[illegible] OF EXTERNAL STUDIES

NEW SOUTH WALES

DEPARTMENT OF TECHNICAL EDUCATION

ELECTRICAL ENGINEERING CERTIFICATE

STAGE III

ELECTRICAL MACHINES I

BOOK I

DIRECT CURRENT MACHINES

INTRODUCTION

The subject, Electrical Machines 1, is divided into two major topics. These are:

Part 1

D.C. Machines - covering the more practical aspects of d.c. machines as energy conversion devices with particular emphasis on machine characteristics and behaviour under different steady state load conditions. This section will cover units one (1) to fourteen (14) inclusive.

Part 2

Single Phase Transformers - which will treat transformers from the point of view of the equivalent circuit of the transformer as a means of determining such characteristics of the transformer as the efficiency and regulation and also as a means of determining the operating conditions of parallel connected transformers. In addition, the practical aspects of transformer construction and performance will be treated. These topics will be covered in units fifteen (15) to twenty (20) inclusive.

It should be emphasized at this point that in the final examination of this subject the paper is so structured and marked that the student is required to reach a satisfactory level in both sections of the course in order to obtain a pass.

Regarding text books, there are no books specifically set as text books for the subject as some of the work, particularly in the areas associated with load matching and practical design considerations for machines intended for S.C.R. drives, is not treated in texts dealing with this subject at the level of treatment given by this course. Consequently, the books mentioned are for reference only and in general only small sections of each text are applicable. When a particular text covers some aspect of the course in a noteworthy fashion this will be referred to in the unit. A list of references is given at the end of the introduction but these are only intended for reference where available and there is no necessity to purchase such texts.

However, the student is required either to have access to or purchase the following standard publications:

1) AS C 61 - Power Transformers.
2) AS C 388 - Instrument Transformers.
3) AS C 319 - The Electrical Performance of Rotating Electrical Machinery.

The reason for the emphasis placed on these publications arises from the fact that they are intended for use by everyone associated with the equipment covered and, as technicians concerned with the power aspects of the electrical field, students of this course should be acquainted both with the scope and content of these standards.

With regard to the content of the actual lesson units, due to the nature of the subject material, much of the teaching and instruction will be by way of worked examples. It is suggested therefore that the student attempt each unit in the following way:

1) Read the introductory section of each unit as this will generally establish both the direction and scope of the subject material of the unit.

2) Observe the methods and techniques employed in the solutions of the worked examples given in the unit material endeavouring both to follow the logic of the method and to comprehend the pattern of approach.

3) Re-do the worked example without reference to the solution given.

4) Check the solution obtained with that given in the unit making due allowance for difference in answers particularly in problems involving graphical solutions.

5) When satisfied both with the appreciation of the method and the accuracy of the solution, pass on to the next section of the work until all the material contained in the unit is covered.

At the end of each unit a number of review questions are given which are intended to focus the attention of the student on the salient features of the particular unit and to give the student a basis for self evaluation to assist in gauging the degree of comprehension of a particular topic. As such it is not intended that the student submit the answers to these review questions for marking. The assignments, the answers to which are to be submitted for marking, will as a rule be five in number and be similar in difficulty to problems appearing in the units and follow the same general pattern. If the student has difficulty with a particular problem he should therefore be able to resolve this difficulty by referring back to the appropriate example in the unit.

In connection with assignments required for submission, a word about the method of presentation.

Firstly, never be skimpy with the paper used for answers. For preference, the paper used should be approximately 300 mm by 200 mm and adequate space left, either by a wide margin or a space at the bottom of each page, for the marker to write his advice or comments on the student's work. This is of particular importance where the student has had difficulty with a certain topic and feels that the marker may have some helpful advice and/or criticism.

Secondly, all graphical examples should be done on graph paper. With graphical work the practice of drawing freehand curves should be discouraged and all axes should be clearly drawn and adequately labelled. Where several curves are drawn on the same set of axes each curve should be uniquely identified either by colour coding or by the use of different types of lines.

Thirdly, except in extreme circumstances a student should never submit more than one unit in a given subject at any one time. This is of particular importance where difficulty is being experienced in some aspect of the work. Ideally, the student should await the return of one marked unit before submitting the next in the sequence. In this way errors in technique and understanding may be rectified before further work is submitted.

In conclusion, the student can attempt this subject with the objective of acquiring a knowledge and understanding of the machines dealt with or may simply view the subject as one of the obstacles to be surmounted before he is entitled to receive the final certificate.

Whatever the initial intention of the students, the majority of whom it is hoped will be included in the former category, it is hoped that all students, having completed the course, will be richer both in the understanding and appreciation of the applications and operations of the different machines.

A final note regarding the conventions adopted with the symbols. In general the symbols will be those of AS.1046. However, there will be two major departures from this generalization.

1) Whereas the symbol for speed in the standard is "n" where speed is measured in revolutions per second, as in most practical situations speed is given in revolutions per minute, this convention has been followed with the symbol "N" assigned to speed. Thus, in all expressions where speed is involved:

$$\frac{N}{60} = n$$

2) Similarly, although the standard uses the term "pairs of poles" and the symbol "p" the more usual practice is to refer to poles and hence the symbol "P" has been used. Thus:

$$P = 2p$$

Although there was some hesitation in deciding to depart from the standard it was felt that the result would be a more practically oriented set of relationships.

1

wk ① x3w

ELECTRICAL MACHINES I

UNIT NO. I

DIRECT CURRENT MACHINES

This unit will cover the following topics:

D.C. machines as energy conversion devices.

Generator and motor action.

Angular motion relationship.

Description of various parts of d.c. machines, excluding armature windings.

Description of field windings.

Field coil construction.

Review questions.

Assignments.

ELECTRICAL MACHINES AS ENERGY CONVERSION DEVICES

Amongst the most important forms of energy conversion devices are those called electrical generators which convert mechanical energy to electrical energy and those called electric motors which convert electrical energy to mechanical energy.

Machines that convert mechanical energy to electrical energy are termed generators or dynamos and machines that convert electrical energy to mechanical energy are termed motors. In this course the major emphasis will be d.c. machines with the partial exception that some work will be done on those machines where the supply is derived from a.c. sources through controlled rectifier devices.

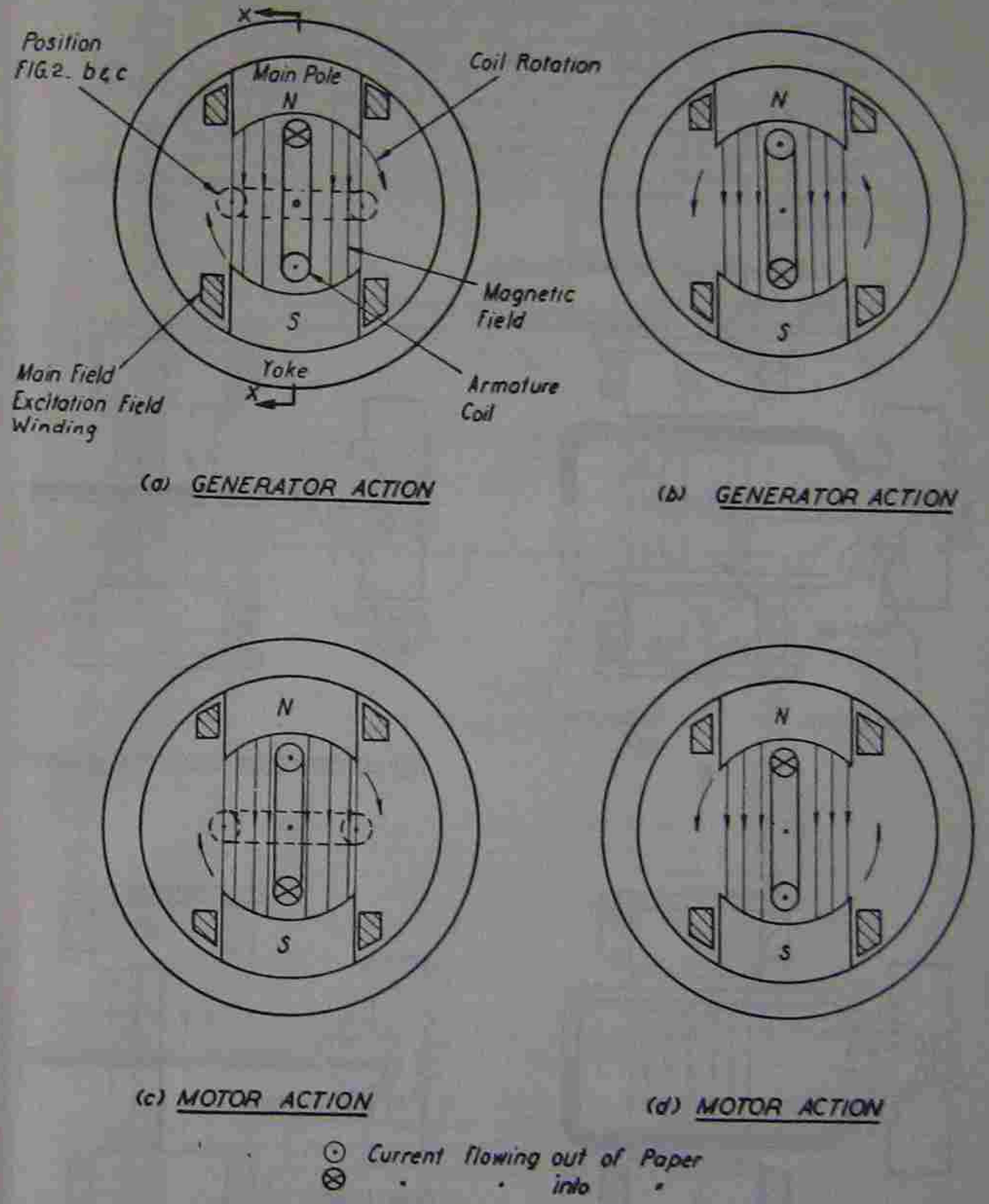
GENERATOR AND MOTOR ACTION

Generator action is based upon the fact that an e.m.f. is induced in a conductor when the conductor moves in such a direction relative to a magnetic field that the conductor cuts the magnetic field. The magnitude of the e.m.f. is governed by the rate of cutting.

Motor action is based upon the fact that a mechanical force is exerted on a current carrying conductor in a magnetic field. The magnitude of the force depends on the field strength and the current.

There are certain relationships between the directions of the magnetic field, current in conductor and rotation. These are shown in Fig. 1.1

1



RELATIONSHIP BETWEEN DIRECTION OF MAGNETIC FIELD ARMATURE CONDUCTOR CURRENT & ROTATION

Figure 1.1

If the instantaneous value of current in the conductor is given by i the electrical power associated with the conductor is:

$$P = ei = Blvi \text{ watts} \qquad - \qquad 1.2$$

The force on a current carrying conductor in a magnetic field is given by the expression:

$$F = Bli \text{ newtons} \qquad - \qquad 1.3$$

where B and l have the same significance as in equation 1.1

and i is the instantaneous current (amperes).

The work done by a force is given by:

$$W = Fs \qquad - \qquad 1.4$$

and the power by:

$$P = \frac{W}{t} = \frac{Fs}{t} \qquad - \qquad 1.5$$

Hence the mechanical power associated with a conductor in a magnetic field is:

$$P = \frac{Fs}{t} = Bli\frac{s}{t} \qquad - \qquad 1.6$$

It will be observed that the term $\frac{s}{t}$ is in fact velocity (v) and hence

$$P = Bli\,v \text{ watts} \qquad - \qquad 1.7$$

Comparing equation 1.2 and 1.7 leads to the conclusion that in equilibrium the mechanical and electrical power associated with the conductor are equal. In non-equilibrium conditions the function of the machine will be determined by which of the two power terms is the greater. From equation 1.2 it can be seen that if the velocity of the conductor was increased, as would be the case in the event of an increase in the armature speed in a motor, the electrical power will tend to increase and the motor will tend to operate in the regenerative mode and electrical energy will pass back into the system.

This effect can also be achieved by increasing the flux density; however, the change from motor to generator operation would only be observed where the terminal voltage of the motor was maintained constant.

Alternatively, if a generator was being driven by a constant speed drive and the field flux was decreased the electrical power produced by the generator would be reduced. This would result in a flow of electrical power into the machine causing the machine to operate as a motor. Again this will only occur if the machine speed and terminal voltage are kept constant.

Referring back to the equation for power (equation 1.2) where the conductor moves in a circular path in a radial field of constant flux density the velocity term can be written in terms of the angular velocity θ. That is:

$$\text{since } \frac{s}{t} = \frac{\theta r}{t} \qquad - \qquad 1.8$$

(where r is the radius of the conductor path)

Thus the power expression becomes

$$P = Bli\,\frac{\theta r}{t} \qquad - \qquad 1.9$$

From equation 1.3 the power expression (equation 1.9) may be written as:

$$P = Fr\,\frac{\theta}{t} \qquad - \qquad 1.9$$

Since force by radius is the turning moment or torque exerted by a force and $\frac{\theta}{t}$ is the angular velocity, ω, the power associated with a conductor may now be written as:

$$P = T\omega \text{ watts} \qquad - \qquad 1.10$$

A more practical expression in terms of the speed of the armature in revolutions per minute is given by

$$P = \frac{2\pi N}{60}\,T \text{ watts} \qquad - \qquad 1.11$$

While on the subject of rotational motion it should be noted that for uniformly accelerated angular motion the following relationships apply:

$$\omega_2 = \omega_1 + \alpha t \qquad - \qquad 1.12$$

From which

$$\frac{\omega_2 - \omega_1}{\alpha} = t \qquad - \qquad 1.12\text{ (a)}$$

$$\text{or} \quad \frac{\omega_2 - \omega_1}{t} = \alpha \qquad - \qquad 1.12\text{ (b)}$$

$$T = I\alpha \qquad - \qquad 1.13$$

where ω_1 and ω_2 are angular velocities (rad s^{-1})

α the angular acceleration (rad s^{-2})

T the torque (Nm)

t the time interval

and I the moment of inertia of the system (Nm s^2).

If the moment of inertia of a system is known the relationship between acoleration torque and accelerating time for a given change of speed can be established if it is assumed that the acceleration is uniform and frictional effects are neglected.

<u>Example 1.1</u>

A motor has a combined moment of inertia of 10 Nm s^2 and an initial velocity of 200 radians per second. If the torque produced by the motor was increased by 50 Nm, calculate:

1) The time for the speed to reach 300 radians per second.
2) The final speed if the torque was maintained for 10 seconds.
3) The torque increase necessary to obtain an increase of 50 radians per second in   seconds.

25

Solution

1) From equation 1.13

$$T = I\alpha$$

$$\therefore \alpha = \frac{T}{I}$$

$$= \frac{50}{10}$$

$$= 5 \text{ rad. sec.}^{2}$$

Substituting this value for α in equation 1.12 (a) and using the given values for ω_1 and ω_2

$$\frac{\omega_2 - \omega_1}{\alpha} = t$$

$$\frac{300 - 200}{5} = t$$

$$t = 20 \text{ seconds}$$

2) From equation 1.12

$$\omega_2 = \omega_1 + \alpha t$$

$$= 200 + 5 \times 10$$

$$= 250 \text{ rad. s}^{-1}.$$

3) From equation 1.12 (b)

$$\alpha = \frac{\omega_2 - \omega_1}{t}$$

$$= \frac{50}{2}$$

$$= 2 \text{ rad s}^{-2}$$

From equation 1.13

$$T = I\alpha$$

$$= 10 \times 2$$

$$= 20 \text{ Nm}$$

In practice the acceleration is not linear for constant torque due to the fact that the expression relating torque and acceleration also includes a velocity dependent term. The expression should be written:

$$\frac{dT}{dt} = I\frac{d^2\theta}{dt^2} + \beta\frac{d\theta}{dt} \qquad - \qquad 1.14$$

where β is the damping coefficient.

