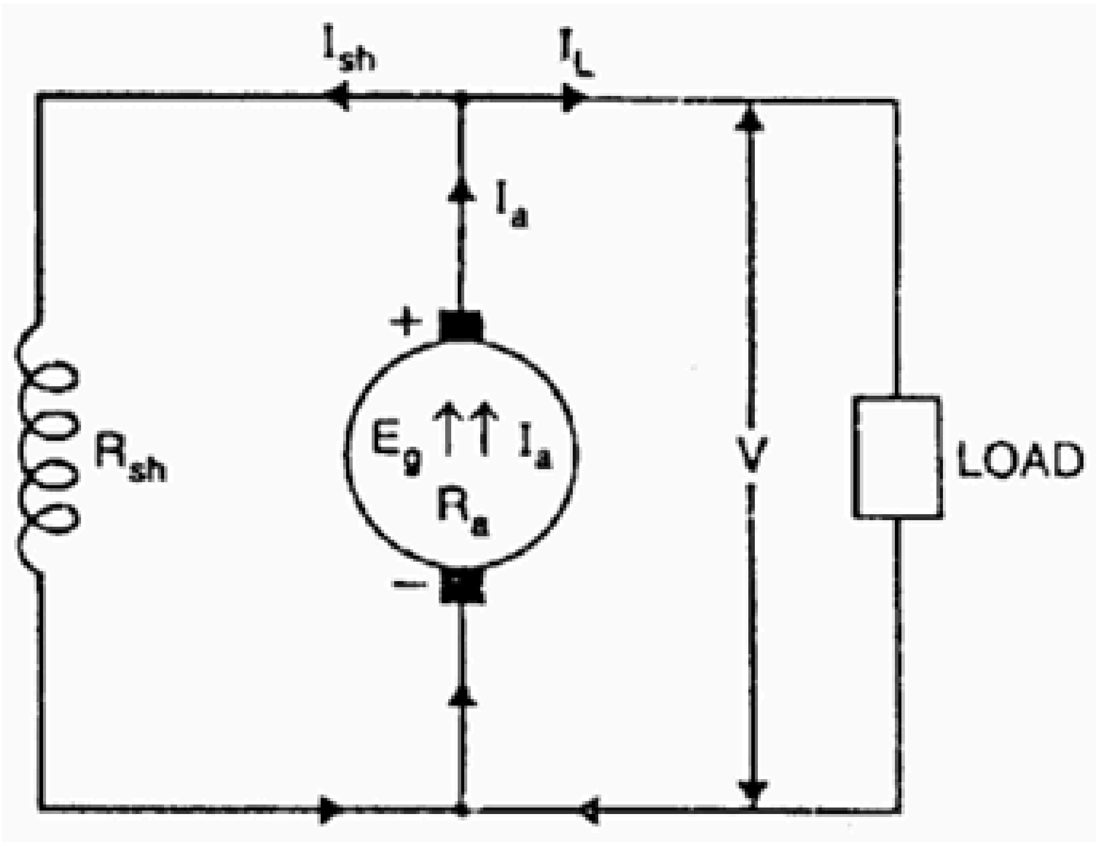
Terminal voltage, $V = E_G - I(R_a + R_{se})$

Power developed in armature $= E_g I_a$

Power delivered to load

$$= E_g I_a - I_a^2 (R_a + R_{se}) = I_a \left[E_g - I_a (R_a - R_{se})\right] = VI_a \text{ or } VI_L$$





Shunt Generator

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load. Fig. shows the connections of a shunt-wound generator.

Shunt field current, $I_{sh} = V/R_{sh}$

Armature current, $I_a = I_L + I_{sh}$

Terminal voltage, $V = E_g - I_aR_a$

Power developed in armature $= E_gI_a$

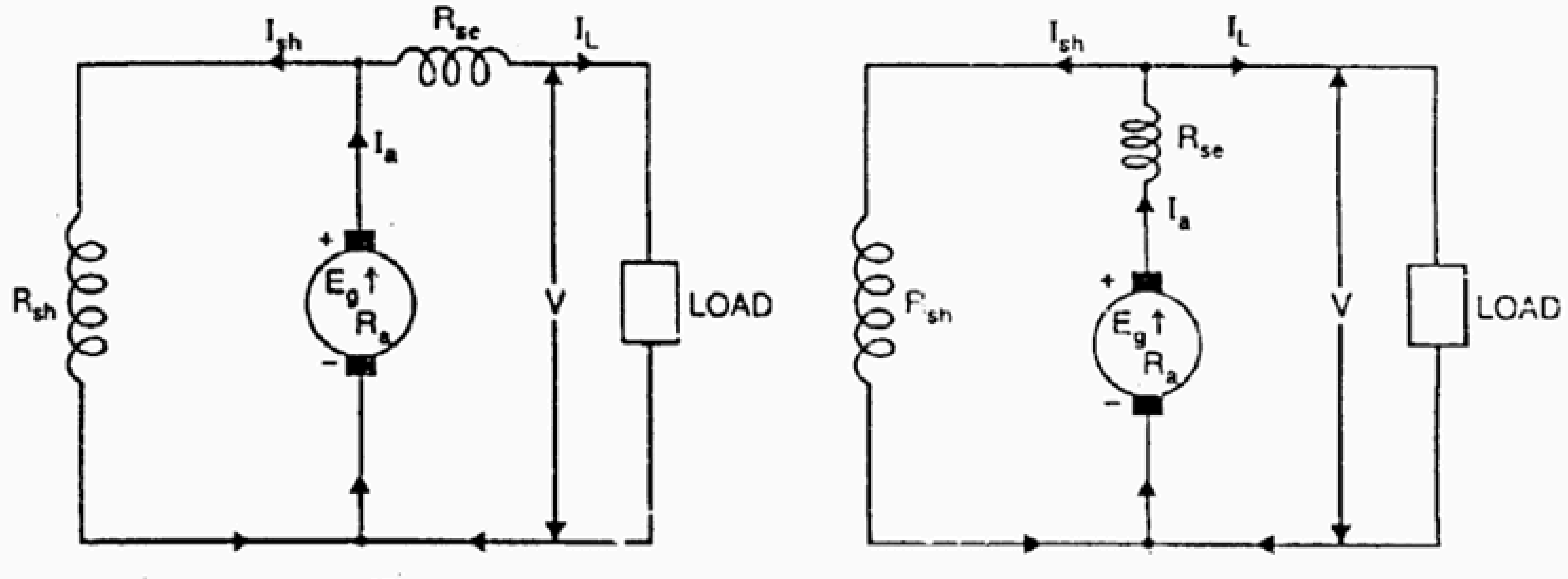
Power delivered to load $= VI_L$

Compound Generator

In a compound-wound generator, there are two sets of field windings on each pole—one is in series and the other in parallel with the armature. A compound wound generator may be:

(a) Short Shunt in which only shunt field winding is in parallel with the armature winding .

(b)Long Shunt in which shunt field winding is in parallel with both series field and armature winding



(i) (ii)

Compound Generator

Short shunt

Series field current, $I_{se} = I_L$

Shunt field current, $I_{sh} = \frac{V + I_{se}R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_s$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

Long shunt

Series field current, $I_{se} = I_a = I_L + I_{sh}$

Shunt field current, $I_{sh} = V/R_{sh}$

Terminal voltage, $V = E_g - I_a(R_a + R_{se})$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

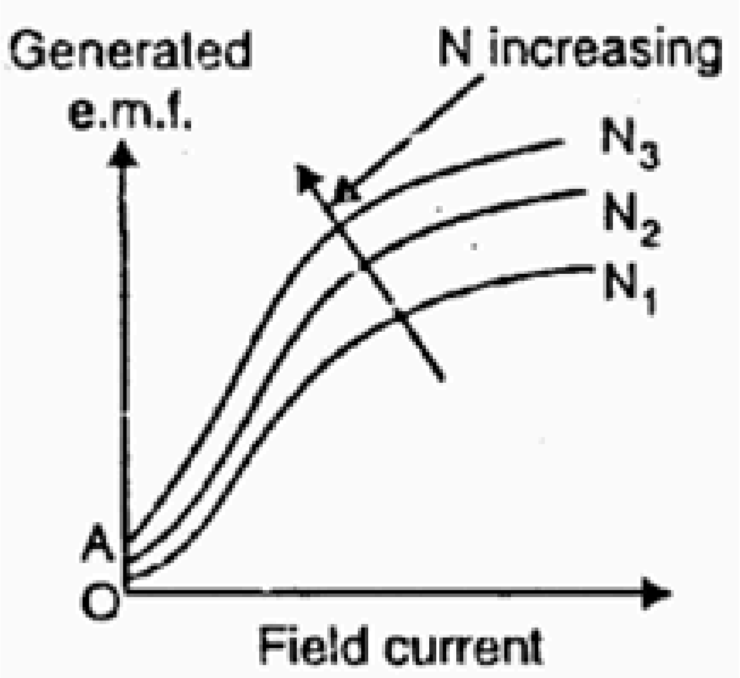
WEEK 12

PAGE 96 - 107

Characteristics of a Separately Excited D.C. Generator

(i) Open circuit characteristic.

The O.C.C. of a separately excited generator is determined in a manner described in Fig. shows the variation of generated e.m f. on no load with field current for various fixed speeds. Note that if the value of constant speed is increased, the steepness of the curve also increases. When the field current is zero, the residual magnetism in the poles will give rise to the small initial e.m.f. as shown.



Characteristics of a Separately Excited D.C. Generator

(ii) Internal and External Characteristics

The external characteristic of a separately excited generator is the curve between the terminal voltage (V) and the load current I_L (which is the same as armature current in this case). In order to determine the external characteristic, the circuit set up is as shown in Fig. (i). As the load current increases, the terminal voltage falls due to two reasons:

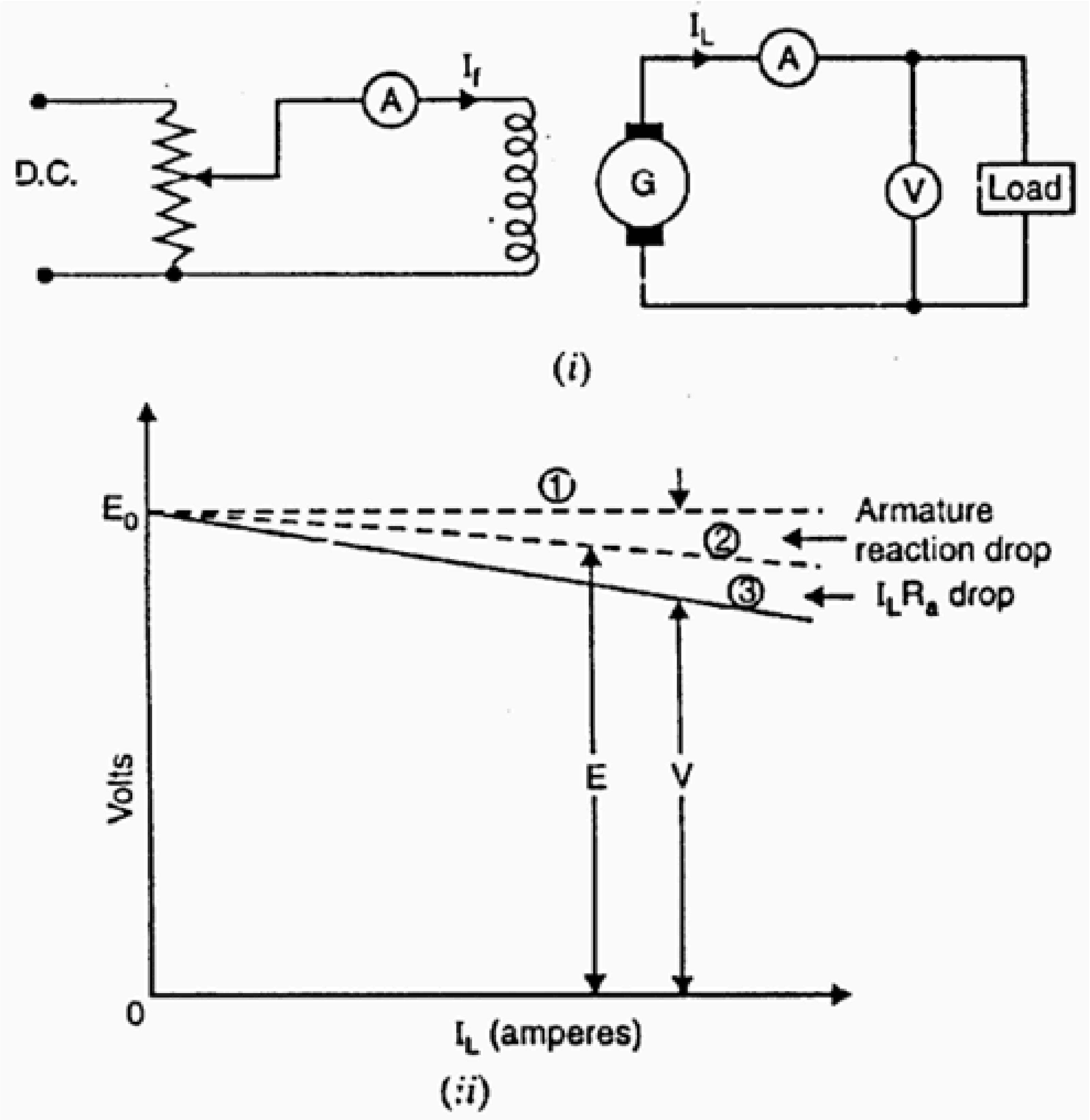
(a) The armature reaction weakens the main flux so that actual e.m.f. generated E on load is less than that generated (E_0) on no load.

(b) There is voltage drop across armature resistance ($= I_L R_a = I_a R_a$).

Due to these reasons, the external characteristic is a drooping curve [curve 3 in Fig. 3.3 (ii)]. Note that in the absence of armature reaction and armature drop, the generated e.m.f. would have been E_0 (curve 1).

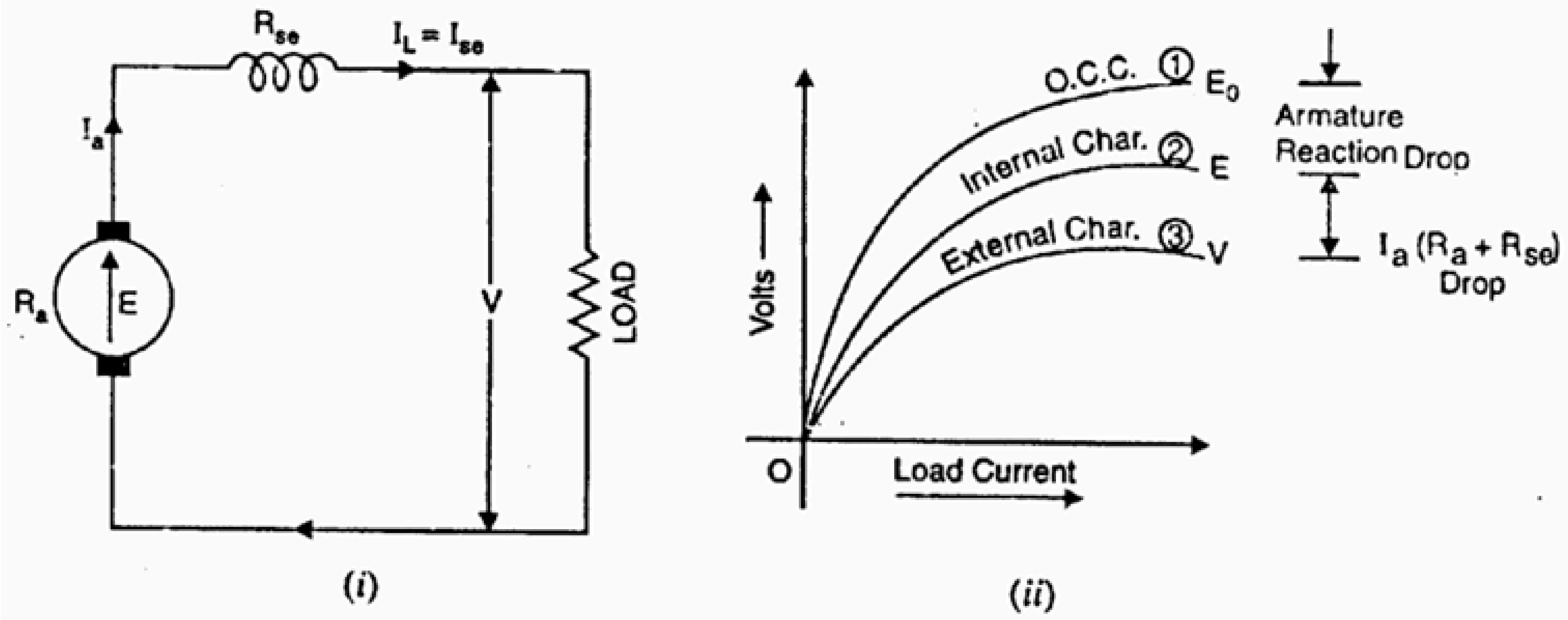
The internal characteristic can be determined from external characteristic by adding $I_L R_a$ drop to the external characteristic. It is because armature reaction drop is included in the external characteristic. Curve 2 is the internal

Characteristics of a Separately Excited D.C. Generator



Characteristics of Series Generator

Fig. (i) shows the connections of a series wound generator. Since there is only one current (that which flows through the whole machine), the load current is the same as the exciting current.



Characteristics of Series Generator

(i) O.C.C.

Curve 1 shows the open circuit characteristic (O.C.C.) of a series generator. It can be obtained experimentally by disconnecting the field winding from the machine and exciting it from a separate d.c. source

(ii) Internal characteristic

Curve 2 shows the total or internal characteristic of a series generator. It gives the relation between the generated e.m.f. E. on load and armature current. Due to armature reaction, the flux in the machine will be less than the flux at no load. Hence, e.m.f. E generated under load conditions will be less than the e.m.f. E_0 generated under no load conditions. Consequently, internal characteristic curve lies below the O.C.C. curve; the difference between them representing the effect of armature reaction

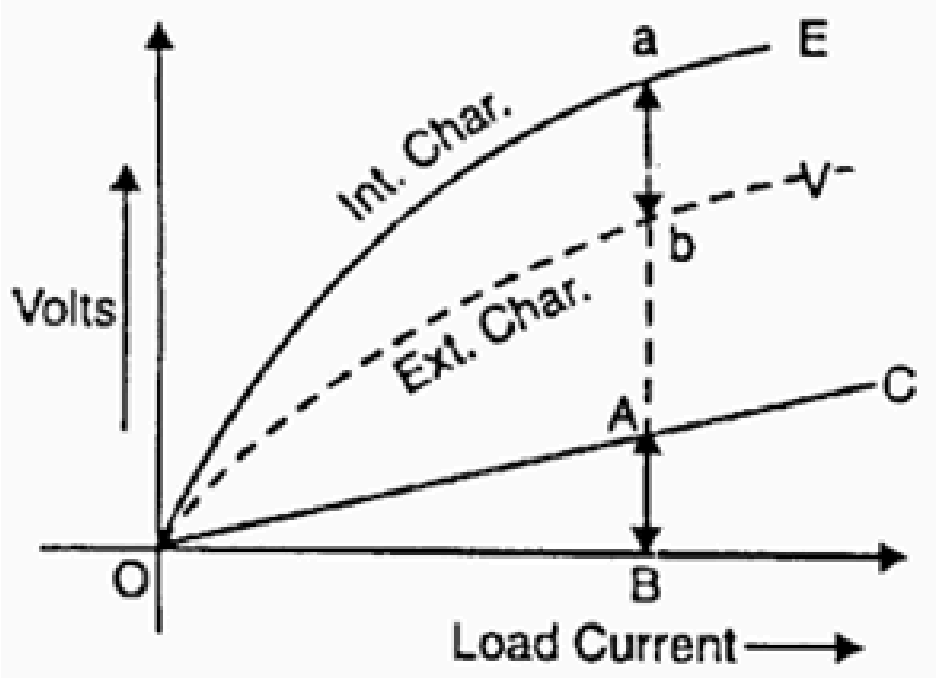
Characteristics of Series Generator

(iii) External characteristic

Curve 3 shows the external characteristic of a series generator. It gives the relation between terminal voltage and load current $I_{L:}$.

$$V = E - I_a(R_a + R_{se})$$

Therefore, external characteristic curve will lie below internal characteristic curve by an amount equal to ohmic drop [i.e., $I_a(R_a + R_{se})$] in the machine as shown in Fig. (ii).



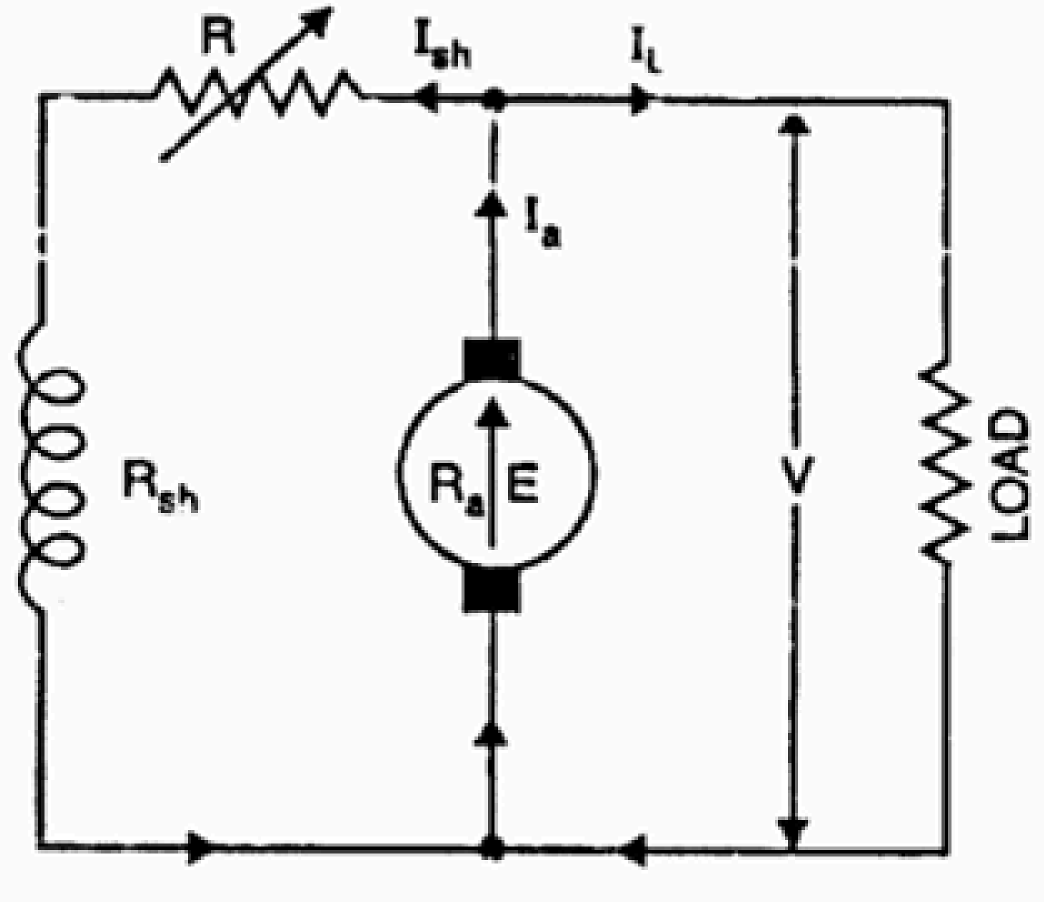
The internal and external characteristics of a d.c. series generator can be plotted from one another as shown in Fig. Suppose we are given the internal characteristic of the generator. Let the line OC represent the resistance of the whole machine i.e. $R_a + R_{se}$. If the load current is OB, drop in the machine is AB i.e.