As β may also be a function of θ the problem becomes somewhat complicated and, as will be the case with the later work on accelerating times of motors, a graphical solution is generally used. The disadvantage of the graphical method is the limitation that it is only possible to readily determine accelerating times and these are only approximate in that they are obtained by averaging the torque over a given change in speed and determining the acceleration time for each of these speed changes.

Although this method will be expanded more fully in the section on motor selection an example of a simple problem will be given by way of introduction.

Example 1.2

A mechanical load has the torque speed curve shown in Fig. 1.3 and a constant torque of 7.5 Nm is applied to the load. Determine:

a) the final speed of the system;

b) the time taken to reach the equilibrium speed assuming that the moment of inertia of the complete system is 0.5 Nm s^2.

Solution

The system will accelerate as long as the applied torque is greater than the load torque. Equilibrium is reached where the two torques are equal. Hence:

a) Final speed = 140 rad s^{-1}

To obtain the accelerating time the speed curve is divided into speed increments of 20 radians per second and the distance between the two curves at the mid-point of each section taken as the average accelerating torque. The accelerating time can now be found by using the expression obtained from combining equations 1.12 and 1.13.

$$\frac{\Delta\omega I}{T} = t$$

where $\Delta\omega$ is the increase in speed

I the moment of inertia

T the average accelerating torque

and t the time in seconds.

For example, in the first interval, the average accelerating torque (from curve) is 7.25 Nm.

Hence

$$t = \frac{20 \times .5}{7.25}$$

$$= 1.4 \text{ seconds}$$

The times for the remaining sections are shown in the following table.

Interval	$\Delta\omega$ (rad s^{-1})	Accelerating Torque (Nm)	Time (s)
a - b	20	7.25	1.4
b - c	"	6.7	1.5
c - d	"	6.0	1.7
d - e	"	5.2	1.9
e - f	"	4.2	2.4
f - g	"	3.0	3.3
g - h	"	1.3	7.7
		Total	19.9

Therefore, the accelerating time would be approximately 20 seconds.

<u>Note</u>: It would be meaningless and misleading to give the answer as 19.9 seconds as this implies that the answer is accurate to 3 significant figures, that is, an accuracy in the order of 0.5% whereas the order of accuracy due to the graphical construction would be closer to 5% or one part in 20.

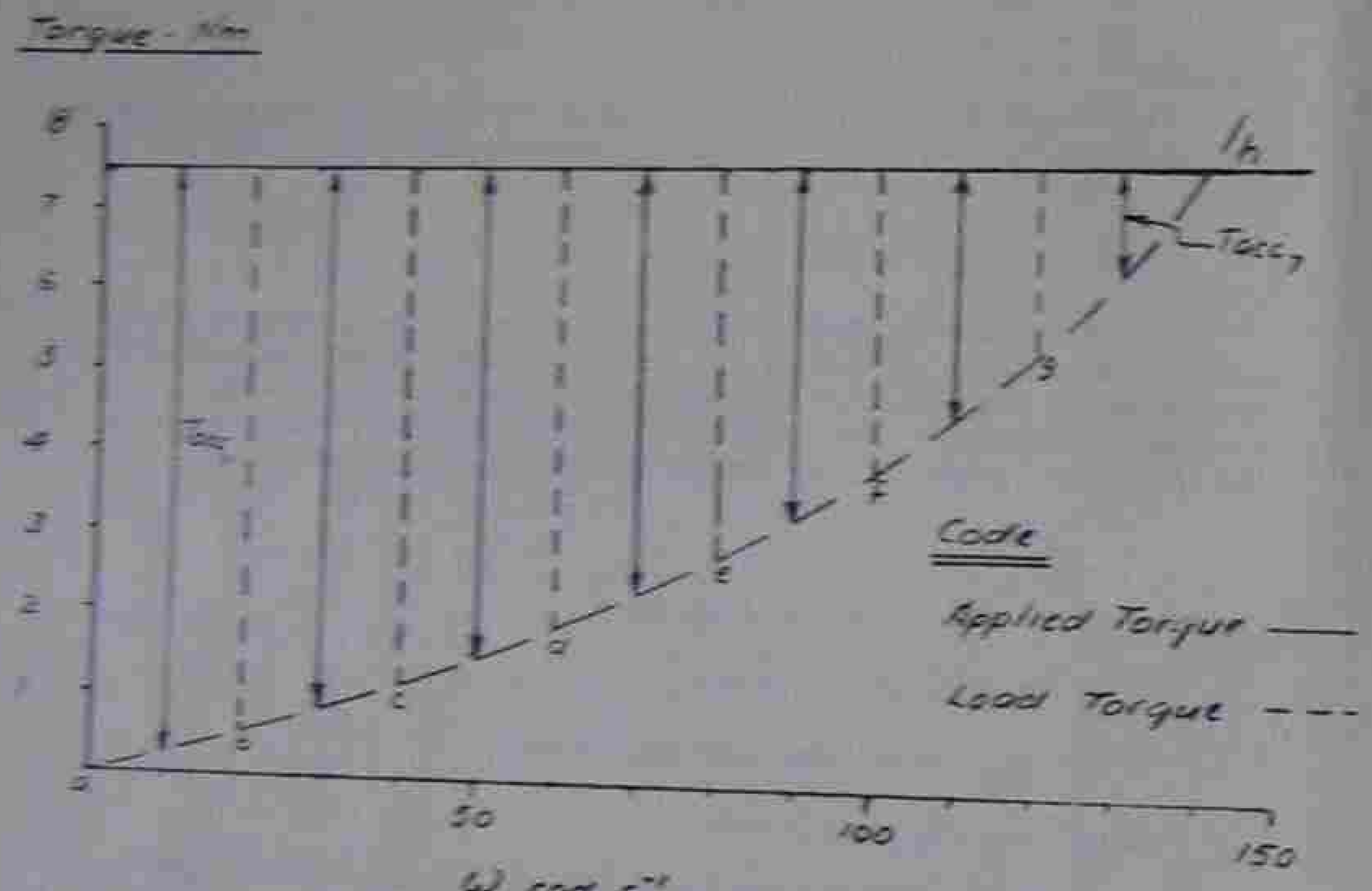


Fig 1·3 Diagram for example 1·2

DESCRIPTION OF VARIOUS PARTS OF D.C. MACHINES (EXCLUDING ARMATURE WINDINGS).

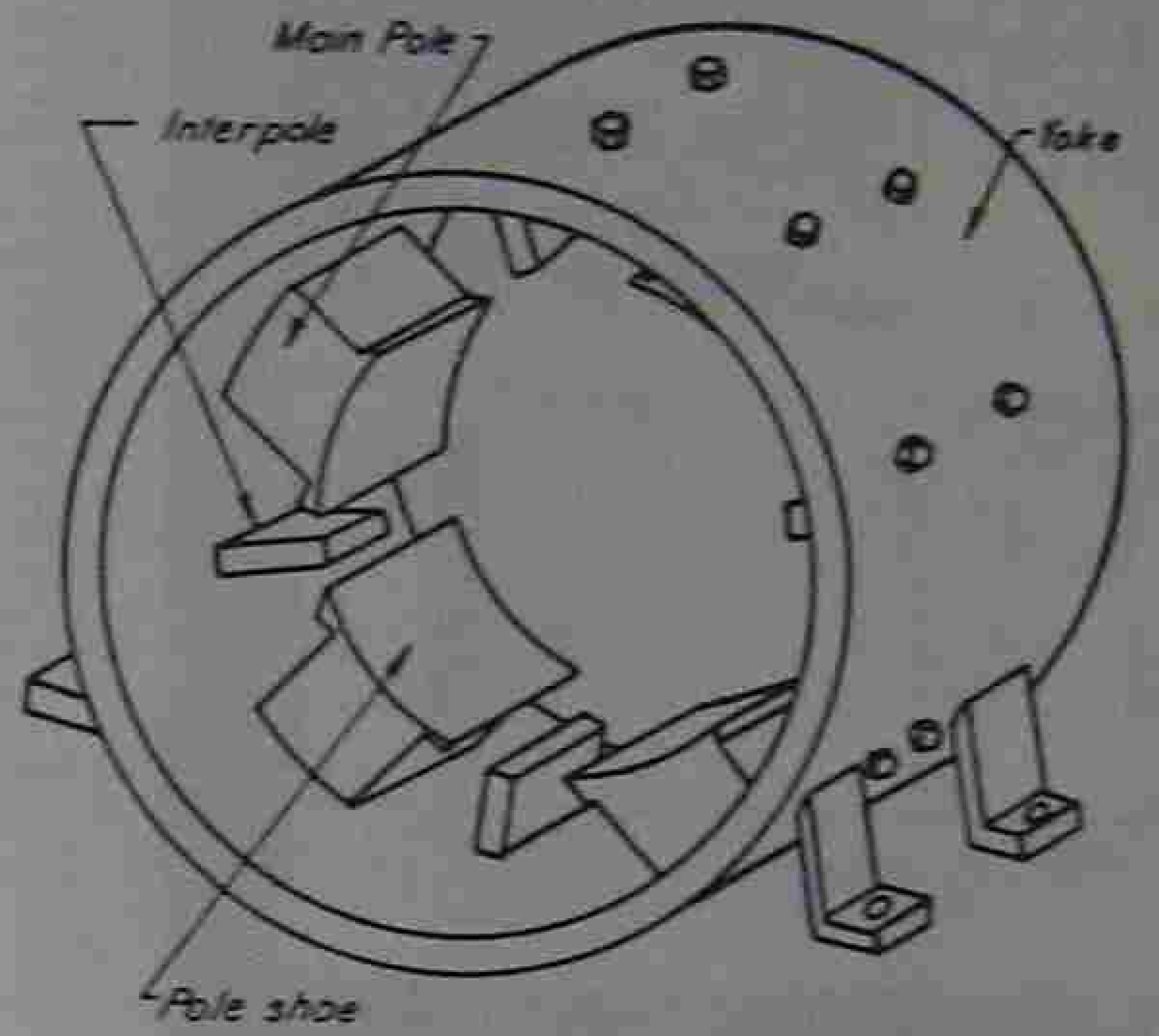
In the following descriptions, a material having good magnetic characteristics is a material that can be worked at high values of flux density without saturation occurring and with a low hysteresis loss. The alternative names by which the component is known are given in brackets.

<u>YOKE</u> (Frame, Body)

(a) The yoke completes the magnetic circuit comprising the poles, air gaps and armature.

(b) Modern practice is to make the yoke of steel plate or cast steel of a good magnetic characteristic. In this instance a low hysteresis loss is not important.

(c) The yoke also acts as rigid frame to which poles and endshields are bolted and to which holding down feet are welded. These are an integral part of the yoke where the yoke is cast.



FRAME WITH MAIN AND INTERPOLES BOLTED IN POSITION (4 POLE MACHINE)

Figure 1.4 (a)

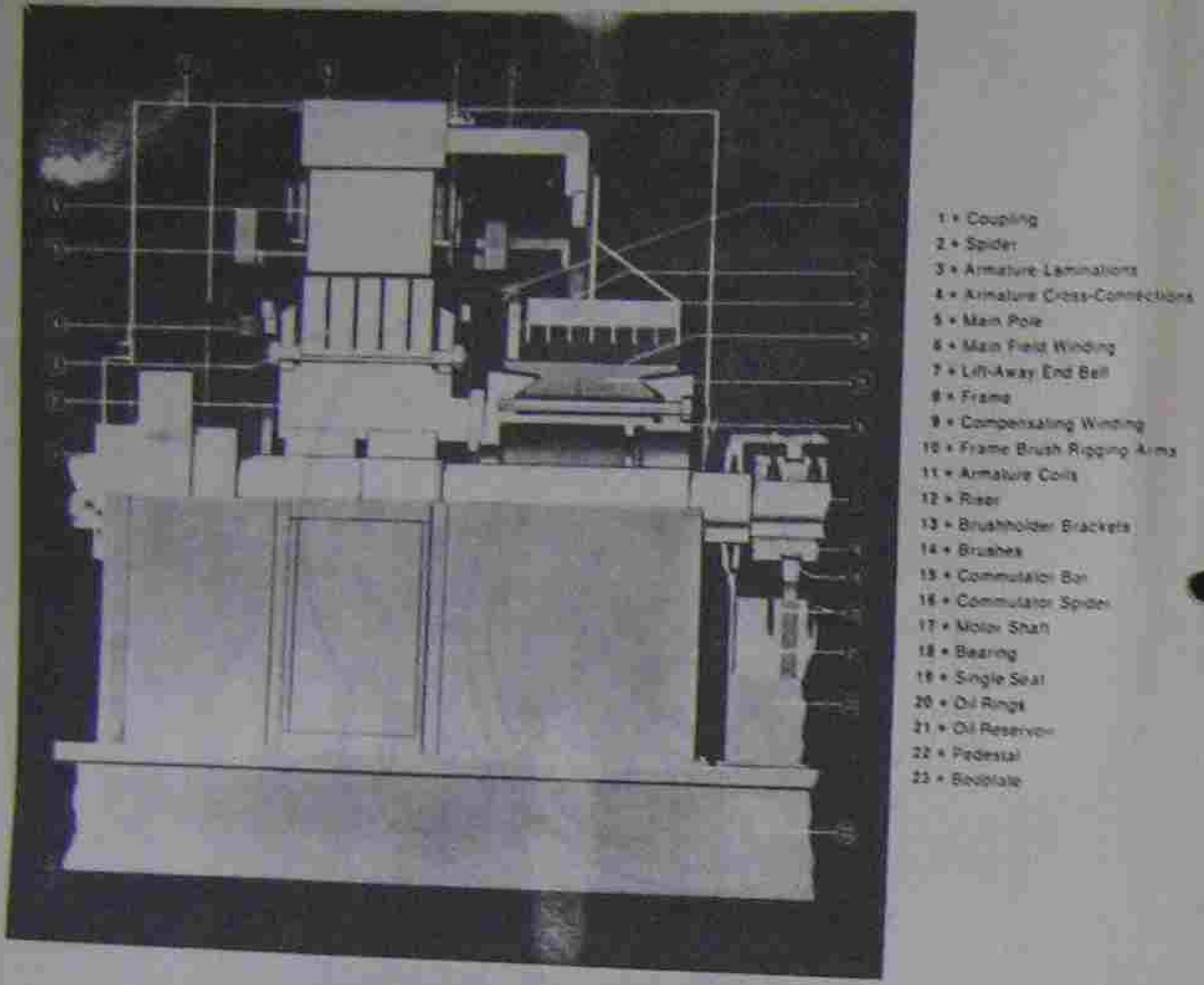


Figure 1.4 (b)

- By courtesy of Westinghouse.