$$AB = \text{Ohmic drop in the machine} = OB(R_a + R_{se})$$

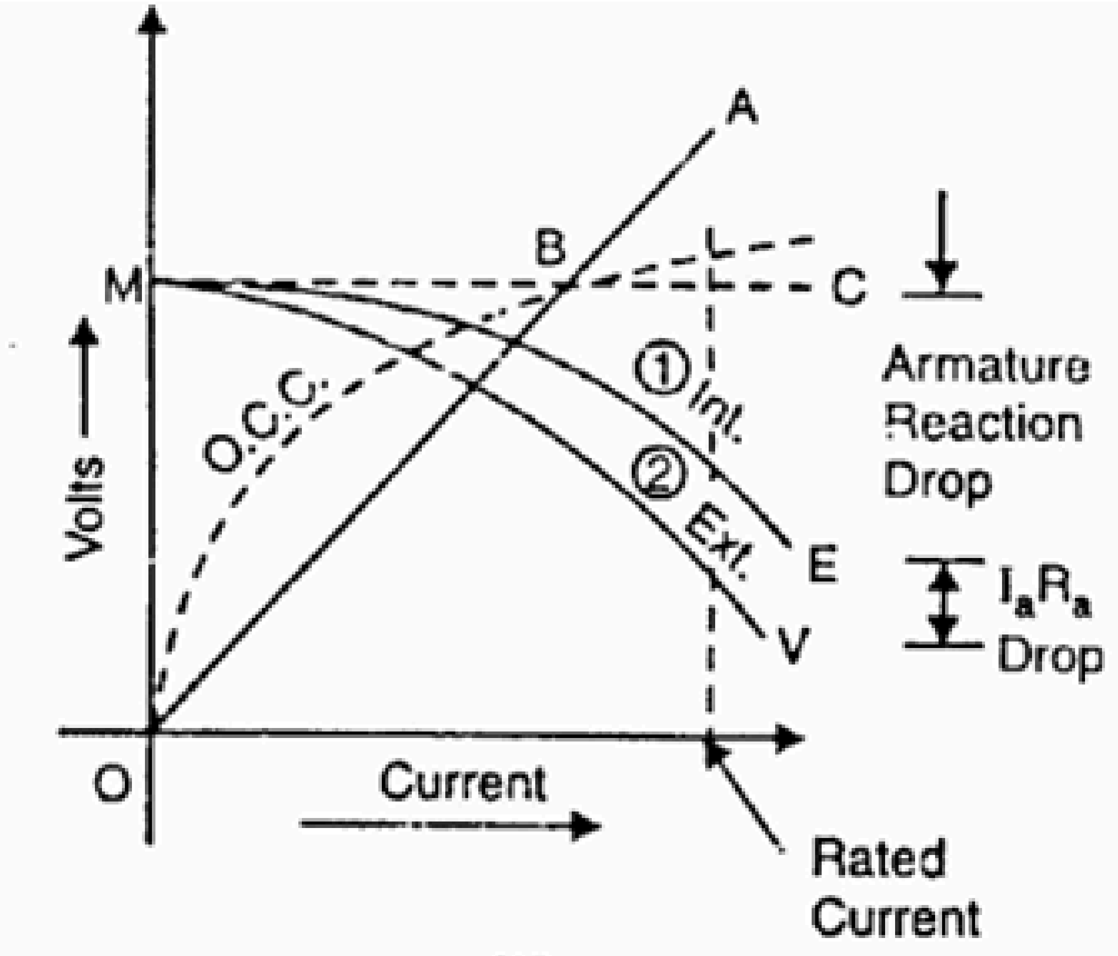
Characteristics of a Shunt Generator

(i) O.C.C.

The O.C.C. of a shunt generator is similar in shape to that of a series generator as shown in Fig. (ii). The line OA represents the shunt field circuit resistance. When the generator is run at normal speed, it will build up a voltage OM. At no-load, the terminal voltage of the generator will be constant (= OM) represented by the horizontal dotted line MC.



(i)



(ii)

Characteristics of a Shunt Generator

(ii) Internal characteristic

When the generator is loaded, flux per pole is reduced due to armature reaction. Therefore, e.m.f. E generated on load is less than the e.m.f. generated at no load. As a result, the internal characteristic (E/I_a) drops down slightly as shown in Fig. (ii).

(iii) External characteristic

Curve 2 shows the external characteristic of a shunt generator. It gives the relation between terminal voltage V and load current I_L.

$$V = E - I_a R_a = E - (I_L + I_{sh}) R_a$$

Therefore, external characteristic curve will lie below the internal characteristic curve by an amount equal to drop in the armature circuit [i.e., $(I_L + I_{sh})R_a$] as shown in Fig. (ii).

Note. It may be seen from the external characteristic that change in terminal voltage from no-load to full load is small. The terminal voltage can always be maintained constant by adjusting the field rheostat R automatically

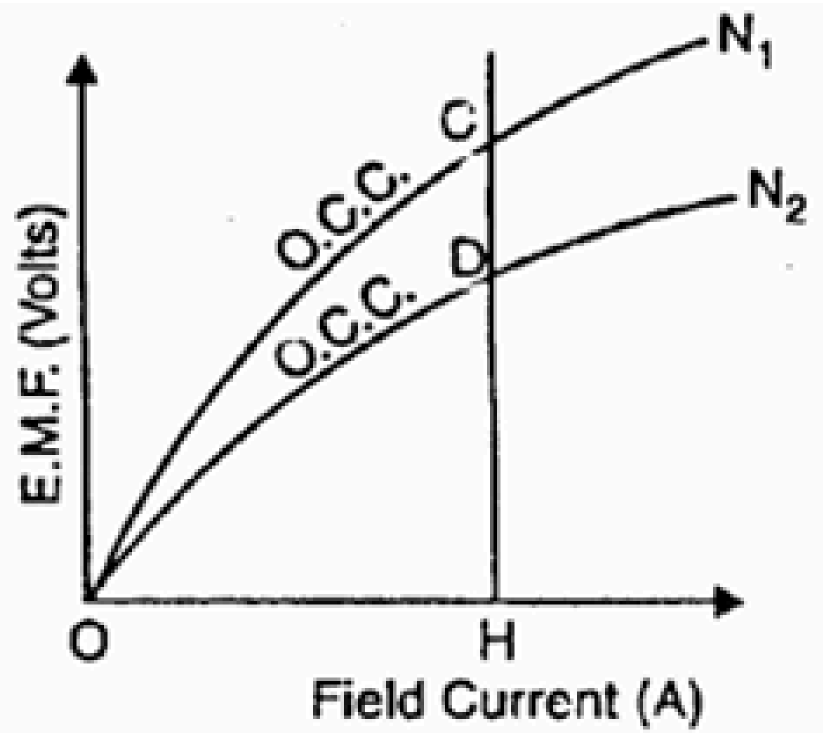
How to Draw O.C.C. at Different Speeds?

If we are given O.C.C. of a generator at a constant speed N_1, then we can easily draw the O.C.C. at any other constant speed N_2. Fig illustrates the procedure. Here we are given O.C.C. at a constant speed N_1. It is desired to find the O.C.C. at constant speed N_2 (it is assumed that $n_1 < N_2$). For constant excitation, $E \propto N$.

$$\therefore \quad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

or

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



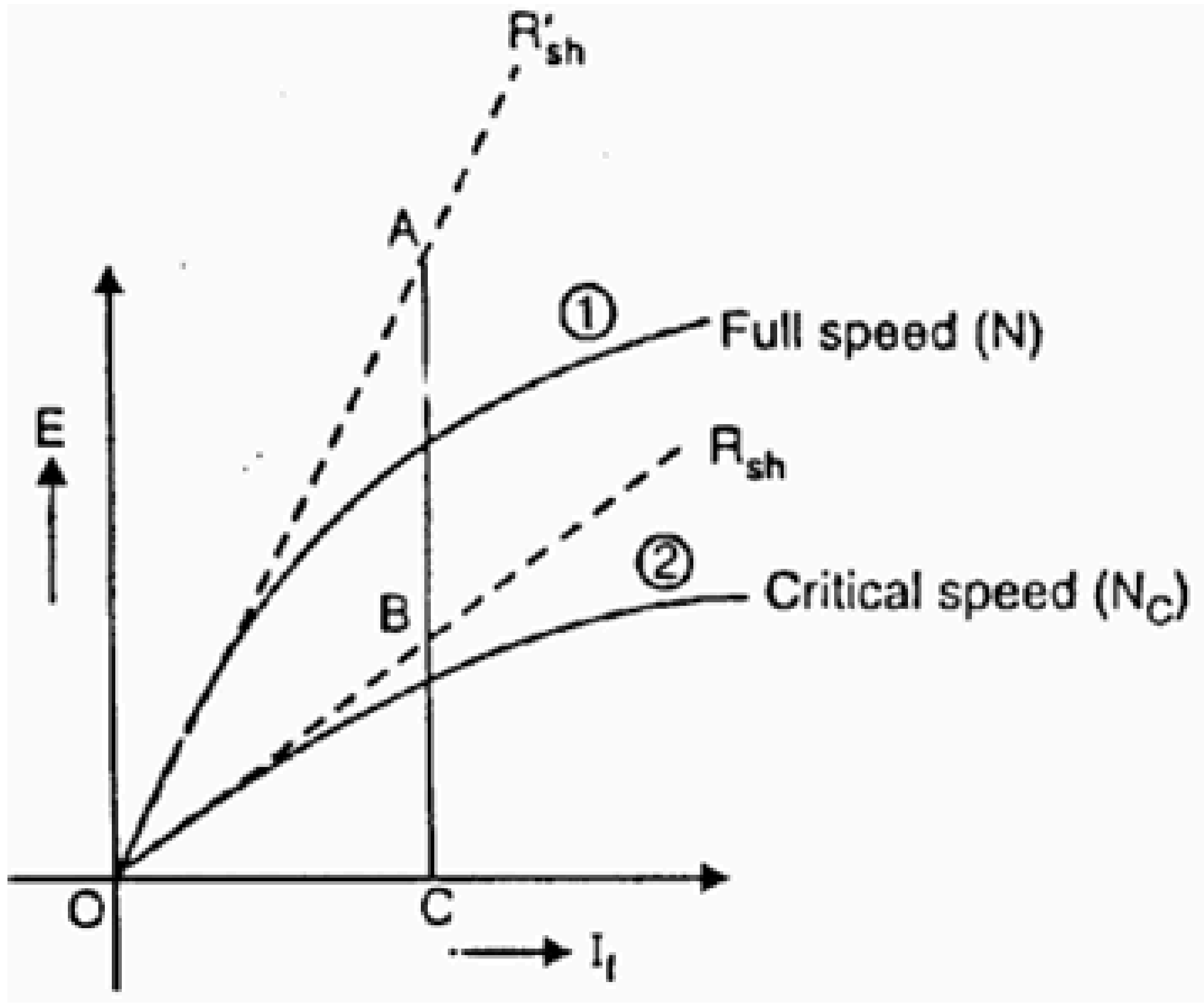
As shown in Fig. for I_f = OH, E_1 = HC. Therefore, the new value of e.m.f. (E_2) for the same I_f but at N_2 i

$$E_2 = HC \times \frac{N_2}{N_1} = HD$$

This locates the point D on the new O.C.C. at N_2. Similarly, other points can be located taking different values of I_f. The locus of these points will be the O.C.C. at N_2.

Critical Speed (NC)

The critical speed of a shunt generator is the minimum speed below which it fails to excite. Clearly, it is the speed for which the given shunt field resistance represents the critical resistance. In Fig. curve 2 corresponds to critical speed because the shunt field resistance (R_{sh}) line is tangential to it. If the generator runs at full speed N, the new O.C.C. moves upward and the R'_{sh} line represents critical resistance for this speed.



$$\therefore \quad \text{Speed} \propto \text{Critical resistance}$$

In order to find critical speed, take any convenient point C on excitation axis and erect a perpendicular so as to cut R_{sh} and R'_{sh} lines at points B and A respectively. Then,

$$\frac{BC}{AC} = \frac{N_C}{N}$$

or

$$N_C = N \times \frac{BC}{AC}$$

Conditions for Voltage Build-Up of a Shunt Generator

The necessary conditions for voltage build-up in a shunt generator are:

(i) There must be some residual magnetism in generator poles.

(ii) The connections of the field winding should be such that the field current strengthens the residual magnetism.

(iii) The resistance of the field circuit should be less than the critical resistance. In other words, the speed of the generator should be higher than the critical speed.

Voltage Regulation

The change in terminal voltage of a generator between full and no load (at constant speed) is called the voltage regulation, usually expressed as a percentage of the voltage at full-load.

$$\%\,\text{Voltage regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

where V_{NL} = Terminal voltage of generator at no load

V_{FL} = Terminal voltage of generator at full load

Note that voltage regulation of a generator is determined with field circuit and speed held constant. If the voltage regulation of a generator is 10%, it means that terminal voltage increases 10% as the load is changed from full load to no load.

WEEK 13

PAGE 109

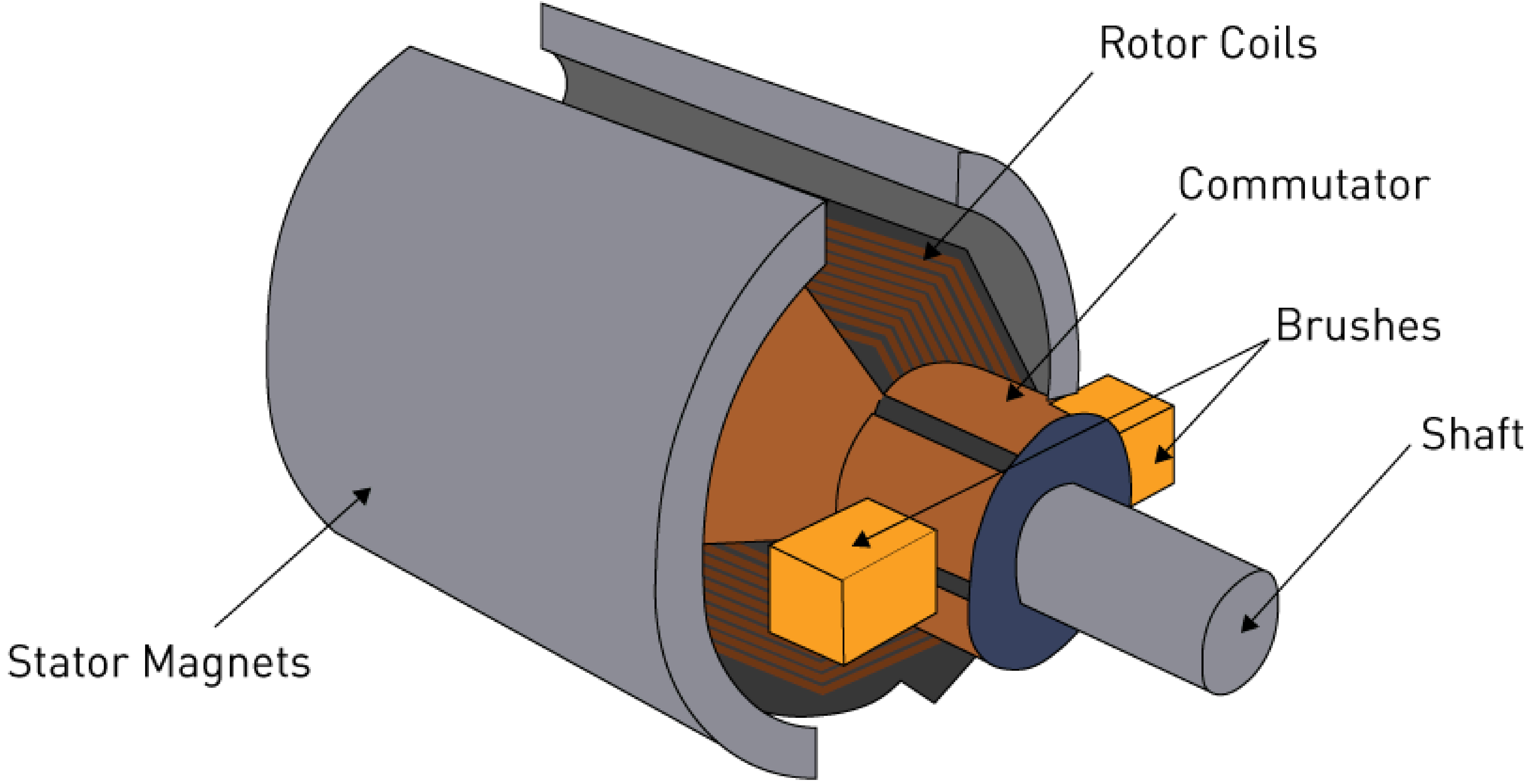
Mathematical Problems on D.C Generator

Mathematical problems related to transformers will be practiced and solved during classroom sessions. Problems from the prescribed reference book will be addressed, and additional practice materials will be provided to enhance understanding and proficiency.

WEEK 14

PAGE 111 - 126

D.C. Motors



D.C. Motor Principle

A machine that converts d.c. power into mechanical power is known as a d.c. motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule and magnitude is given by;

$$F = BIl \quad \text{newtons}$$

Basically, there is no constructional difference between a d.c. motor and a d.c. generator. The same d.c. machine can be run as a generator or motor.

Working of D.C. Motor

Consider a part of a multipolar d.c. motor as shown in Fig. When the terminals of the motor are connected to an external source of d.c. supply:

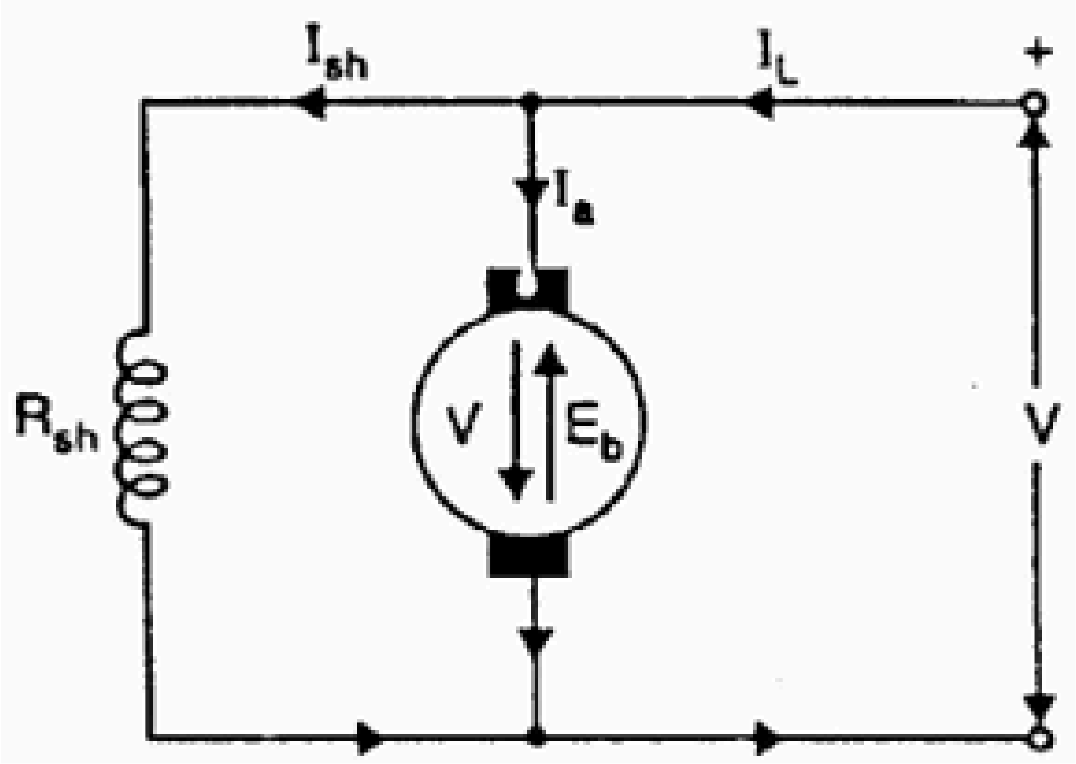
(i) the field magnets are excited developing alternate N and S poles;

(ii) the armature conductors carry ^currents. All conductors under N-pole carry currents in one direction while all the conductors under S-pole carry currents in the opposite direction.

Back or Counter E.M.F

When the armature of a d.c. motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence e.m.f. is induced in them as in a generator The induced e.m.f. acts in opposite direction to the applied voltage V(Lenz's law) and in known as back or counter e.m.f. E_b. The back e.m.f. $E_b(= P\phi ZN/60\ A)$ is always less than the applied voltage V, although this difference is small when the motor is running under normal conditions.