MAIN POLE SYSTEM

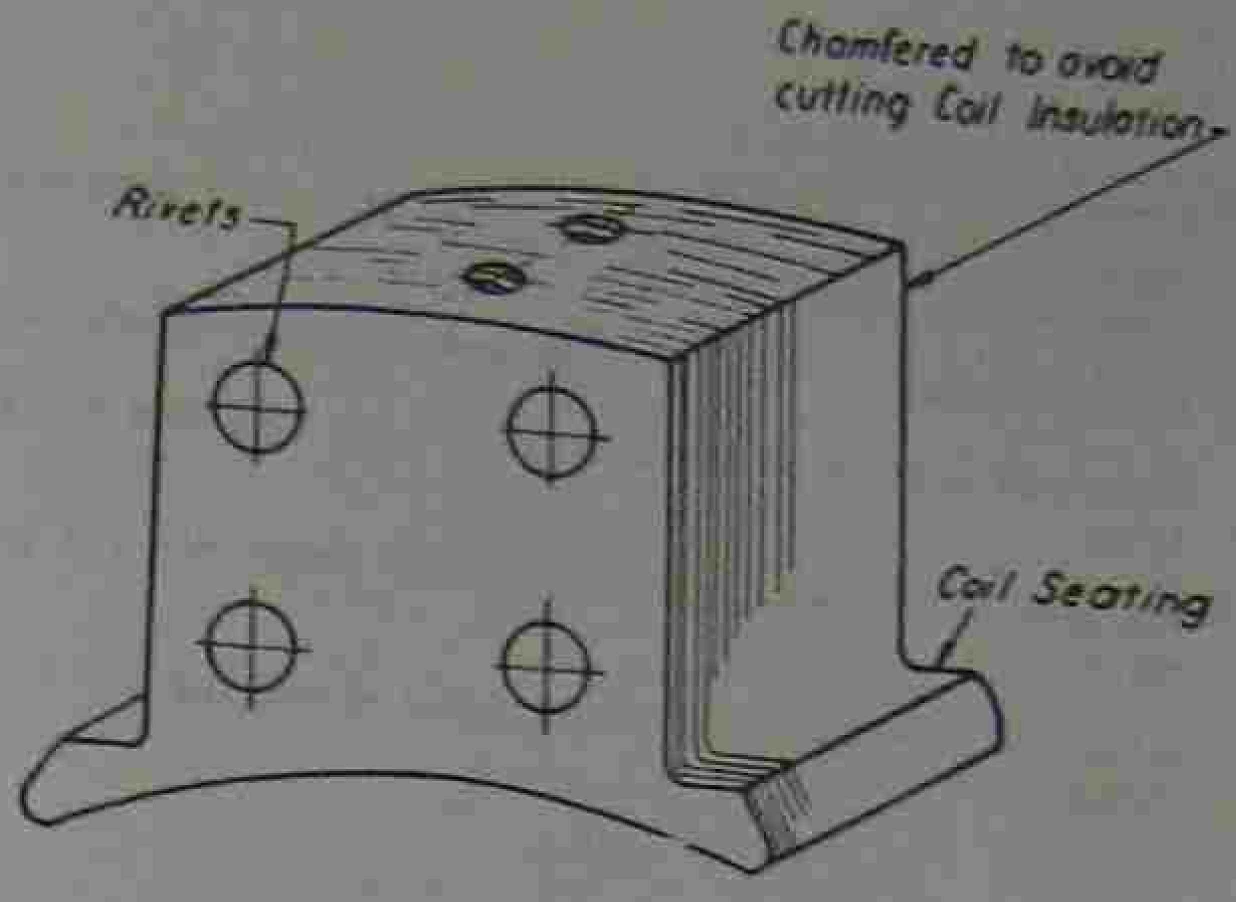
(a) Each main pole is an assembly of steel laminations of between 1.0 - 1.5 mm thick riveted together and of the same length as armature core.

(b) The steel making up the laminations has good magnetic characteristics.

(c) The pole provides a level seat for supporting a main field excitation coil.

(d) The reduced body shank tends to keep the mean length of turn of a main field coil to a minimum thereby reducing the coil resistance and losses.

(e) Generally a given number of poles (e.g., 2, 4, 6) covers a given output range. It will be appreciated that the number of poles will be an even number. The larger the output the greater the number of poles.



MAIN POLE ASSEMBLY

Figure 1.5

INTERPOLES (Commutating Poles)

(a) Interpoles are fitted in the interpolar arc between the main poles and are generally the same in number as main poles. In some cases, however, only every alternate pole carries on excitation winding.

(b) The poles are generally rectangular in shape and sometimes shaped at the armature end of a pole.

(c) Alternatively they are either of laminated construction, similar to the main pole or a rectangular steel bar.

(d) Where steel bar construction is used the interpole coil is held in position by clips or a similar device.

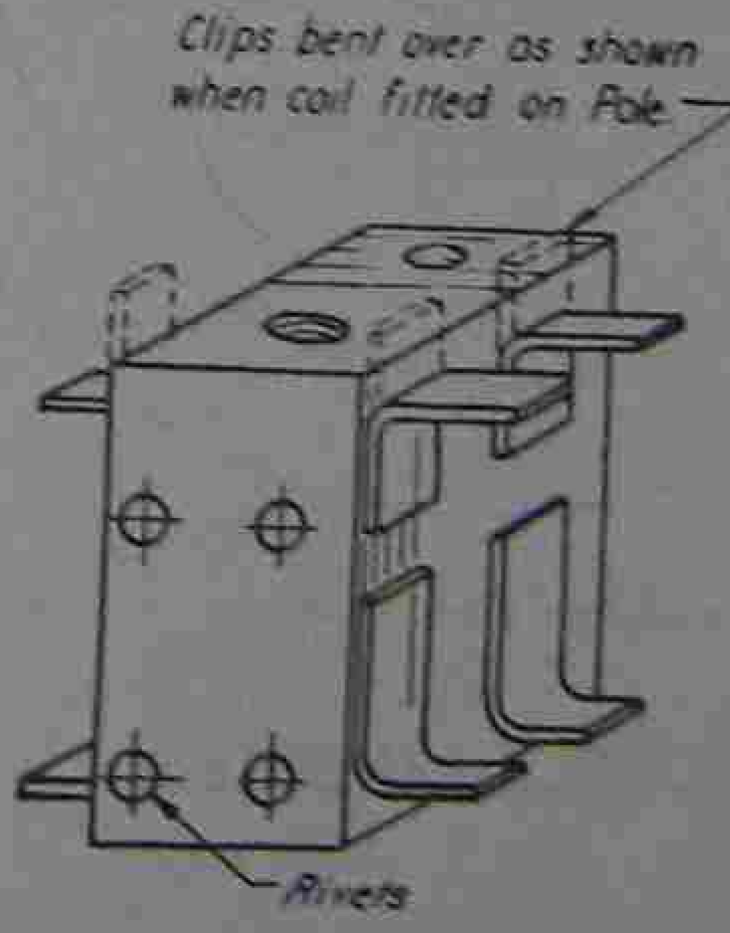


Figure 1.6

INTERPOLE ASSEMBLY

ARMATURE CORE

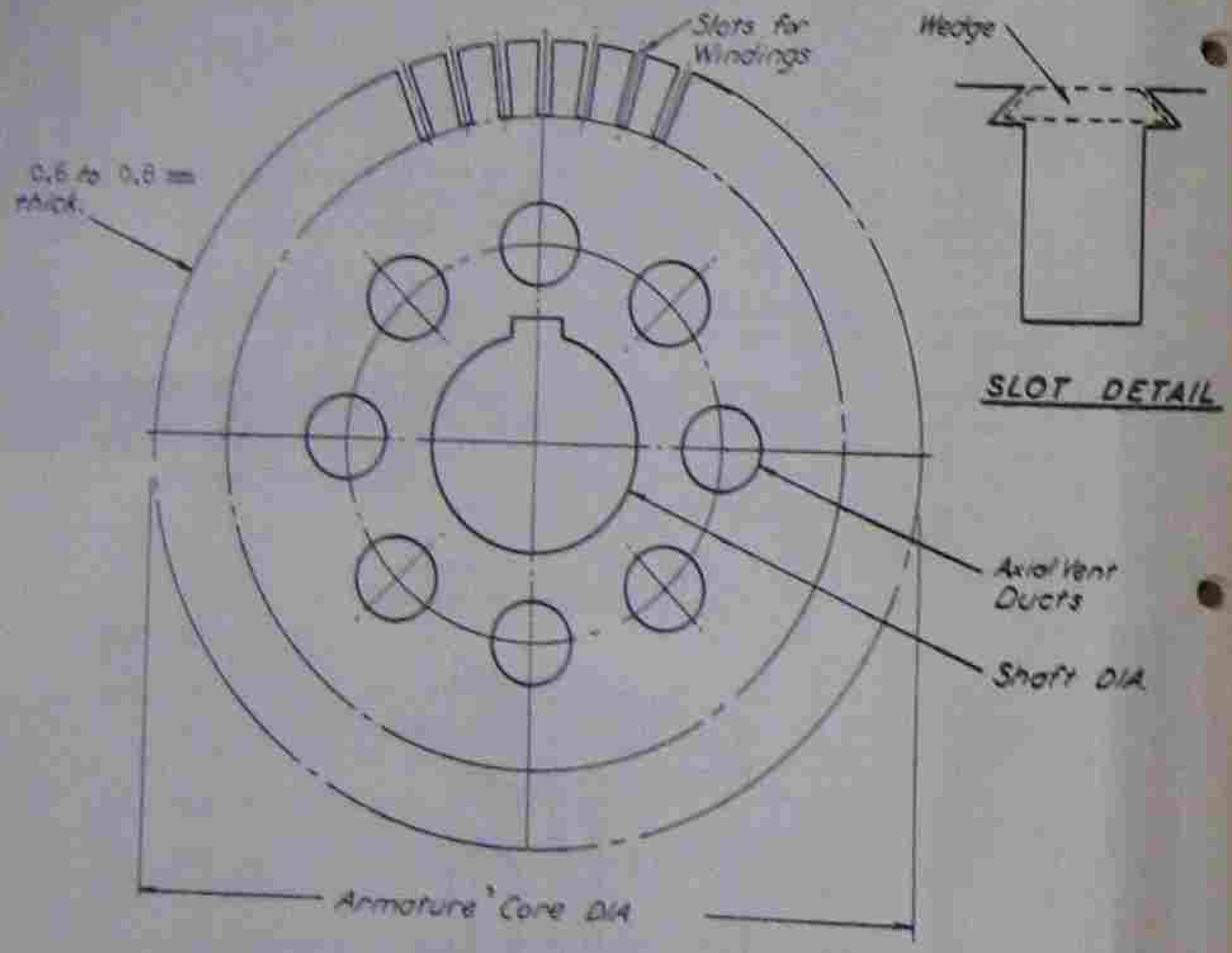
(a) This is made up of iron laminations, with very good magnetic characteristics and low iron loss.

(b) Each lamination is insulated to reduce eddy current losses further.

(c) Slots are notched on the periphery: the armature coils fit into these.

(d) The core is clamped firmly between two endplates and is keyed to shaft.

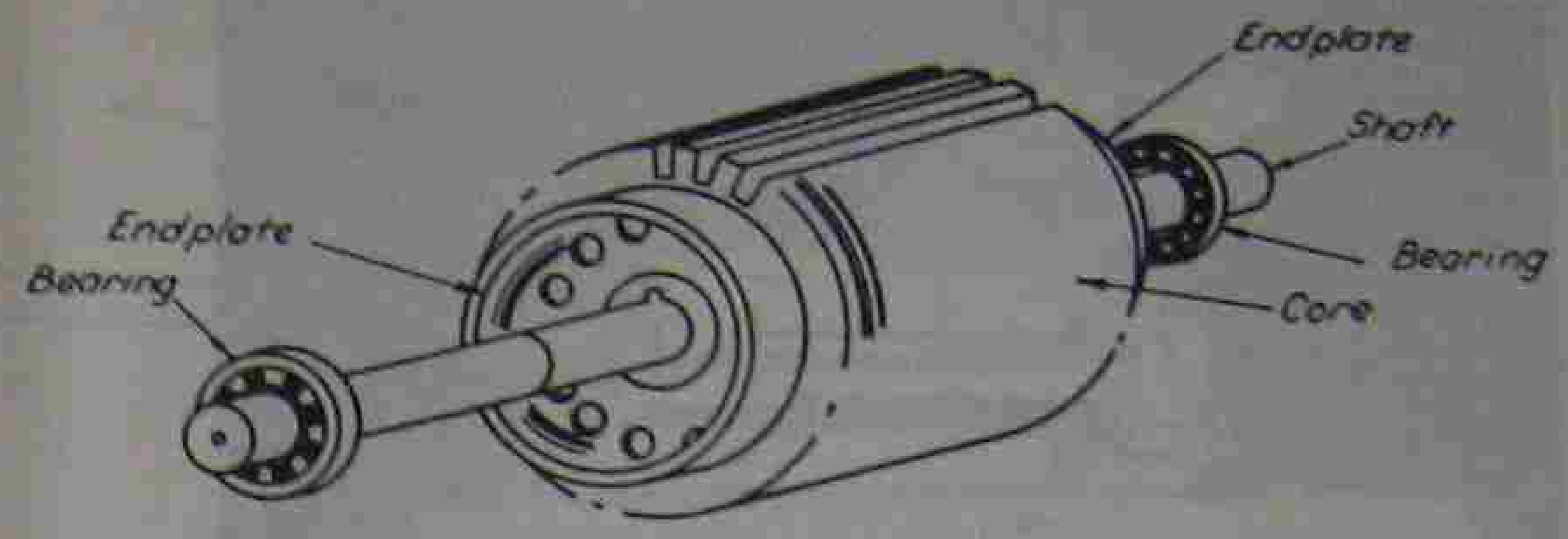
(e) Holes are provided in the core to allow cooling air to pass through.



SLOT DETAIL

ARMATURE LAMINATION

Figure 1.7



ARMATURE CORE HELD IN POSITION BY ENDPLATES

Figure 1.8

COMMUTATOR

(a) The commutator bars (or segments) are made of hard drawn or silvered copper.

(b) Steel vees are either of cast steel or machined from a bar.

(c) Insulation vees are made of mica.

(d) Insulation between segments is of mica.

(e) Each bar is slotted in riser portion and armature conductors are then soldered in.

(f) They must be machined to a very high degree of accuracy to ensure a smooth true surface for brushes to run on at all speeds.