Consider a shunt wound motor shown in Fig. When d.c. voltage V is applied across the motor terminals, the field magnets are excited and armature conductors are supplied with current. Therefore, driving torque acts on the armature which begins to rotate. As the armature rotates, back e.m.f.



Back or Counter E.M.F

E_b is induced which opposes the applied voltage V. The applied voltage V has to force current through the armature against the back e.m.f. E_b. The electric work done in overcoming and causing the current to flow against E_b is converted into mechanical energy developed in the armature. It follows, therefore, that energy conversion in a d.c. motor is only possible due to the production of back e.m.f. E_b.

Net voltage across armature circuit = $V - E_b$

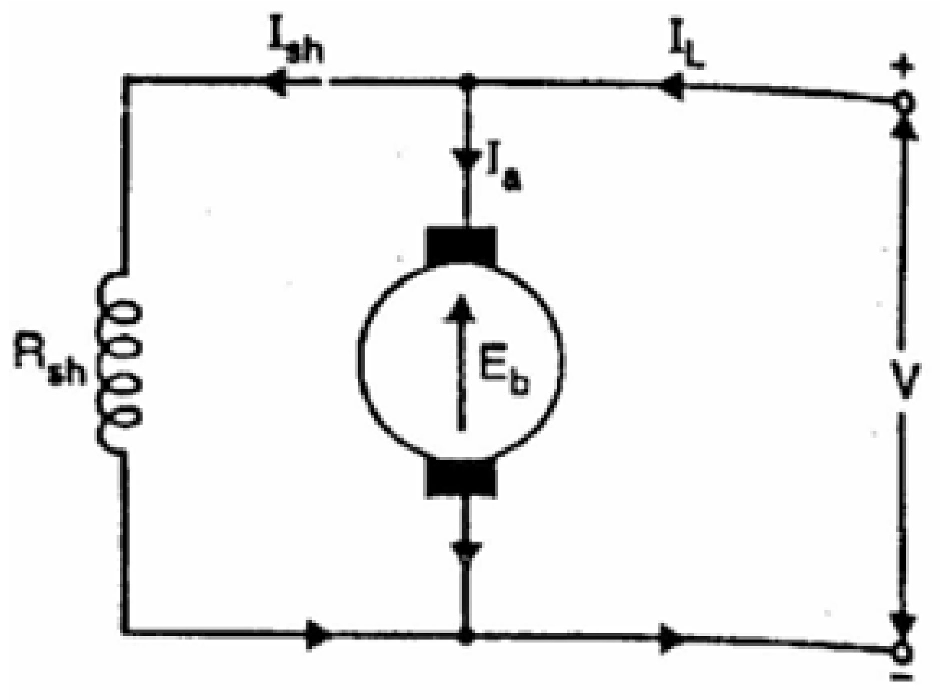
If R_a is the armature circuit resistance, then, $I_a = \frac{V - E_b}{R_a}$

Since V and R_a are usually fixed, the value of E_b will determine the current drawn by the motor. If the speed of the motor is high, then back e.m.f. E_b (= $P \phi Z N / 60 A$) is large and hence the motor will draw less armature current and vice-versa.

Voltage Equation of D.C. Motor

Let in a d.c. motor

V = applied voltage
E_b = back e.m.f.
R_a = armature resistance
I_a = armature current



Since back e.m.f. E_b acts in opposition to the applied voltage V, the net voltage across the armature circuit is $V - E_b$. The armature current I_a is given by;

$$I_a = \frac{V - E_b}{R_a}$$

or $$V = E_b + I_a R_a \quad \text{(i)}$$

This is known as voltage equation of the d.c. motor.

Power Equation

If Eq. (i) above is multiplied by ly throughout, we get,

$$VI_a = E_bI_a + I_a^2R_a$$

This is known as power equation of the d.c. motor.

VI_a = electric power supplied to armature (armature input)

E_bI_a = power developed by armature (armature output)

$I_a^2R_a$ = electric power wasted in armature (armature Cu loss)

Thus out of the armature input, a small portion (about 5%) is wasted as $I_a^2R_a$ and the remaining portion E_bI_a is converted into mechanical power within the armature.

Condition For Maximum Power

The mechanical power developed by the motor is $P_m = E_b I_a$

Now $$P_m = VI_a - I_a^2 R_a$$

Since, V and R_a are fixed, power developed by the motor depends upon armature current. For maximum power, dP_m/dI_a should be zero.

$$\therefore \quad \frac{dP_m}{dI_a} = V - 2I_a R_a = 0$$

or $$I_a R_a = \frac{V}{2}$$

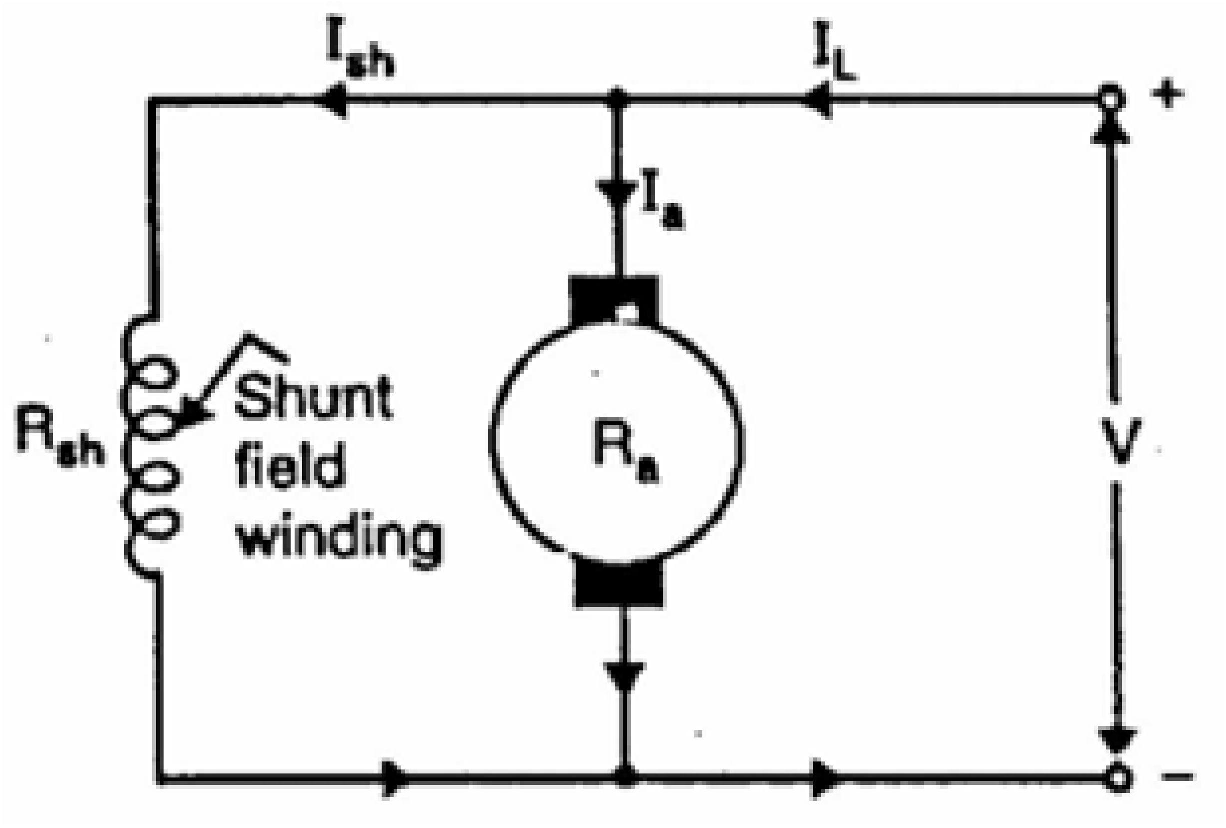
Now, $$V = E_b + I_a R_a = E_b + \frac{V}{2} \qquad \left[\because\ I_a R_a = \frac{V}{2}\right]$$

$$\therefore \quad E_b = \frac{V}{2}$$

Hence mechanical power developed by the motor is maximum when back e.m.f. is equal to half the applied voltage.

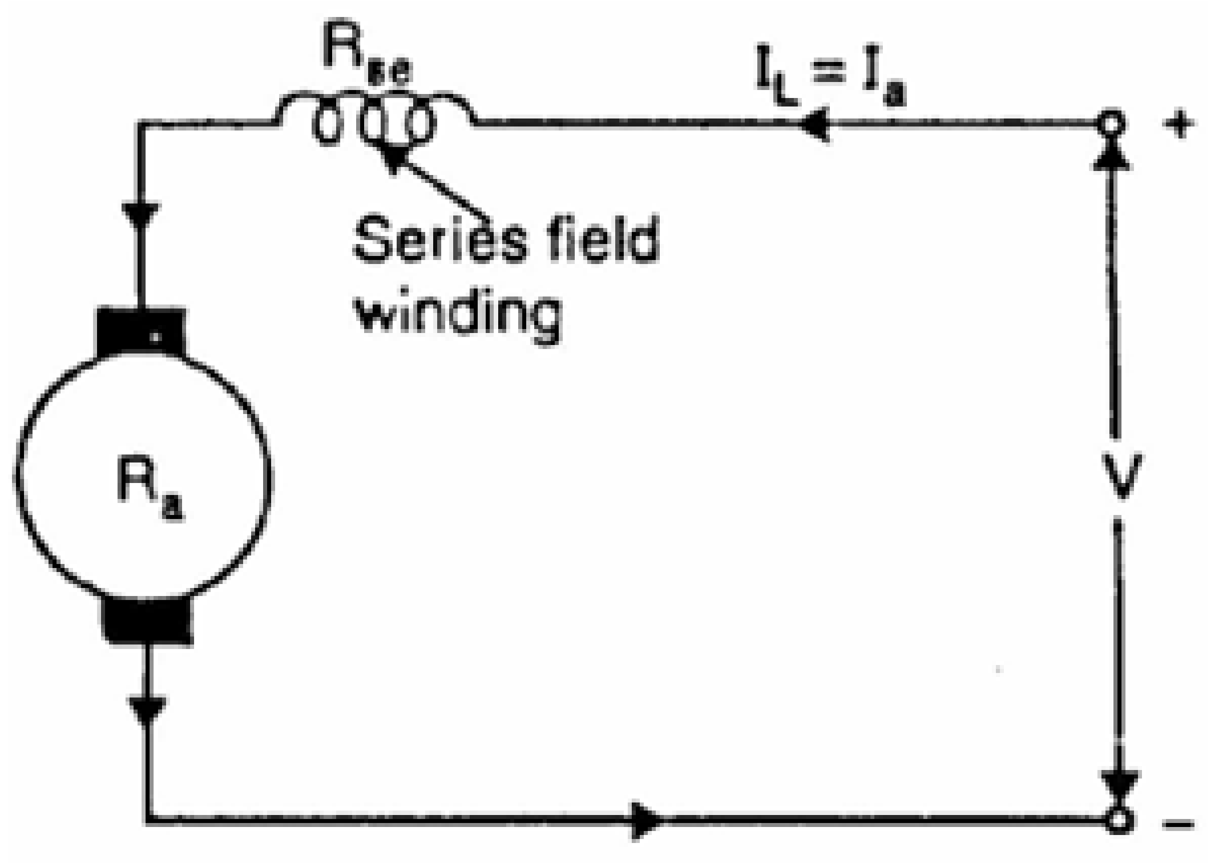
Types of D.C. Motors

(i) **Shunt-wound motor** in which the field winding is connected in parallel with the armature See Fig. The current through the shunt field winding is not the same as the armature current. Shunt field windings are designed to produce the necessary m.m.f. by means of a relatively large number of turns of wire having high resistance. Therefore, shunt field current is relatively small compared with the armature current.



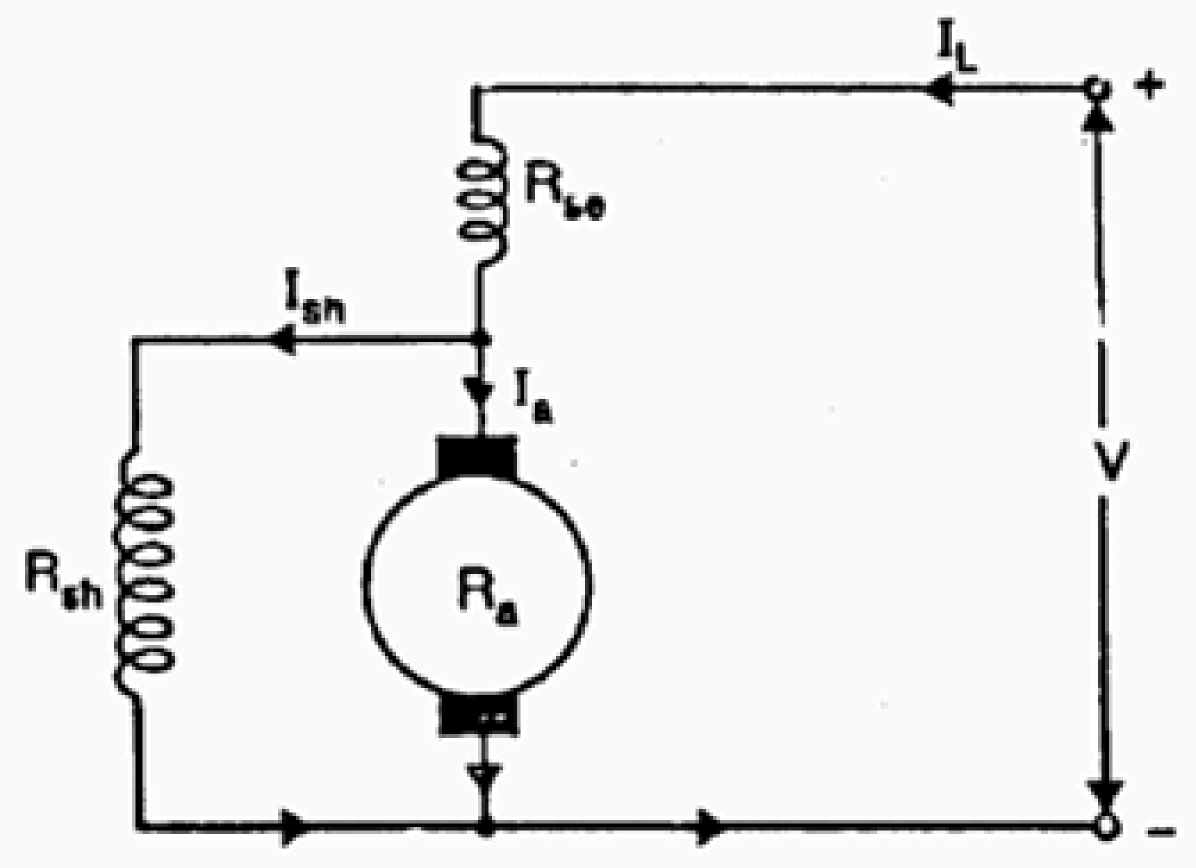
Types of D.C. Motors

(ii) **Series-wound motor** in which the field winding is connected in series with the armature [See Fig.]. Therefore, series field winding carries the armature current. Since the current passing through a series field winding is the same as the armature current, series field windings must be designed with much fewer turns than shunt field windings for the same m.m.f. Therefore, a series field winding has a relatively small number of turns of thick wire and, therefore, will possess a low resistance.

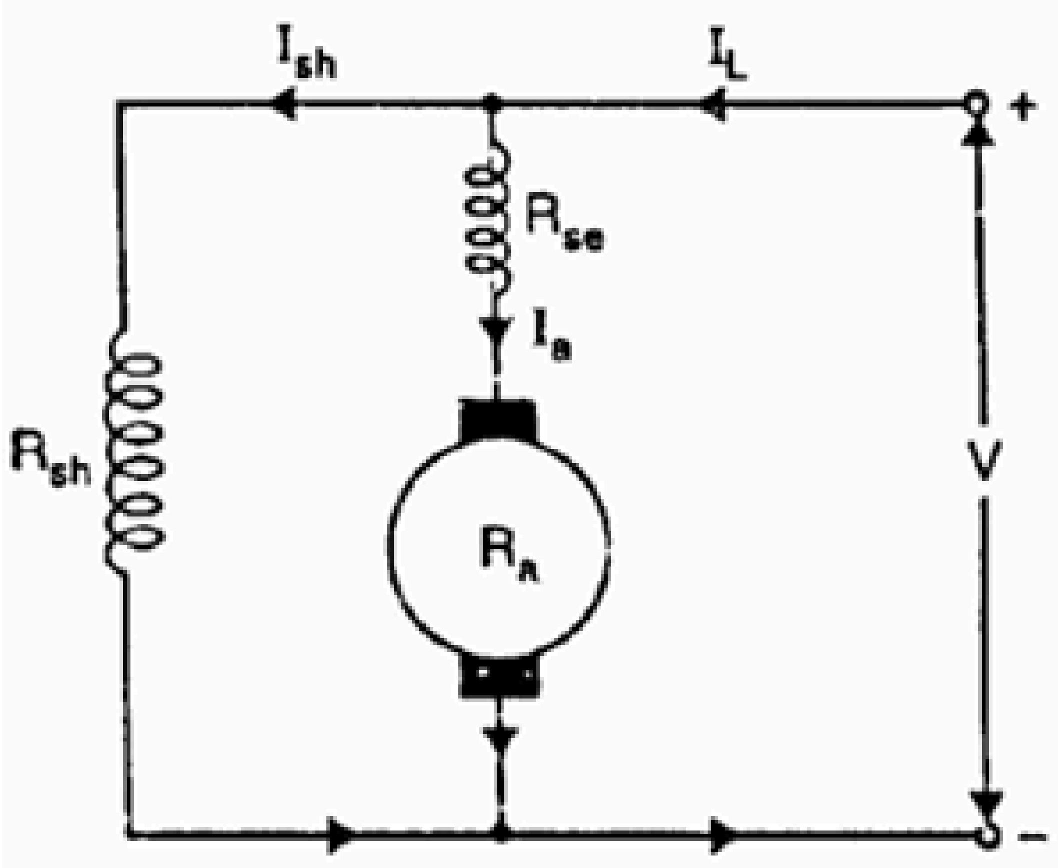


Types of D.C. Motors

(iii) **Compound-wound motor** which has two field windings; one connected in parallel with the armature and the other in series with it. There are two types of compound motor connections (like generators). When the shunt field winding is directly connected across the armature terminals [See Fig. it is called short-shunt connection. When the shunt winding is so connected that it shunts the series combination of armature and series field [See Fig. it is called long-shunt connection.



Short-shunt connection



Long-shunt connection

Speed of a D.C. Motor

$$E_b = V - I_a R_a$$

But $$E_b = \frac{P\phi Z N}{60\ A}$$

$$\therefore \quad \frac{P\phi Z N}{60\ A} = V - I_a R_a$$

or $$N = \frac{(V - I_a R_a)}{\phi} \frac{60\ A}{P Z}$$

or $$N = K \frac{(V - I_a R_a)}{\phi}$$ where $$K = \frac{60 A}{PZ}$$

But $$V - I_a R_a = E_a$$

$$\therefore \quad N = K \frac{E_b}{\phi}$$

or $$N \propto \frac{E_b}{\phi}$$

Therefore, in a d.c. motor, speed is directly proportional to back e.m.f. E_b and inversely proportional to flux per pole ϕ.

Speed Relations

If a d.c. motor has initial values of speed, flux per pole and back e.m.f. as N_1, ϕ_1 and E_{b1} respectively and the corresponding final values are N_2, ϕ_2 and E_{b2}, then,

$$N_1 \propto \frac{E_{b1}}{\phi_1} \quad \text{and} \quad N_2 \propto \frac{E_{b2}}{\phi_2}$$

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

(i) For a shunt motor, flux practically remains constant so that $\phi_1 = \phi_2$.

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

(ii) For a series motor, $\phi \propto I_a$ prior to saturation.

$$\therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}$$

where I_{a1} = initial armature current

I_{a2} = final armature current

Speed Regulation

The speed regulation of a motor is the change in speed from full-load to no-loud and is expressed as a percentage of the speed at full-load i.e.

$$\% \text{ Speed regulation } = \frac{\text{N.L. speed} - \text{F.L.speed}}{\text{F.L. speed}} \times 100$$

$$= \frac{N_0 - N}{N} \times 100$$

where N_0 = No - load .speed

N = Full - load speed

Torque and Speed of a D.C. Motor

For any motor, the torque and speed are very important factors. When the torque increases, the speed of a motor increases and vice-versa. We have seen that for a d.c. motor;

$$N = K\frac{(V - I_a R_a)}{\phi} = \frac{K E_b}{\phi} \quad \text{(i)}$$

$$T_a \propto \phi I_a \quad \text{(ii)}$$

If the flux decreases, from Eq.(i), the motor speed increases but from Eq.(ii) the motor torque decreases. This is not possible because the increase in motor speed must be the result of increased torque. Indeed, it is so in this case. When the flux decreases slightly, the armature current increases to a large value. As a result, in spite of the weakened field, the torque is momentarily increased to a high value and will exceed considerably the value corresponding to the load. The surplus torque available causes the motor to accelerate and back e.m.f. ($E_a = P \phi Z N/60 A$) to rise. Steady conditions of speed will ultimately be achieved when back e.m.f. has risen to such a value that armature current [$I_a = (V - E_a)/R_a$] develops torque just sufficient to drive the load.