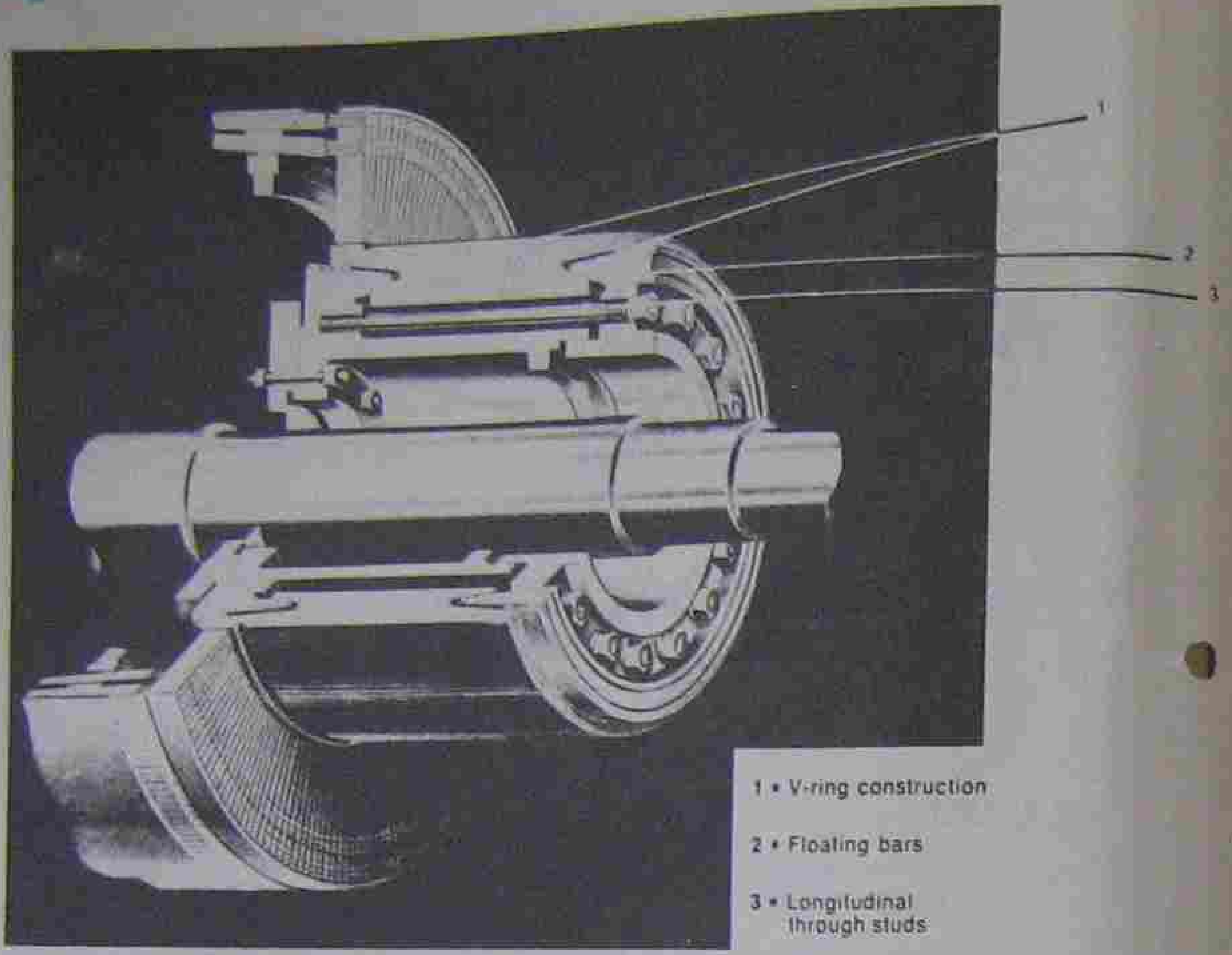


Figure 1.9

- By courtesy of Westinghouse.

BRUSHES

(a) These collect current from, or supply current to, armatures.

(b) They are made of special types of carbon.

(c) Ideal carbon has long life, negligible wearing effect on commutators and good commutating properties.

BRUSH HOLDER (Brushbox)

(a) This holds brush in position allowing it to slide up and down but does not allow side movement.

(b) A spring arrangement presses the brush firmly on to the commutator.

(c) It is clamped to rocker arm.

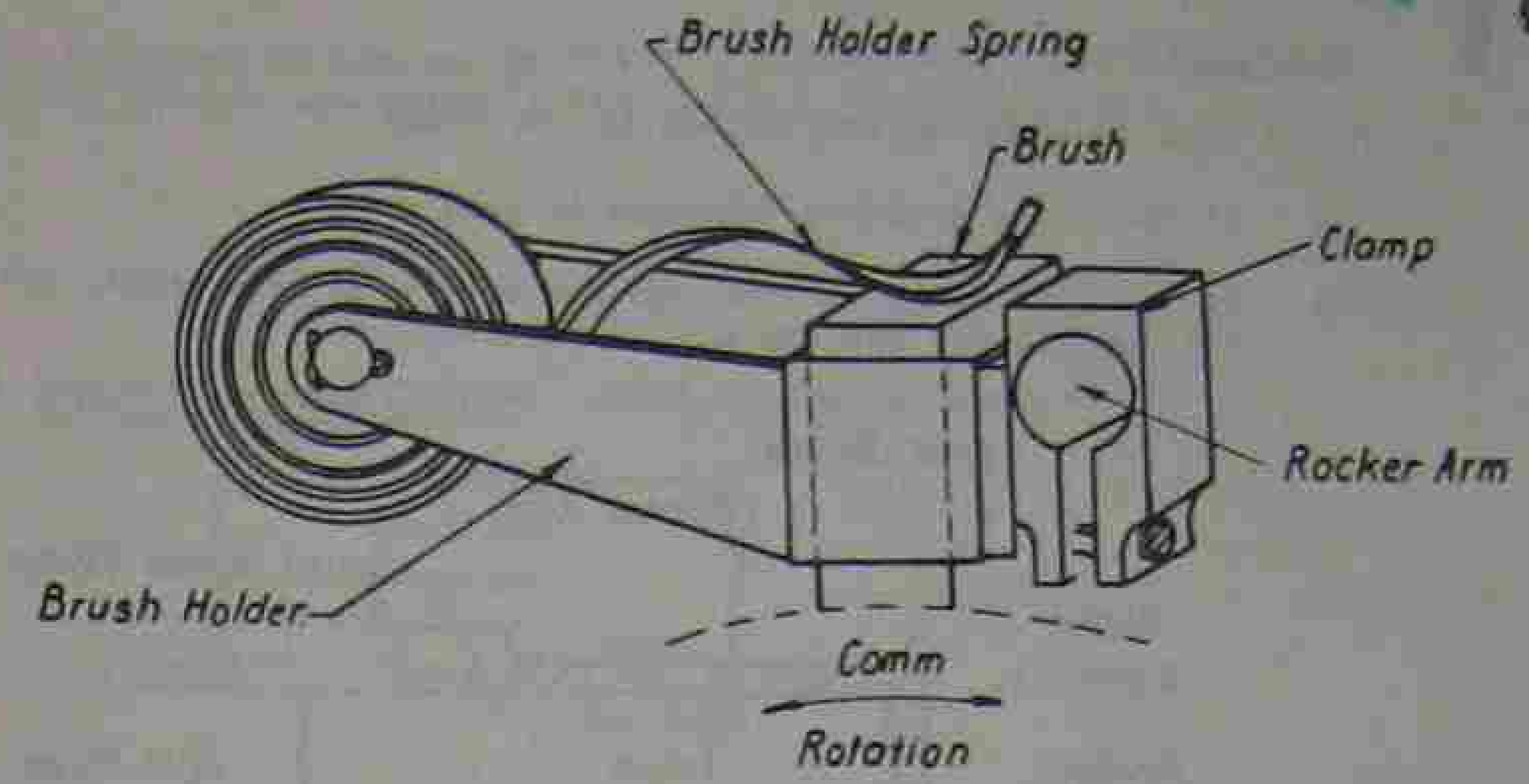


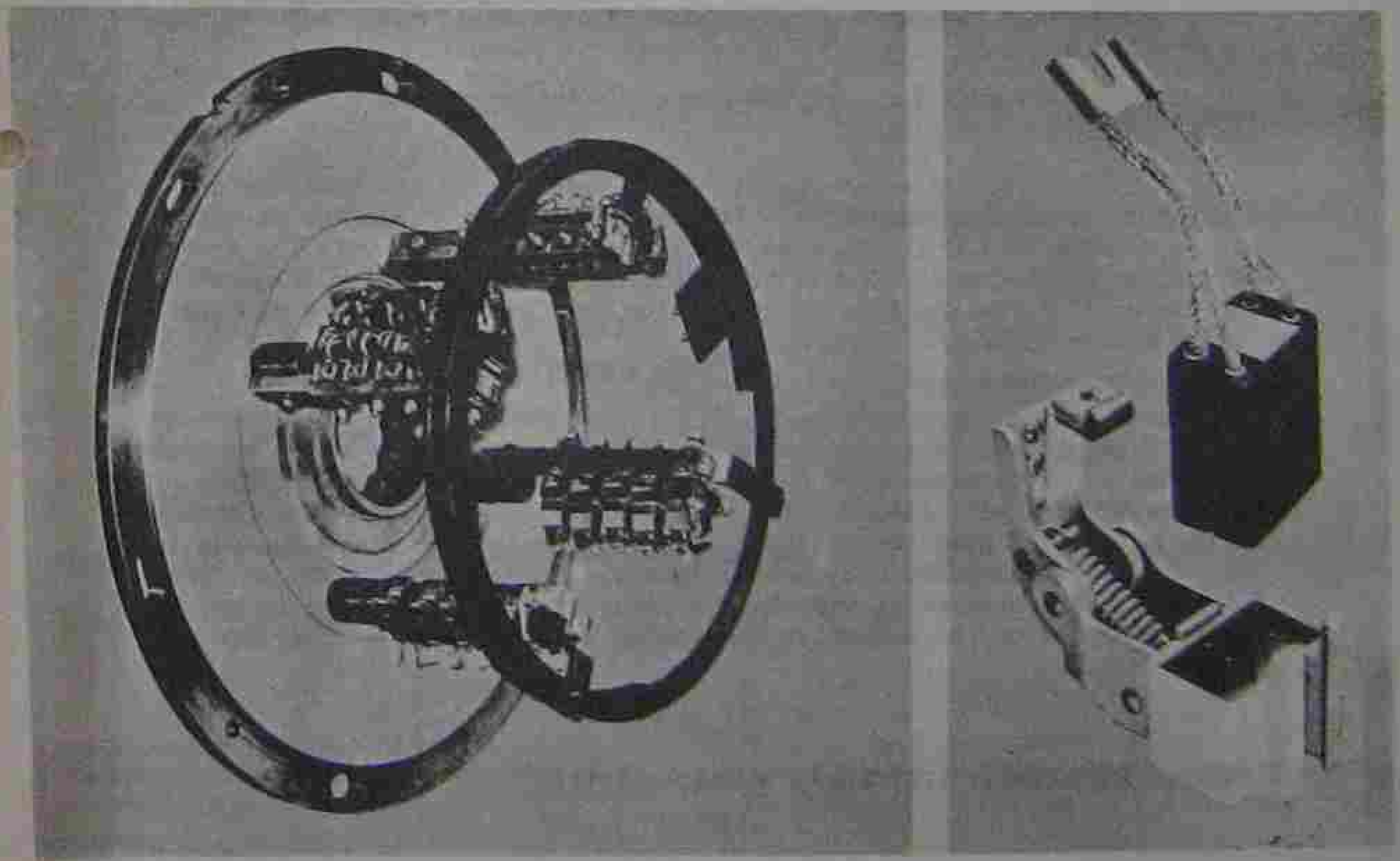
Figure 1.10

BRUSH ROCKER

(a) The brush rocker consists of two parts, a rocker ring and a rocker arm.

(b) The rocker arm is clamped into position on to the rocker ring and is insulated from it.

(c) The brush rocker generally fits on a spigot inside the endshield, enabling the brushes to be rotated round the commutator until the best brush position is obtained. At this position the rocker is clamped and very often dowelled to the endshield.



nd shield with brush device. (74 726)

Brush holder with almost constant pressure characteristic independent of brush wear. (74 897).

Figure 1.11 - By courtesy of ASEA, June, 1969.

ENDSHIELD

(a) This is spigoted and bolted to the frame.

(b) It holds the armature bearings in position.

(c) It contains suitable openings for servicing of brushes, has inlets and outlets for cooling air if required.

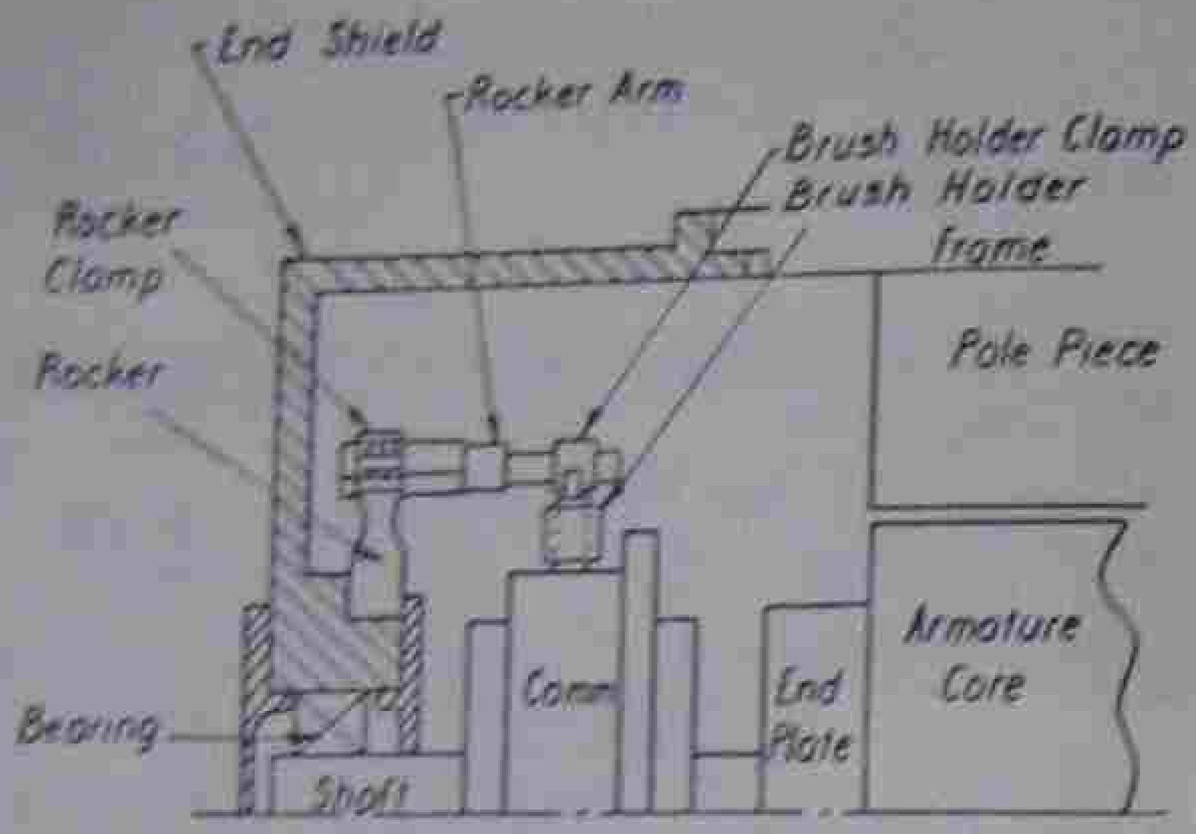


Figure 1.12

MAIN FIELD WINDING

The purpose of the magnetomotive force produced by this winding is to establish the magnetic field through which the armature conductors move. It is possible to construct a curve showing the relationship between field current and magnetic flux for a given magnetic circuit.

INTERPOLE COIL

This coil produces a magnetic field which helps the armature coil current to reverse or commutate. It also helps to overcome the magnetic field produced by the armature and is connected in series with the armature as will be shown later. The number of turns on this coil are related to the number of turns and type of connection used on the armature winding.

COMPENSATING WINDING

This winding is generally only used on large, highly rated machines. Very simply, it compensates for and cancels out the detrimental effect of the armature magnetic field on the main magnetic field. The shoe portion of the main field pole lamination is made deeper and slots are punched in the pole face facing the armature to take the compensating winding. The interpole and compensating winding are considered the same winding and any m.m.f. produced by the compensating winding is added to the interpole winding m.m.f.

The four ways of connecting the main field circuit relative to the armature circuit are shown in Fig. 1.13.

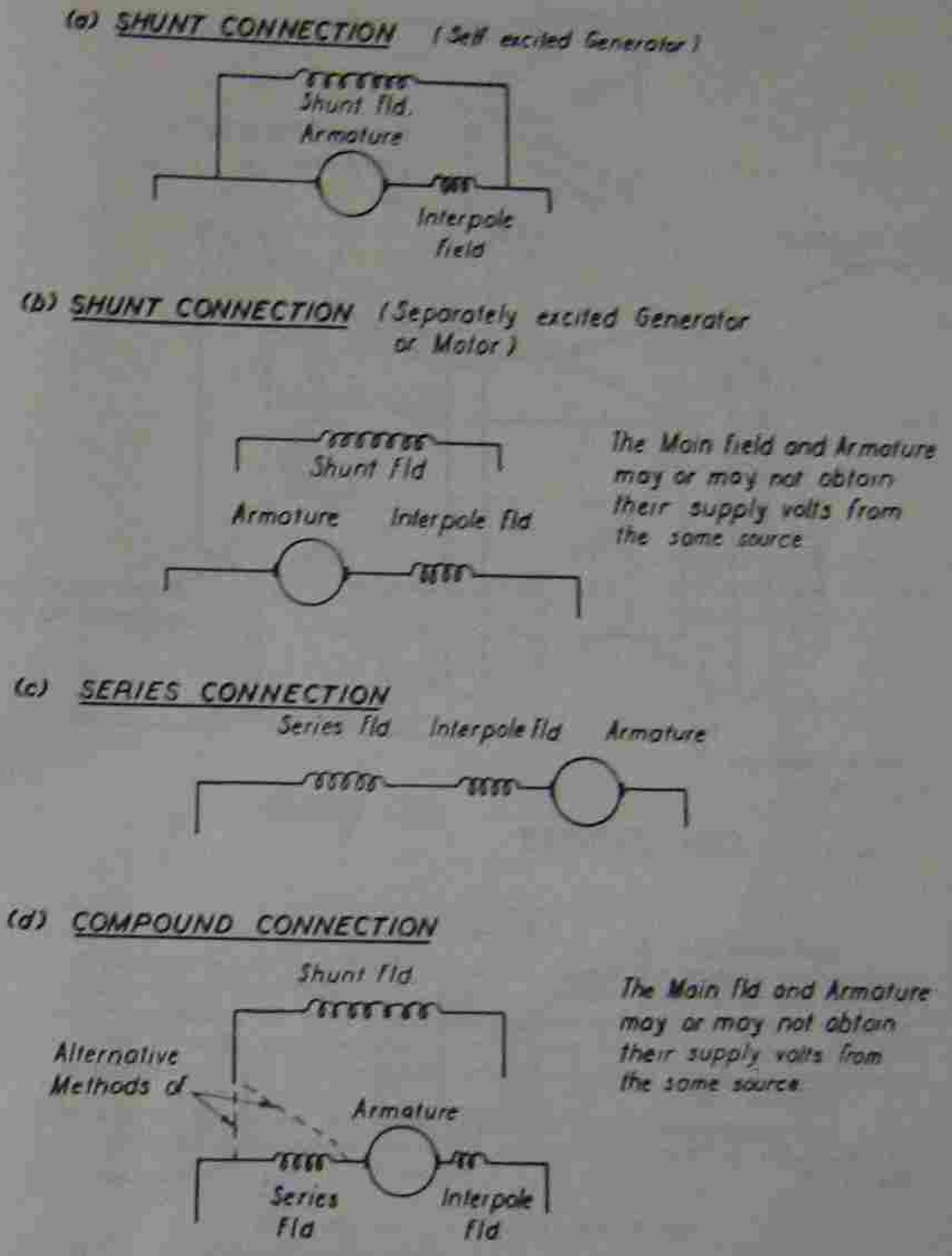
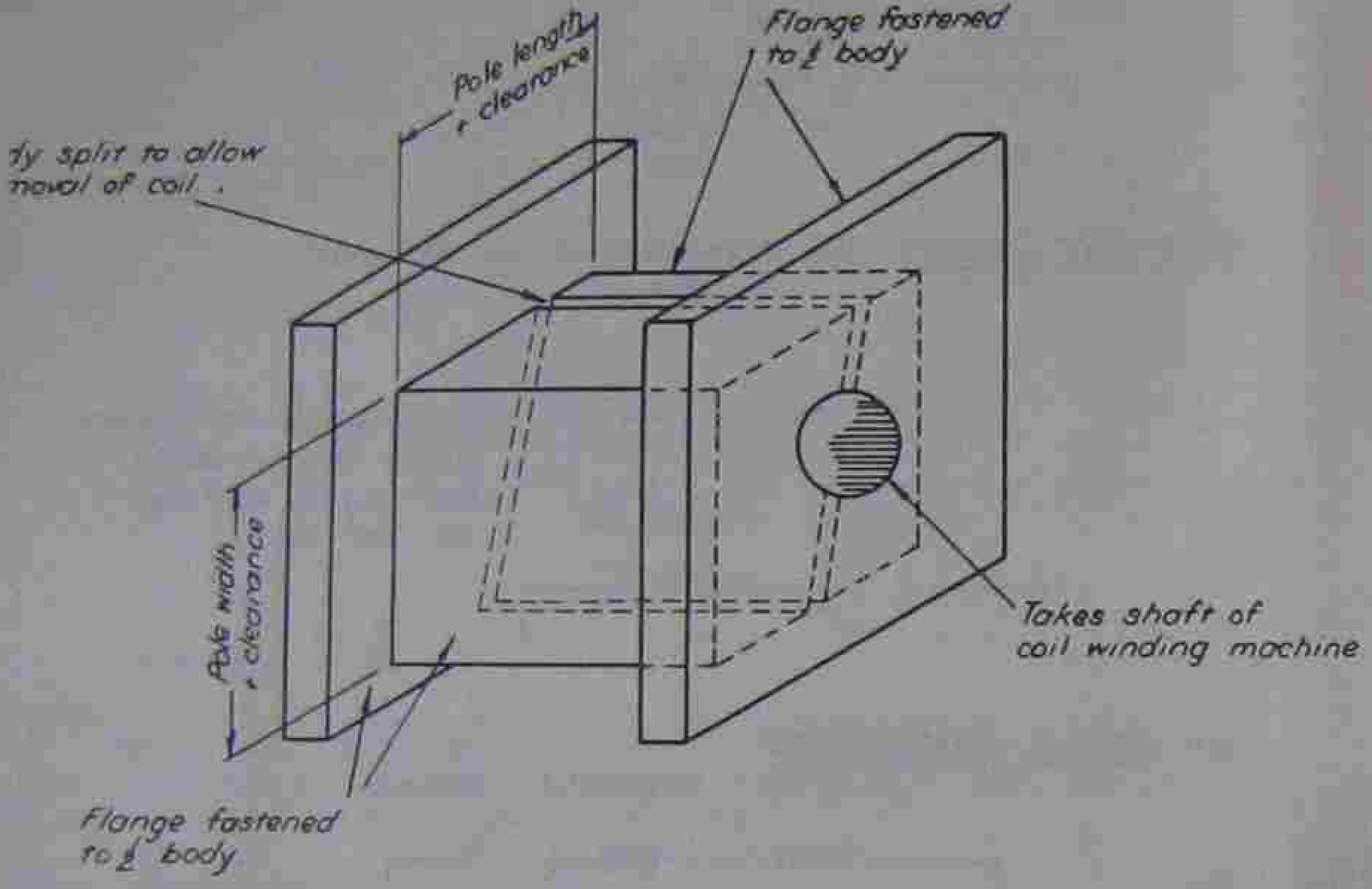


Figure. 1.13

The main and interpole coils are wound on coil formers (Fig. 1.14) and have the following basic insulation system:

1. Inter turn or conductor insulation.
2. Inter winding insulation.
3. Main earth insulation.



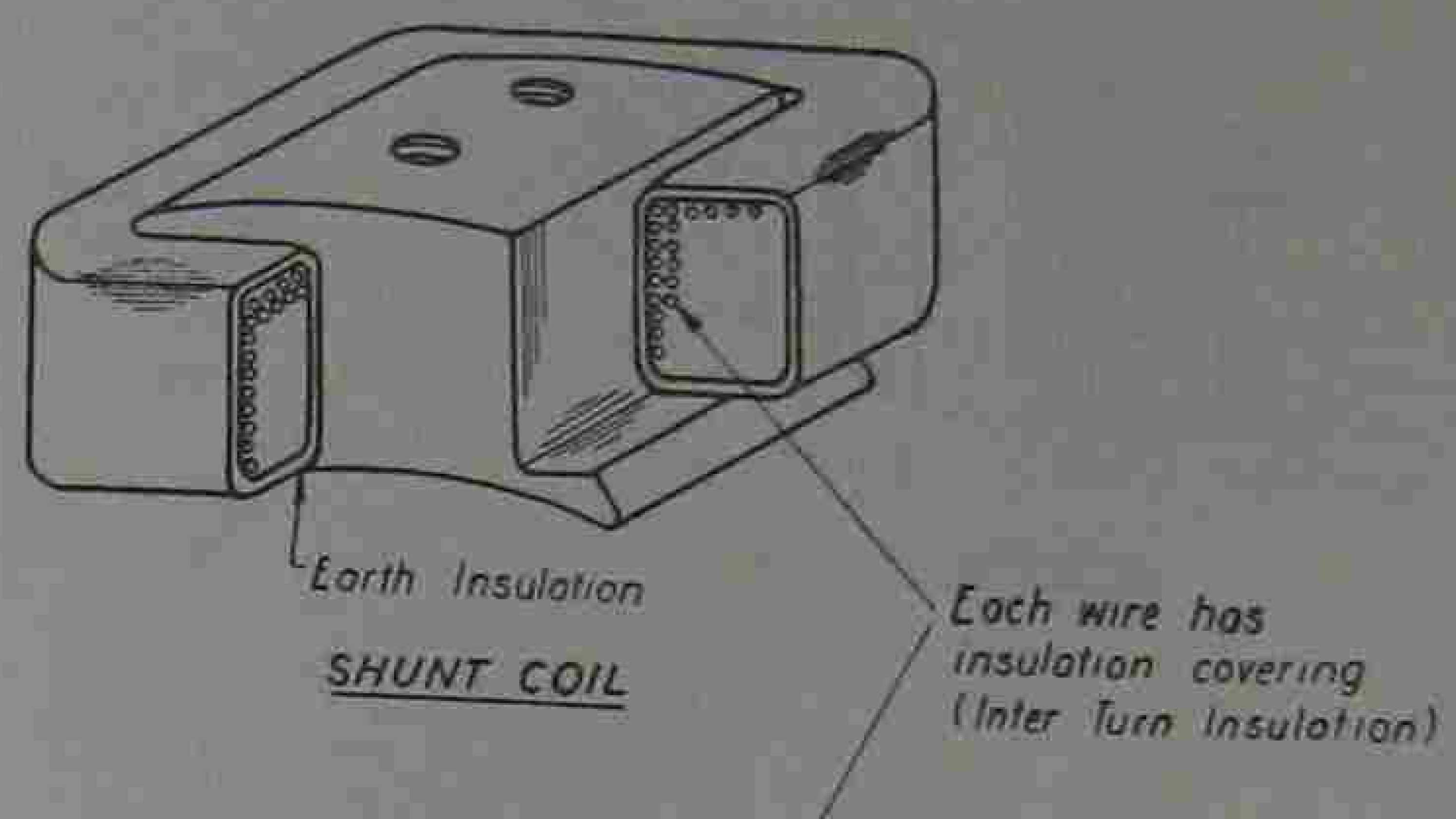
COIL FORMER

Figure. 1.14

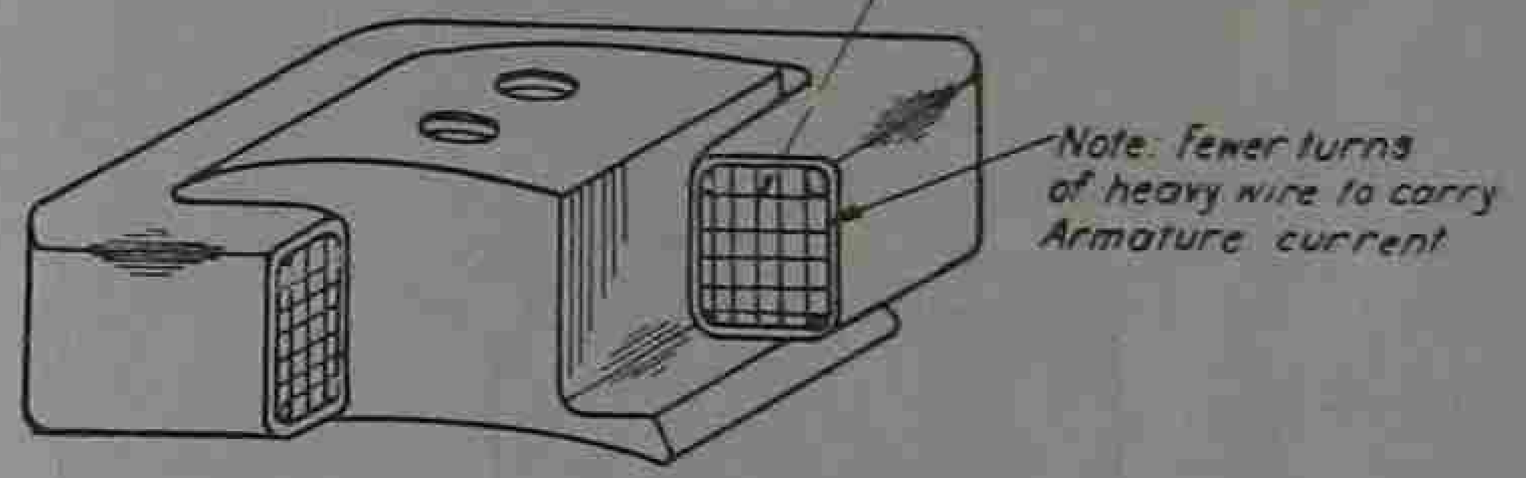
After winding and taping the coils are dipped in an insulation varnish and baked until the coil is one solid unit with little chance of inter turn insulation becoming worn through due to vibration. The coil is held firmly on the pole by clips or something similar, thus preventing the earth insulation being worn through.

A cross section of the shunt, compound and series coils is shown in Fig. 1.15, interpole coils Fig. 1.16, and compensating winding Fig. 1.17.