Efficiency of a D.C. Motor

Like a d.c. generator, the efficiency of a d.c. motor is the ratio of output power to the input power i.e.

$$\text{Efficiency, } \eta = \frac{\text{output}}{\text{input}} \times 100 = \frac{\text{output}}{\text{output} + \text{losses}} \times 100$$

As for a generator the efficiency of a d.c. motor will be maximum when:

Variable losses = Constant losses

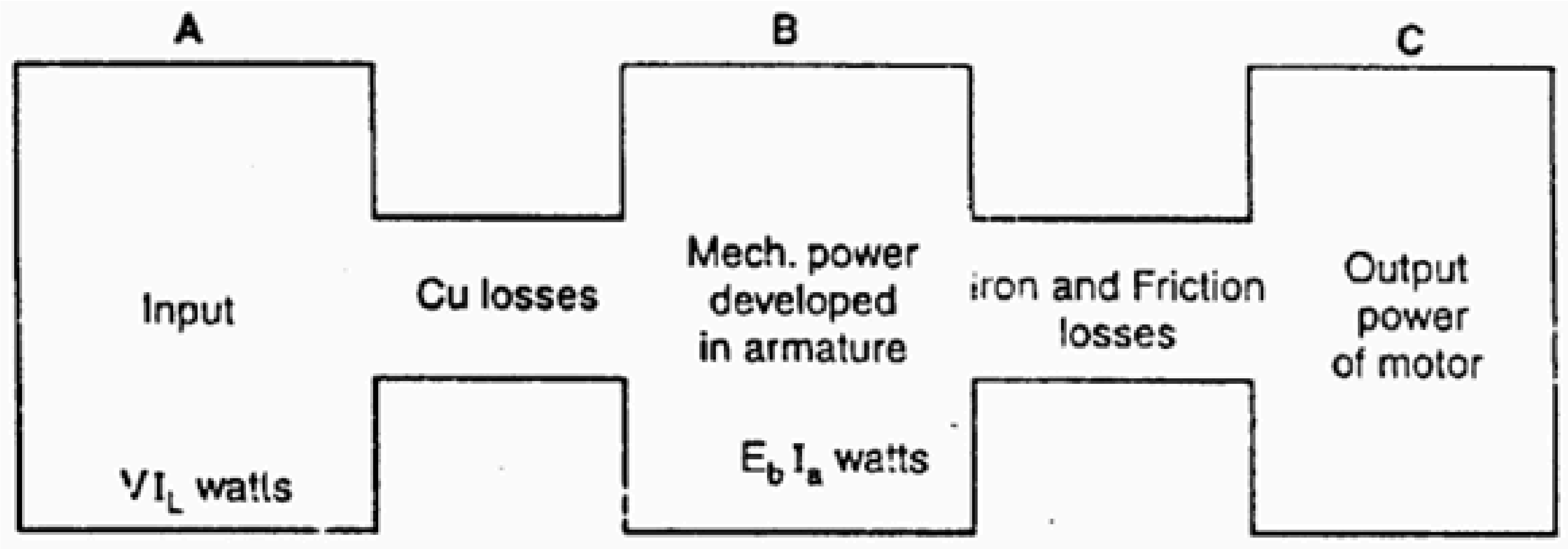
Therefore, the efficiency curve of a d.c. motor is similar in shape to that of a d.c. generator.

Power Stages

The power stages in a d.c. motor are represented diagrammatically in Fig.

A – B = Copper losses

B – C = Iron and friction losses



Overall efficiency, η_c = C/A

Electrical efficiency, η_e = B/A

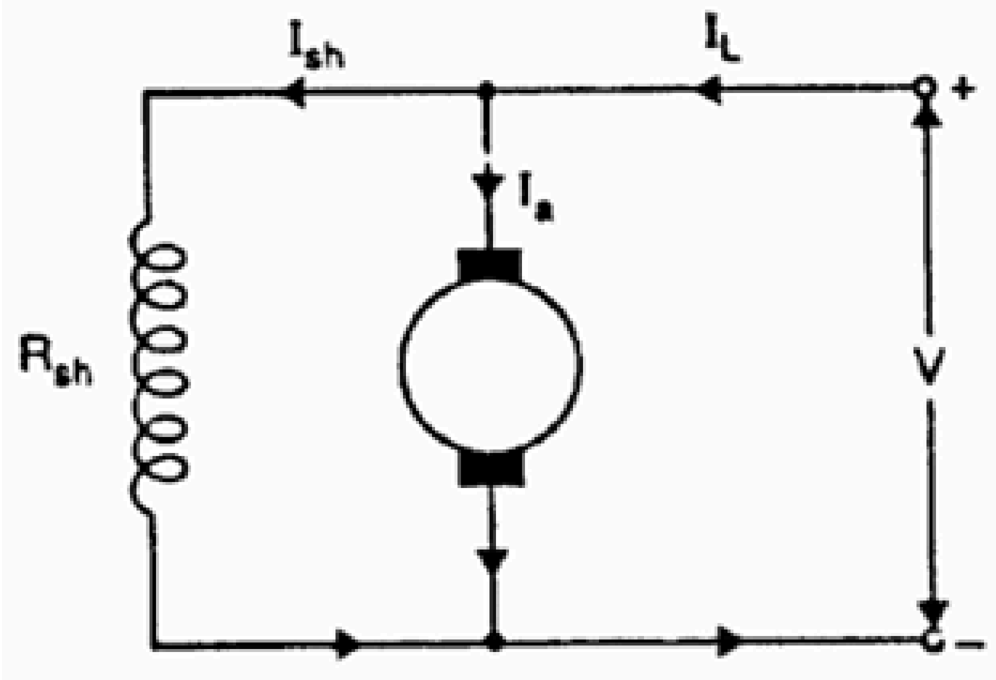
Mechanical efficiency, η_m = C/B

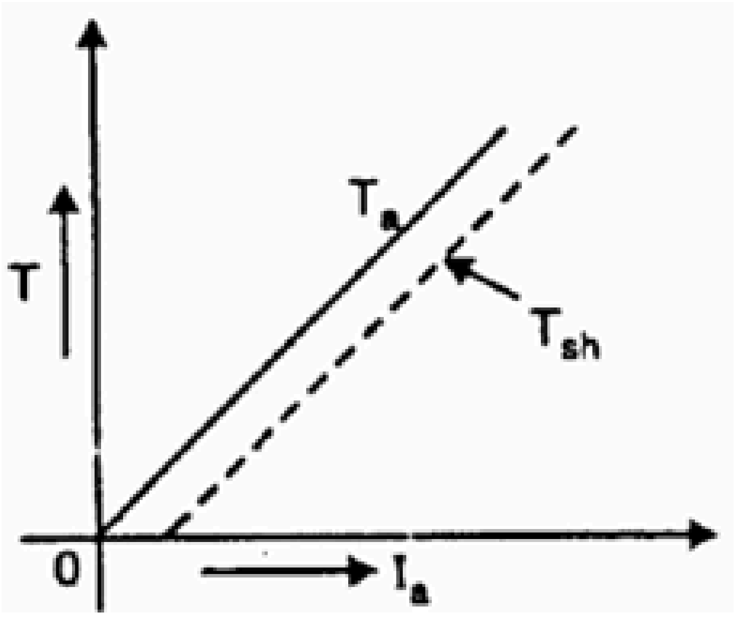
WEEK 15

PAGE 128 - 134

Characteristics of Shunt Motors

Fig. shows the connections of a d.c. shunt motor. The field current I_{sh} is constant since the field winding is directly connected to the supply voltage V which is assumed to be constant. Hence, the flux in a shunt motor is approximately constant.





(i) T_a/I_a Characteristic. We know that in a d.c. motor,

$$T_a \propto \phi I_a$$

Since the motor is operating from a constant supply voltage, flux ϕ is constant (neglecting armature reaction).

$$\therefore \quad T_a \propto I_a$$

Characteristics of Shunt Motors

Hence T_a/I_a characteristic is a straight line passing through the origin as shown in Fig. The shaft torque (T_{sh}) is less than T_a and is shown by a dotted line. It is clear from the curve that a very large current is required to start a heavy load. Therefore, a shunt motor should not be started on heavy load.

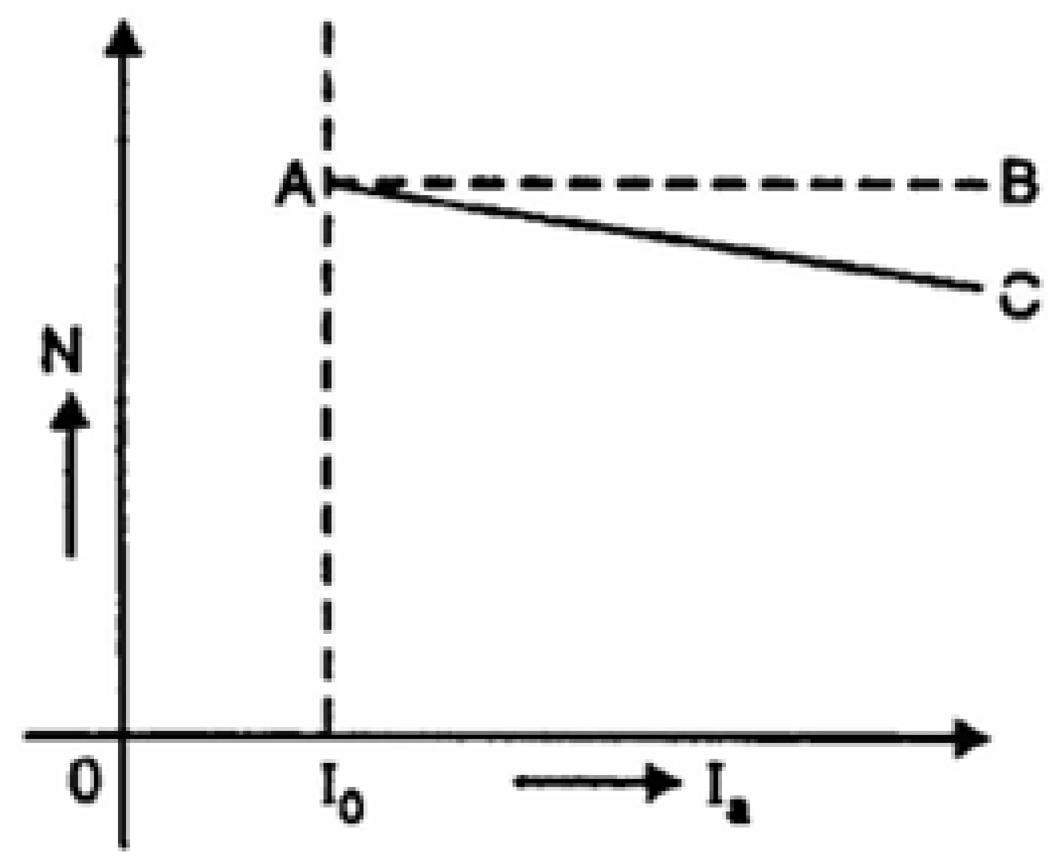
(ii) **N/I_a Characteristic.** The speed N of a. d.c. motor is given by;

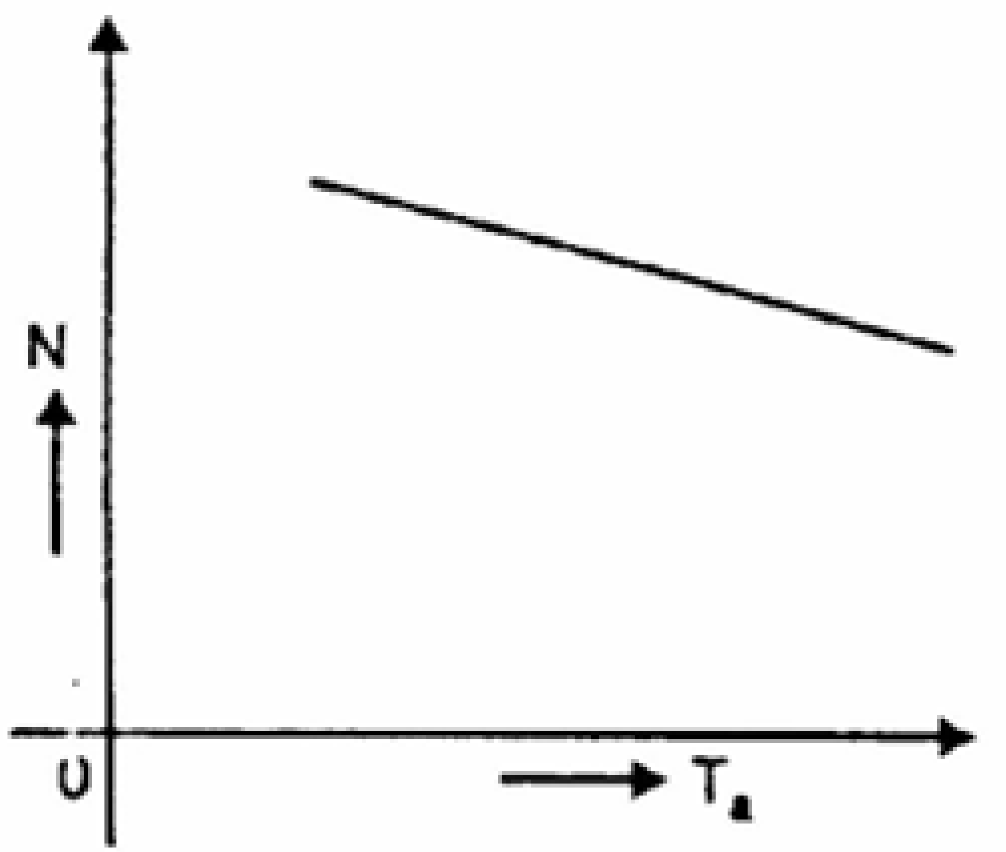
$$N \propto \frac{E_b}{\phi}$$

The flux ϕ and back e.m.f. E_b in a shunt motor are almost constant under normal conditions. Therefore, speed of a shunt motor will remain constant as the armature current varies (dotted line AB in Fig. Strictly speaking, when load is increased, E_b (= $V - I_aR_a$) and ϕ decrease due to the armature resistance drop and armature reaction respectively. However, E_b decreases slightly more than ϕ so that the speed of the motor decreases slightly with load (line AC).

Characteristics of Shunt Motors

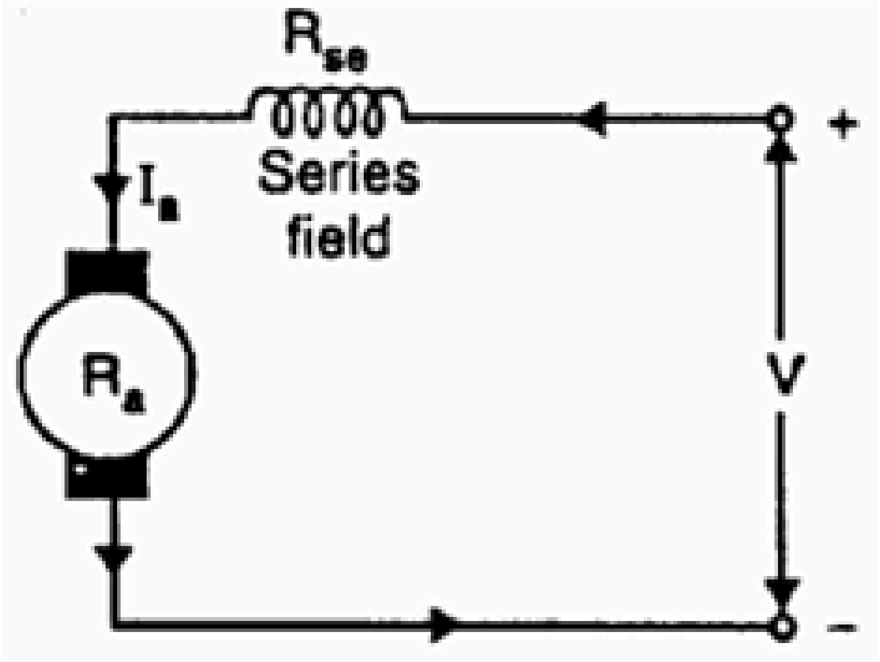
(iii) **N/T_a Characteristic**. The curve is obtained by plotting the values of N and T_a for various armature currents . It may be seen that speed falls somewhat as the load torque increases.

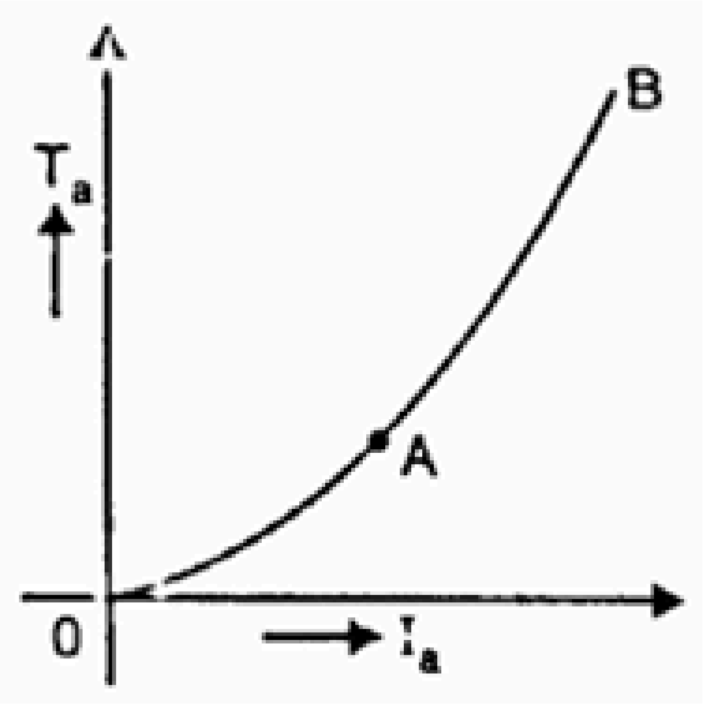




Characteristics of Series Motors

Fig.   shows the connections of a series motor. Note that current passing through the field winding is the same as that in the armature. If the mechanical load on the motor increases, the armature current also increases. Hence, the flux in a series motor increases with the increase in armature current and vice-versa.





Characteristics of Series Motors

(i) **T_a/I_a Characteristic**. We know that:

$$T_a \propto \phi I_a$$

Upto magnetic saturation, $\phi \propto I_a$ so that $T_a \propto I_a^2$

After magnetic saturation, ϕ is constant so that $T_a \propto I_a$

Thus upto magnetic saturation, the armature torque is directly proportional to the square of armature current. If I_a is doubled, T_a is almost quadrupled.

Therefore, T_a/I_a curve upto magnetic saturation is a parabola (portion OA of the curve in Fig.). However, after magnetic saturation, torque is directly proportional to the armature current. Therefore, T_a/I_a curve after magnetic saturation is a straight line (portion AB of the curve).

It may be seen that in the initial portion of the curve (i.e. upto magnetic saturation), $T_a \propto I_a^2$. This means that starting torque of a d.c. series motor will be very high as compared to a shunt motor (where that $T_a \propto I_a$).

Characteristics of Series Motors

(ii) **N/I_a Characteristic.** The speed N of a series motor is given by;

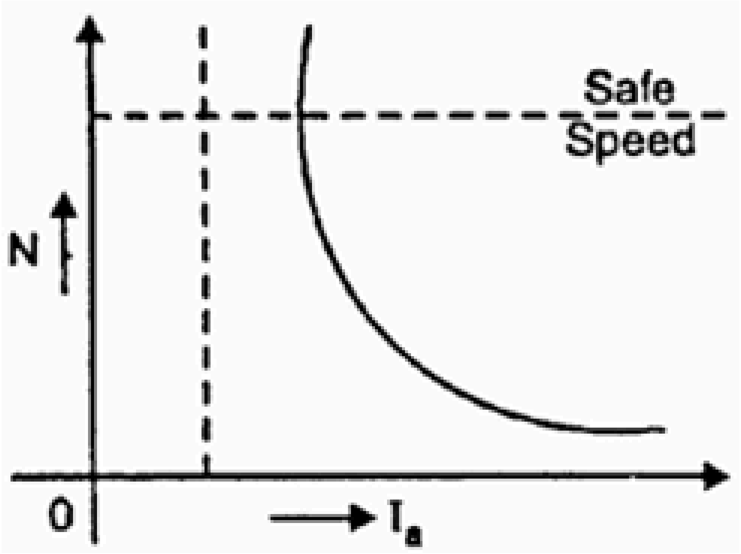
$$N \propto \frac{E_b}{\phi} \qquad \text{where} \qquad E_b = V - I_a(R_a + R_{se})$$

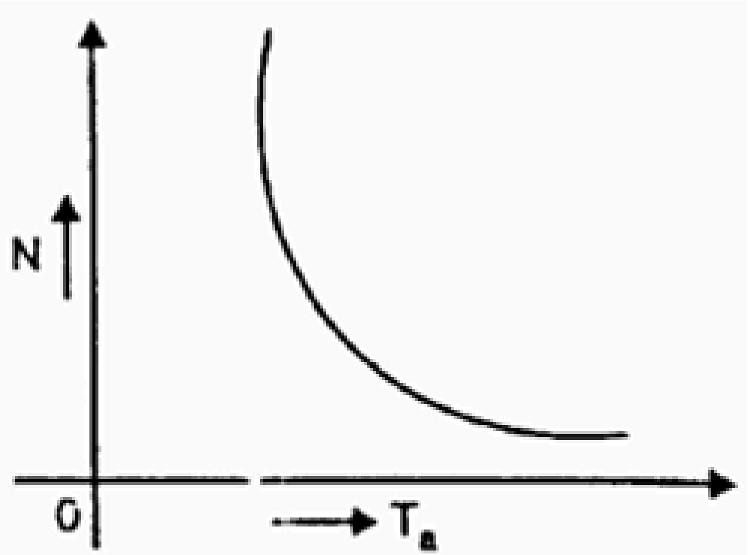
When the armature current increases, the back e.m.f. E_d decreases due to $I_a(R_a + R_{se})$ drop while the flux ϕ increases. However, $I_a(R_a + R_{se})$ drop is quite small under normal conditions and may be neglected.

$$\therefore \quad N \propto \frac{1}{\phi}$$

$$\propto \frac{1}{I_a} \quad \text{upto magnetic saturation}$$

Thus, upto magnetic saturation, the N/I_a curve follows the hyperbolic path as shown in Fig. (4.19). After saturation, the flux becomes constant and so does the speed.





Characteristics of Series Motors

(iii) **N/T_a Characteristic**. The N/T_a characteristic of a series motor is shown in Fig. It is clear that series motor develops high torque at low speed and vice-versa. It is because an increase in torque requires an increase in armature current, which is also the field current. The result is that flux is strengthened and hence the speed drops ($\because$ $N \propto 1/\phi$). Reverse happens should the torque be low.

WEEK 16-17

PAGE 136

Mathematical Problems on D.C Motor

Mathematical problems related to transformers will be practiced and solved during classroom sessions. Problems from the prescribed reference book will be addressed, and additional practice materials will be provided to enhance understanding and proficiency.

THE END

THANK YOU

FOR YOUR ATTENTION