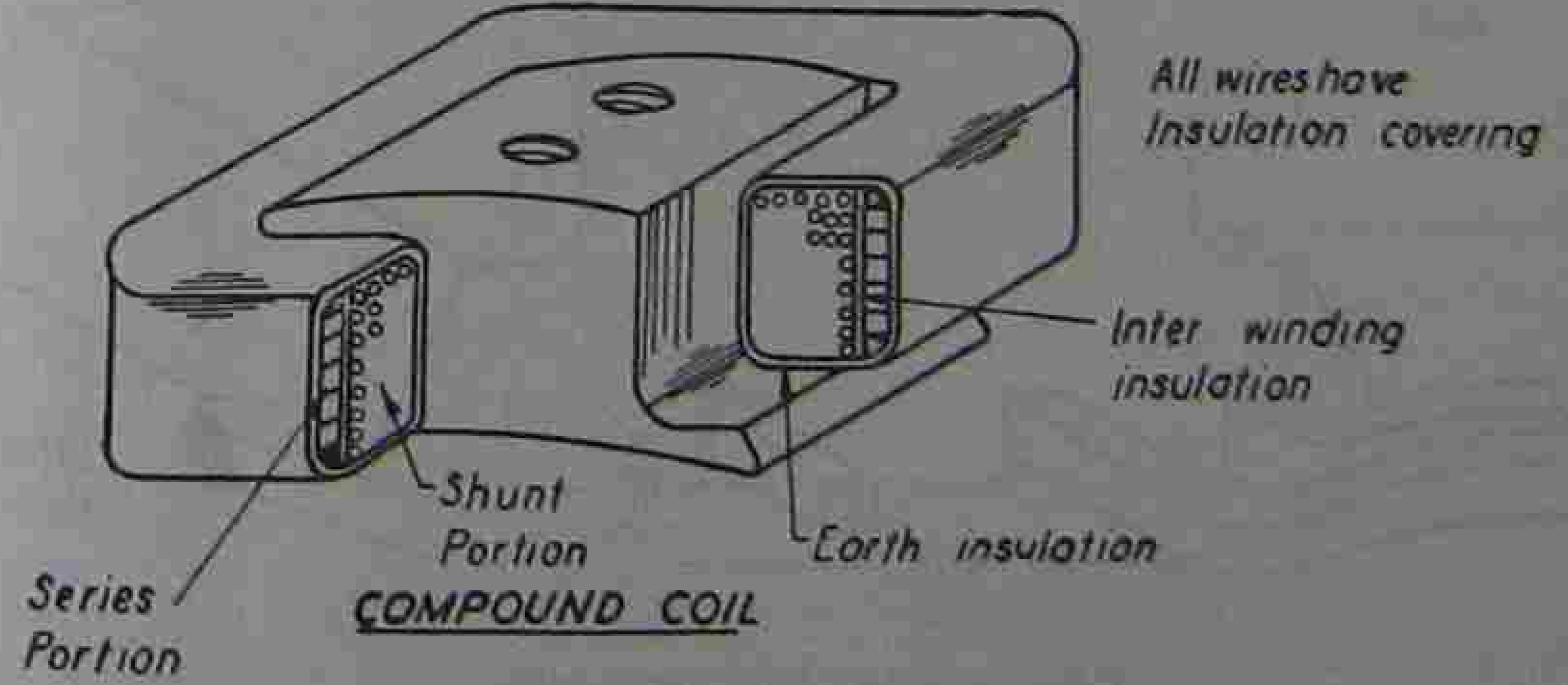
MAIN FIELD COILS



SHUNT COIL

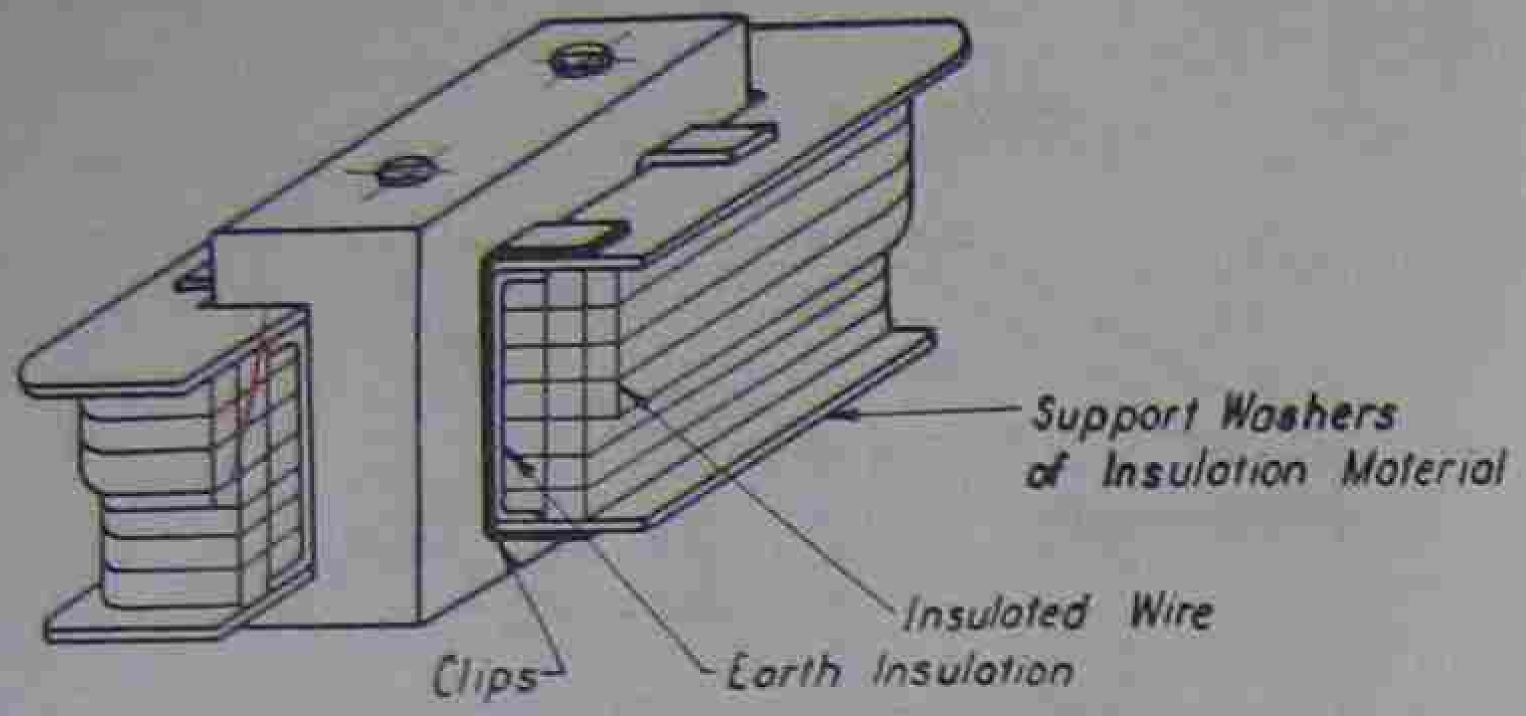


SERIES COIL



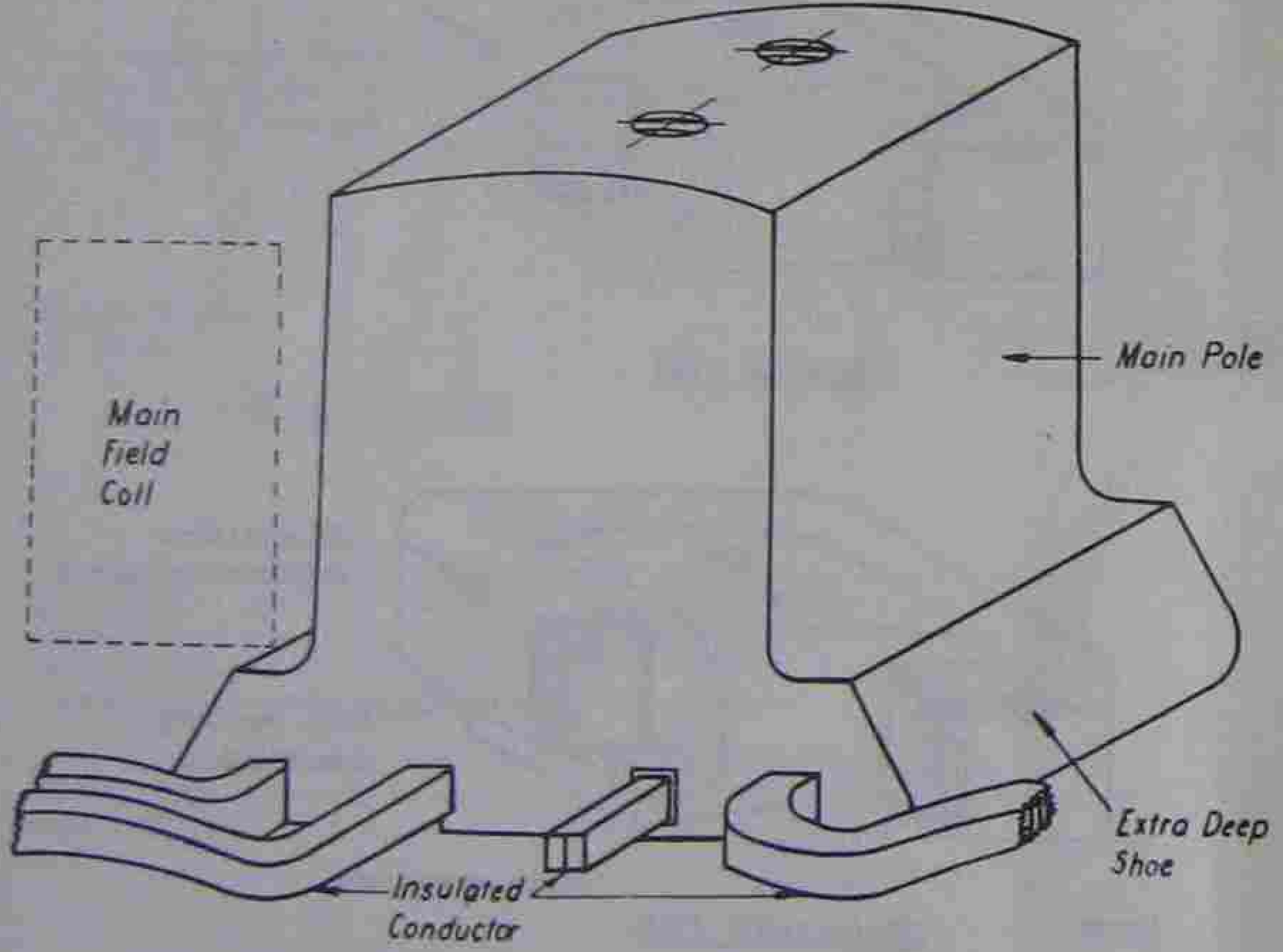
COMPOUND COIL

Figure 1.15



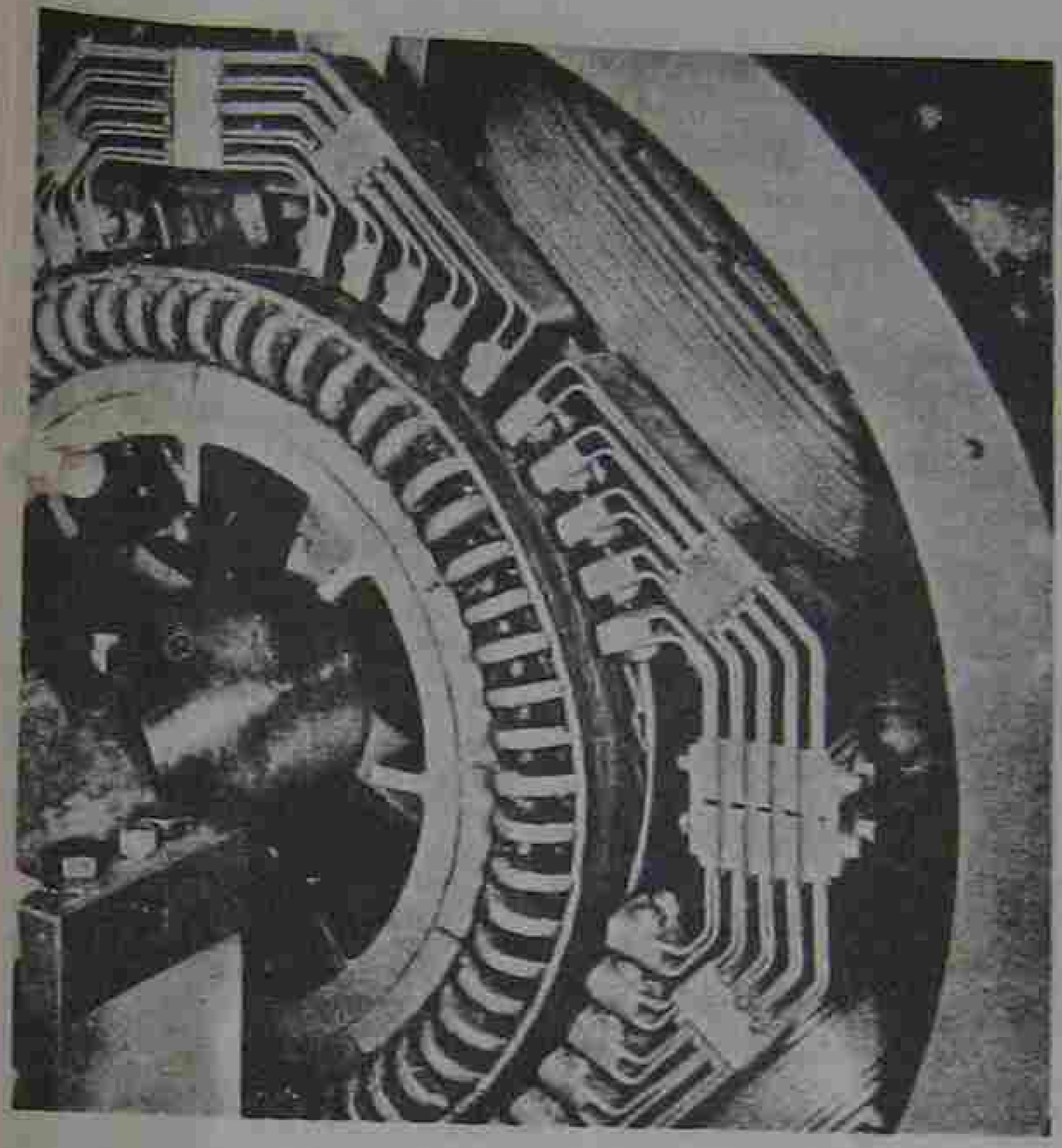
INTERPOLE COIL

Figure 1.16



COMPENSATING WINDING

Figure 1.17 (a)



Fish Plate Splits

The standard construction uses individually bolted connections as shown on page 10. However, if preferred by the customer for fast disassembly, Fish Plate Splits pictured at the left can be furnished.

Figure 1.17 (b)

- By courtesy of Westinghouse.

REVIEW QUESTIONS

1) What is the function of:

   a) an electric motor;

   b) a dynamo?

2) What factors determine whether a particular machine is acting as a motor or as a generator?

3) From considering the basic expressions for power associated with a conductor and for angular motion, show that

$$P = \frac{2\pi N T}{60}$$

4) Show that the accelerating time for a given load depends on the applied torque and the moment of inertia of the system.

5) What is the function of the following parts of a d.c. machine:

   a) yoke;

   b) armature;

   c) commutator and brush gear;

   d) main field system?

ASSIGNMENTS - UNIT NO. I

Marks.

10 1) A conductor of length 1 metre moves at constant speed in a field of one tesla at 5 metres per second. Calculate the e.m.f. induced.

15 2) If the conductor of question 1 was carrying a current of one ampere determine:

   a) the force on the conductor;

   b) the work done in 20 seconds;

   c) the power dissipated.

20 3) A system has a moment of inertia of 5 Nm s^2 and is operated on by a constant torque of 25 newton metres. Calculate:

   a) the time taken by the system to accelerate to 50 radians per second; Assume $w_1 = 0$

   b) the angular velocity after 5 seconds.

15 4) A system is required to accelerate to 100 radians per second in 30 seconds. If the moment of inertia of the system is 2 Nm s^2 calculate the magnitude of the constant torque required to achieve this speed in the required time. $W_1 = 0$

40 5) The torque speed relationship of a load is given by the expression

$$T = \frac{1}{100}\omega^2$$

and the torque applied to the system follows the law

$$T = 50 + 0.5\,\omega$$

where T is torque in Nm
and ω is the angular velocity in radians.
Determine:

   a) the equilibrium speed;

   b) accelerating time. — Assume Moment of Inertia I or (J) = 5 $Nm\,sec^2$

ELECTRICAL MACHINES I

wk 2

UNIT No. 2

DIRECT CURRENT MACHINES

SUMMARY OF CONTENTS

This unit will cover the following topics:

2.1 INTRODUCTION

The e.m.f. or the force produced by one conductor in a motor or generator is insufficient for practical purposes and armatures in practical machines require many conductors to perform effectively. This unit covers the method of interconnection of these conductors and the connection to the commutator to enable the necessary transfer of electrical energy from the armature system to the external circuit to be effected. This combination of conductors and the associated coil to commutator connection system is termed the armature winding.

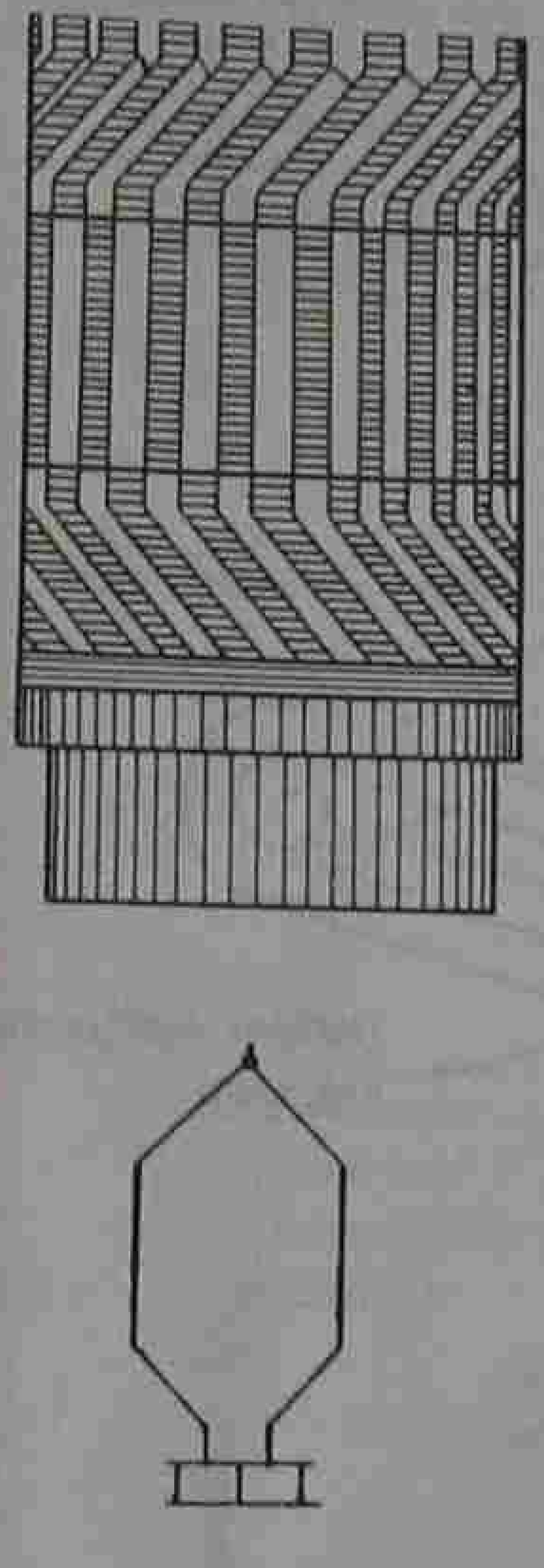
2.2 TYPES OF ARMATURE WINDING

In Figure 1.2 it was shown how the armature conductors were connected at one end to form an open coil and, at the other end, the coil leads were connected to the commutator. This is the basic structure of the armature winding. The calculation of the number of armature conductors and the number of turns in each coil is covered in later work.

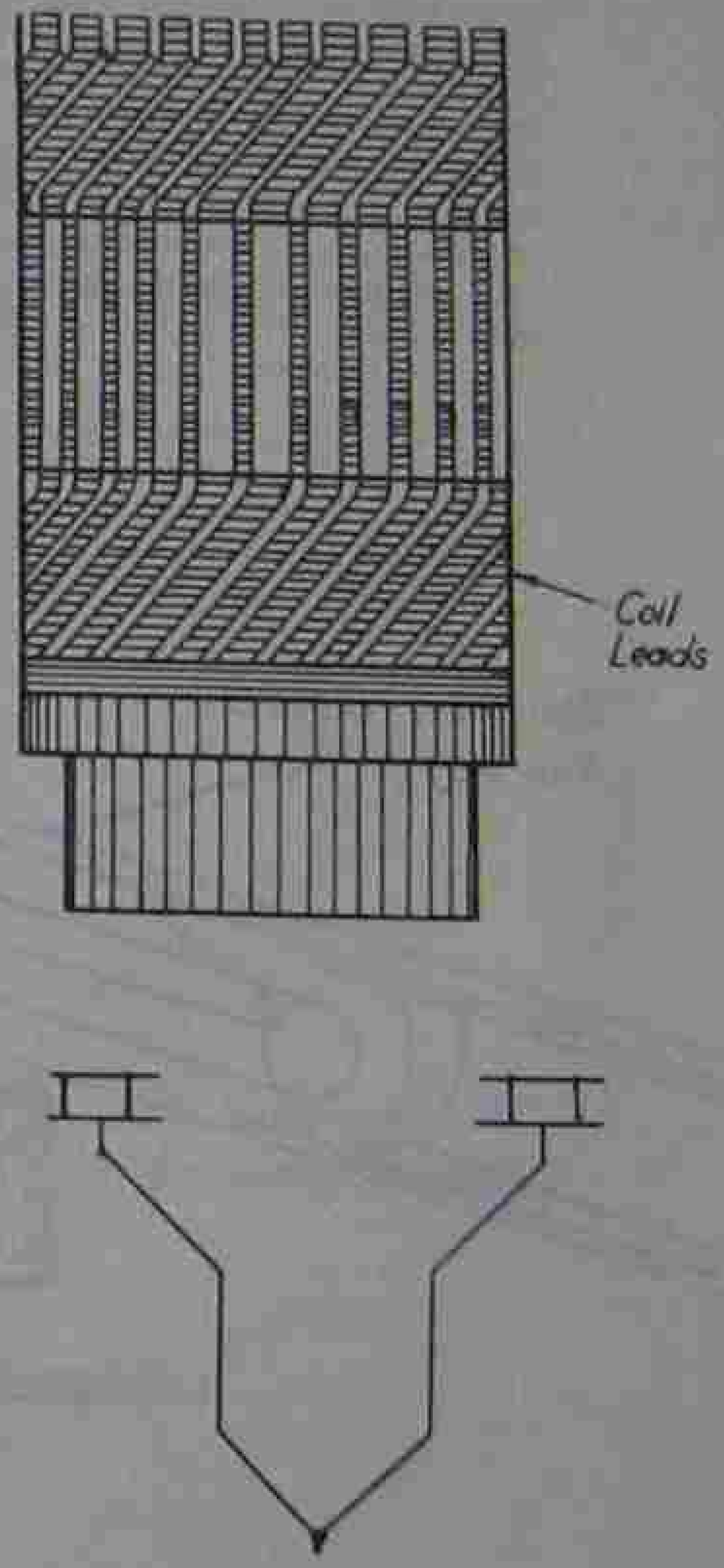
The placing of the coils in the armature slots and connecting them to the commutator is termed winding the armature. There are two types of armature winding used on modern d.c. machines, called LAP and WAVE winding.

In most cases the actual coils are the same, the windings differing from one another only in the manner in which the leads are connected to the commutator, giving the coil and winding patterns as in Figure 2.1.

The discussion on windings will be limited to simplex windings, that is, those windings where the minimum number of parallel armature paths are involved. Modification of the commutator connections can increase the number of paths but this is beyond the scope of this present course.



LAP WOUND



WAVE WOUND

2.3 COIL CONSTRUCTION

Each armature coil is made up of one or more elements, depending on the ratio of armature slots to commutator segments, each element consisting of one or more turns of copper wire. The insulation system of the coil is as follows:

1. Inter conductor insulation to prevent a short circuit occurring between turns, either of the same or adjacent elements.
2. The main earth insulation is in the slot portion of the coil to prevent any of the conductors going to earth.
3. By insulating all the coil supports under the coil overhang it is possible to use a thinner insulation on the coil portion outside the core slots. The coils are formed by first winding the armature wire round two pins as in Figure 2.2 (a) and then pulling the coil out to the correct coil span as in Figure 2.2 (b). The coil slot portion is slightly angled and the coil overhangs slightly, curved to enable it to be fitted quickly and with the least amount of handling. The above shaping is done automatically on a coil winding machine prior to insulating as necessary (see Figure 2.2 (c)).

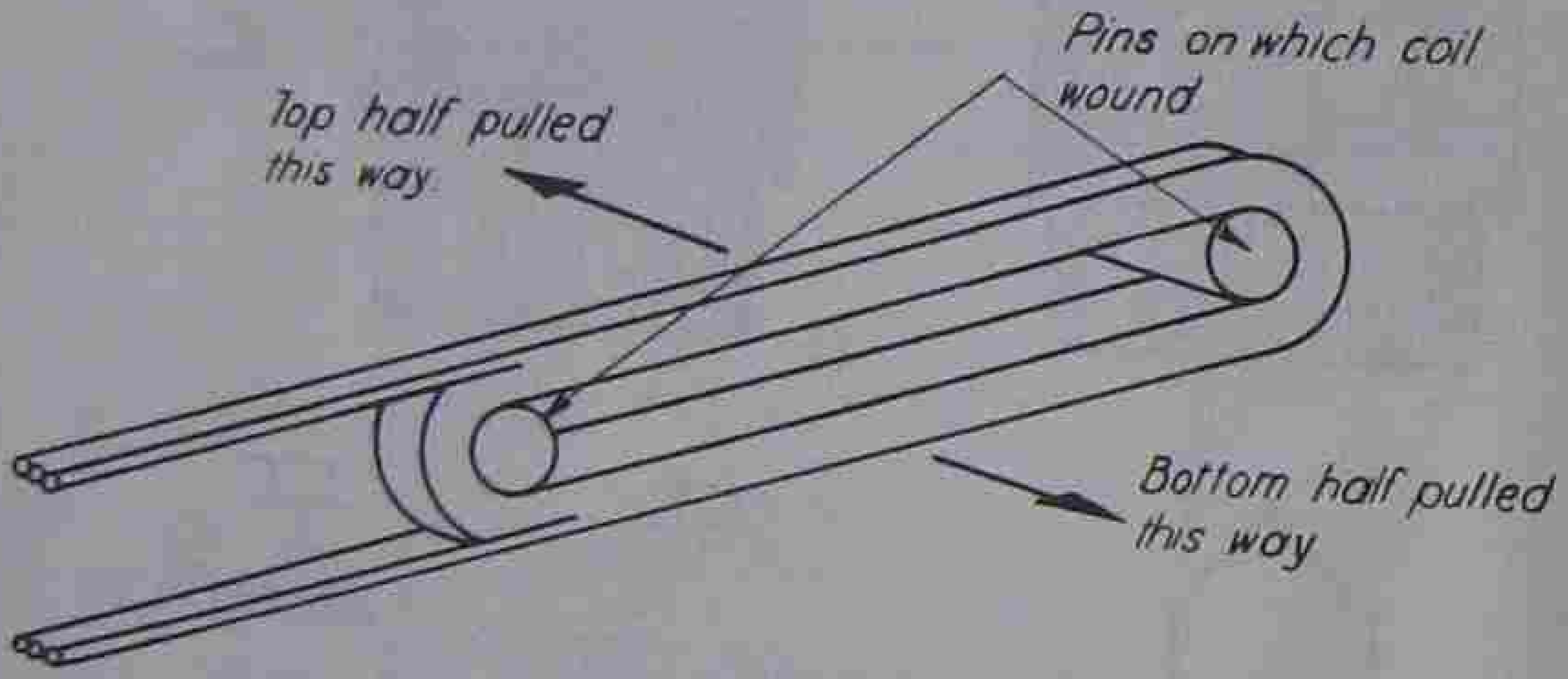


Figure 2.2(a)

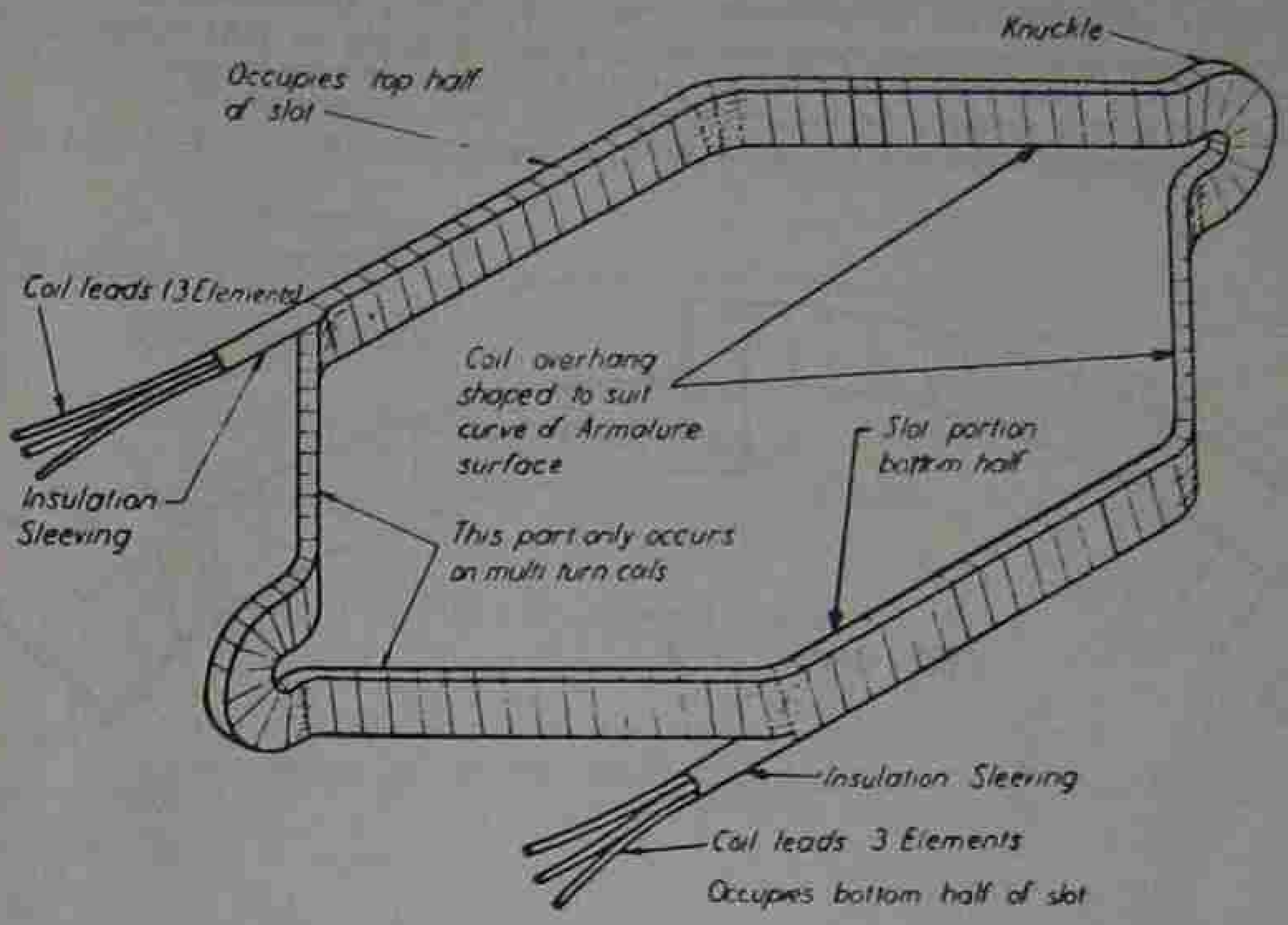


Figure 2.2(b)

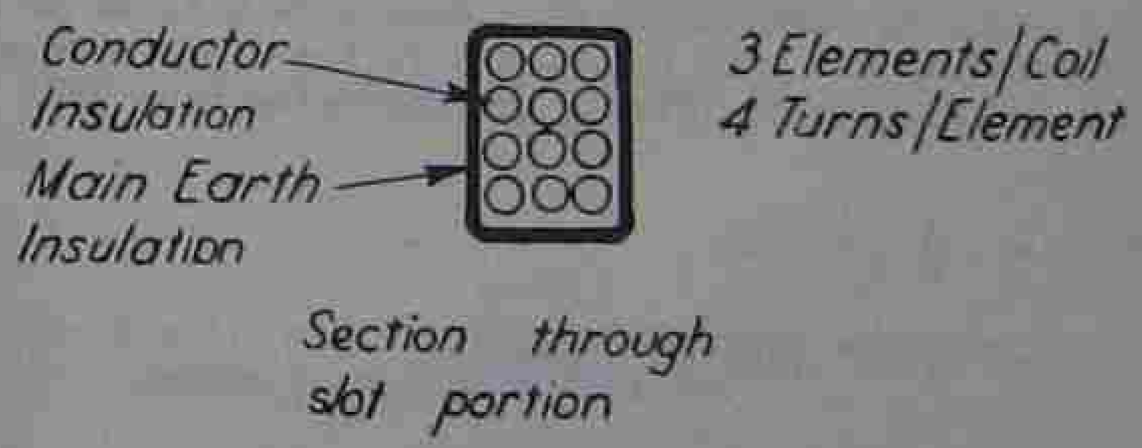


Figure 2.2(c)

The slot portion of each coil is half the total slot depth. The coils occupying the bottom half of the slots are placed in first and when the coil span has been reached the coil top can be fitted to fill the slot (see Figure 2.2 (d)). After fittings, the coils are connected to the commutator riser. It is this last operation that finally determines whether the winding is a lap or a wave winding.

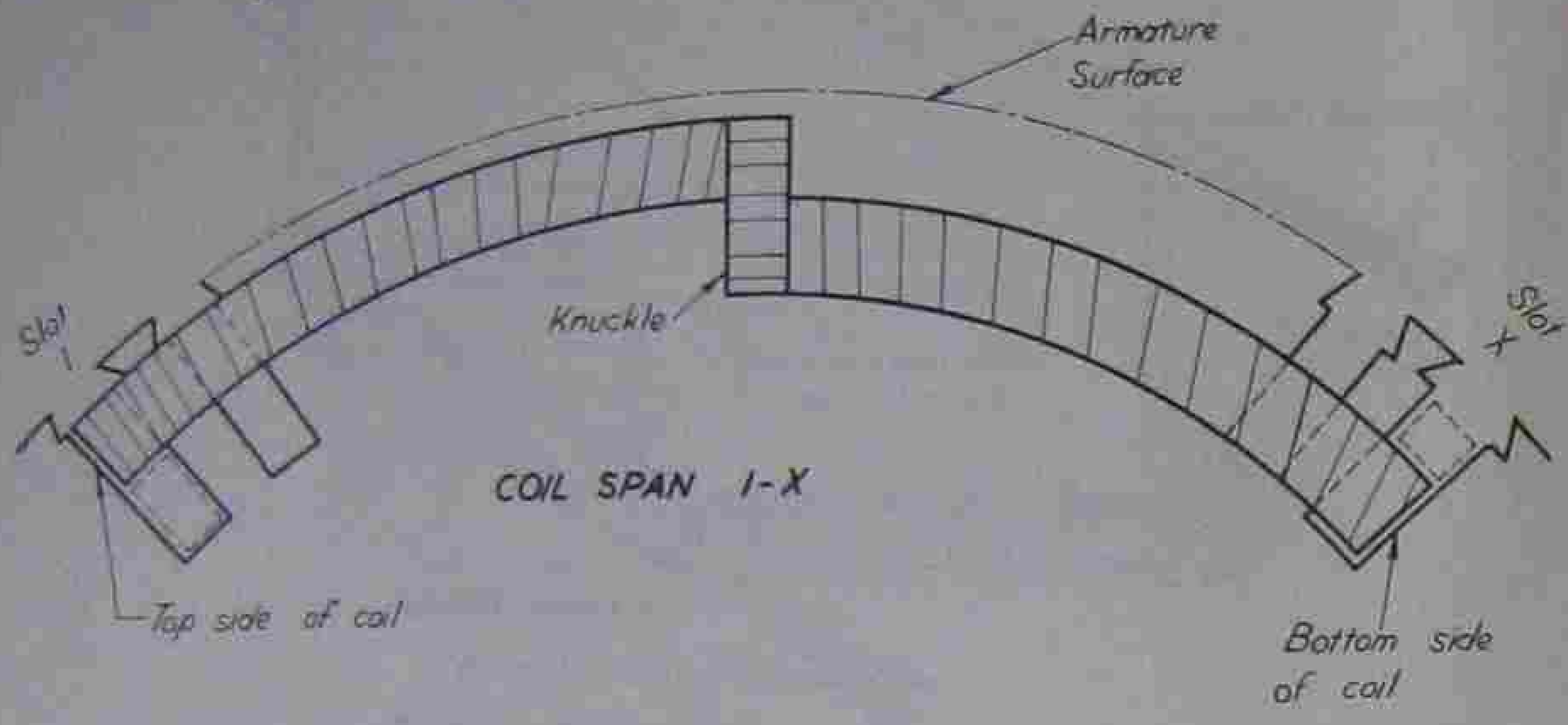


Figure 2.2 (d)

2.4 COIL PITCH

As each coil side of the coil is under a pole of different polarity it is important that the coil sides, as far as possible, be in the same relative positions at all times. The reason for this is shown in Figure 1.2 where it can be seen that if the opposite sides of the coil are in the same relative position under their respective pole faces, then the maximum e.m.f. will be induced in the coil as all the e.m.f.s induced in each slot portion of the coil will be additive. Also, during commutation each coil side will be at the same point of commutation. The coil pitch is therefore made as near as possible to the pole pitch, giving the following equation:

$$Y_s = \frac{S}{P} \pm K \qquad - \qquad 2.1$$

Y_s = coil pitch in slots

S = total number of armature slots

P = number of main poles

K = a fraction that is either added to or subtracted from $\frac{S}{P}$ to make Y_s an integer. This is necessary, for in the practical sense a fractional coil pitch is meaningless.

Example 2.1

Calculate the coil pitch Y_s and indicate the slot numbers in which the first coil is wound for each of the following cases assuming that the details refer to a 4-pole machine.

(a) S = 35. (b) S = 36. (c) S = 37. (d) S = 42.

Solutions

From equation 2.1

(a) $Y_s = \frac{35}{4} + \frac{1}{4} = 9$; slots 1 and 10

alternatively

$Y_s = \frac{35}{4} - \frac{3}{4} = 8$; slots 1 and 9

(b) $Y_s = \frac{36}{4} \pm 0 = 9$; slots 1 and 10

(c) $Y_s = \frac{37}{4} - \frac{1}{4} = 9$; slots 1 and 10

alternatively

$Y_s = \frac{37}{4} + \frac{3}{4} = 10$; slots 1 and 11

(d) $Y_s = \frac{42}{4} - \frac{1}{2} = 10$; slots 1 and 11

alternatively

$Y_s = \frac{42}{4} + \frac{1}{2} = 11$; slots 1 and 12

Example 2.2

Repeat Example 2.1 for the following cases assuming that in each instance the data refers to a 6-pole machine.

(a) S = 72. (b) S = 57. (c) S = 77.

Solutions

(a) $Y_s = \frac{72}{6} \pm 0 = 12$; slots 1 and 13

(b) $Y_s = \frac{57}{6} - \frac{1}{2} = 9$; slots 1 and 10

alternatively

$Y_s = \frac{57}{6} + \frac{1}{6} = 10$; slots 1 and 11.

(c) $Y_s = \frac{77}{6} + \frac{1}{6} = 13$; slots 1 and 14.

alternatively

$Y_s = \frac{77}{6} - \frac{5}{6} = 12$; slots 1 and 13.

In each of the above examples, where two alternatives are given, the most probable choice would be the lesser of the two values.

2.5 COMMUTATOR PITCH

This refers to the span of commutator bars to which the armature coil leads are attached, that is, the number of segments between the start and finish leads of each coil. The commutator pitch is denoted by the symbol Y_c.

As shown in Figure 2.2(b), all the coils have the same shape, only the method of connection of the coils to the armature segment will vary.

A) Lap Windings

In lap windings the leads of each coil are connected to adjacent segments. Where the leads progress around the armature in the same direction as the coils this is termed a progressive winding and

$$Y_c = +1$$

where the leads cross

$$Y_c = -1$$

hence for a lap winding

$$Y_c = \pm 1 \qquad - \qquad 2.2$$

The positive sign denotes a "progressive" winding.

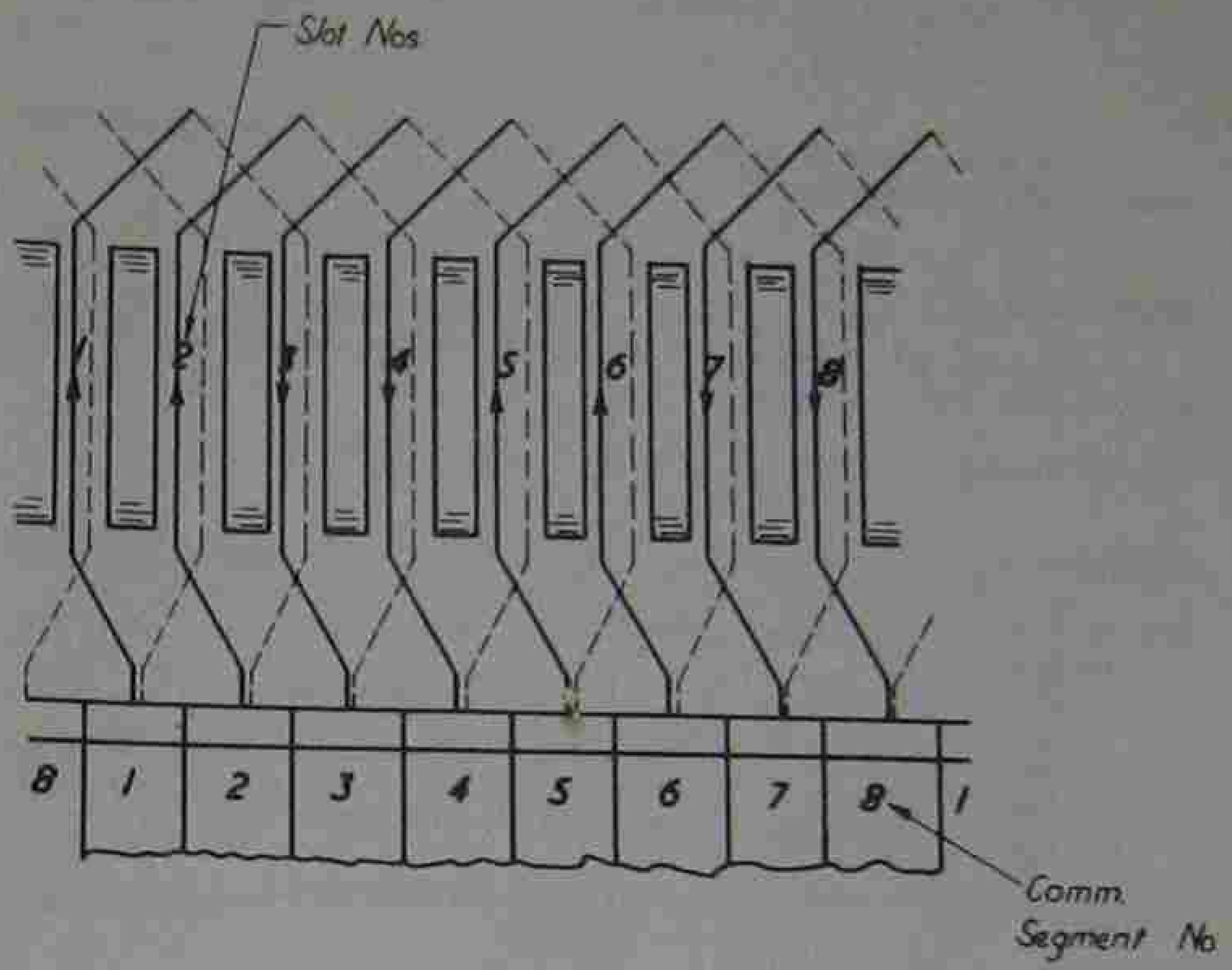
The negative sign denotes a "retrogressive" winding.

Figure 2.3 shows a simplex lap wound armature where S = 8; p = 2; C, number of commutator bars = 8.

$Y_s = \frac{8}{4} \pm 0 = 2$; coil pitch = 1 to 3.

$Y_c = \pm 1$ for simplex lap

It will be noted that in Figure 2.3 the winding forms a closed circuit.



LAP WINDING

——— *Coil side occupies top half of slot*

- - - - -*Coil side occupies bottom half of slot*

Figure 2.3

B) Wave Windings

In simplex wave windings the circuit returns to a segment adjacent to the starting segment after traversing $\frac{P}{2}$ coils.

Hence in wave windings the pitch of $\frac{P}{2}$ coils is $C \pm 1$

where P is the number of poles

and C the number of commutator segments.

Hence the commutator pitch of one coil

where Y_c = commutator pitch in commutator bars

C = total number of commutator bars

and P = number of poles

is given by the expression

$$Y_c = \frac{C \pm 1}{P/2} \qquad - \quad 2.3$$

The most commonly used choice is -1 as this gives the shortest mean length of conductor turn.

Example 2.3

Calculate the commutator bar pitch for the following four-pole simplex wave wound armatures:

(a) 81 bars. (b) 131 bars. (c) 171 bars.

Solutions

(a) $\frac{81 \pm 1}{2}$ = 40 or 41; pitch 1 - 41 (retrogressive)
or 1 - 42 (progressive)

(b) $\frac{131 \pm 1}{2}$ = 65 or 66; pitch 1 - 66 (retrogressive
or 1 - 67 (progressive)

(c) $\frac{171 \pm 1}{2}$ = 85 or 86; pitch 1 - 86 (retrogressive)
or 1 - 87 (progressive)

Example 2.4

Calculate Y_c for the following six-pole simplex wave wound armatures.

(a) 256 bars. (b) 166 bars. (c) 380 bars.

Solutions

(a) $\frac{256 - 1}{3}$ = 85; pitch 1 - 86.

(b) $\frac{166 - 1}{3}$ = 55; pitch 1 - 56.

(c) $\frac{380 + 1}{3}$ = 127; pitch 1 - 128.

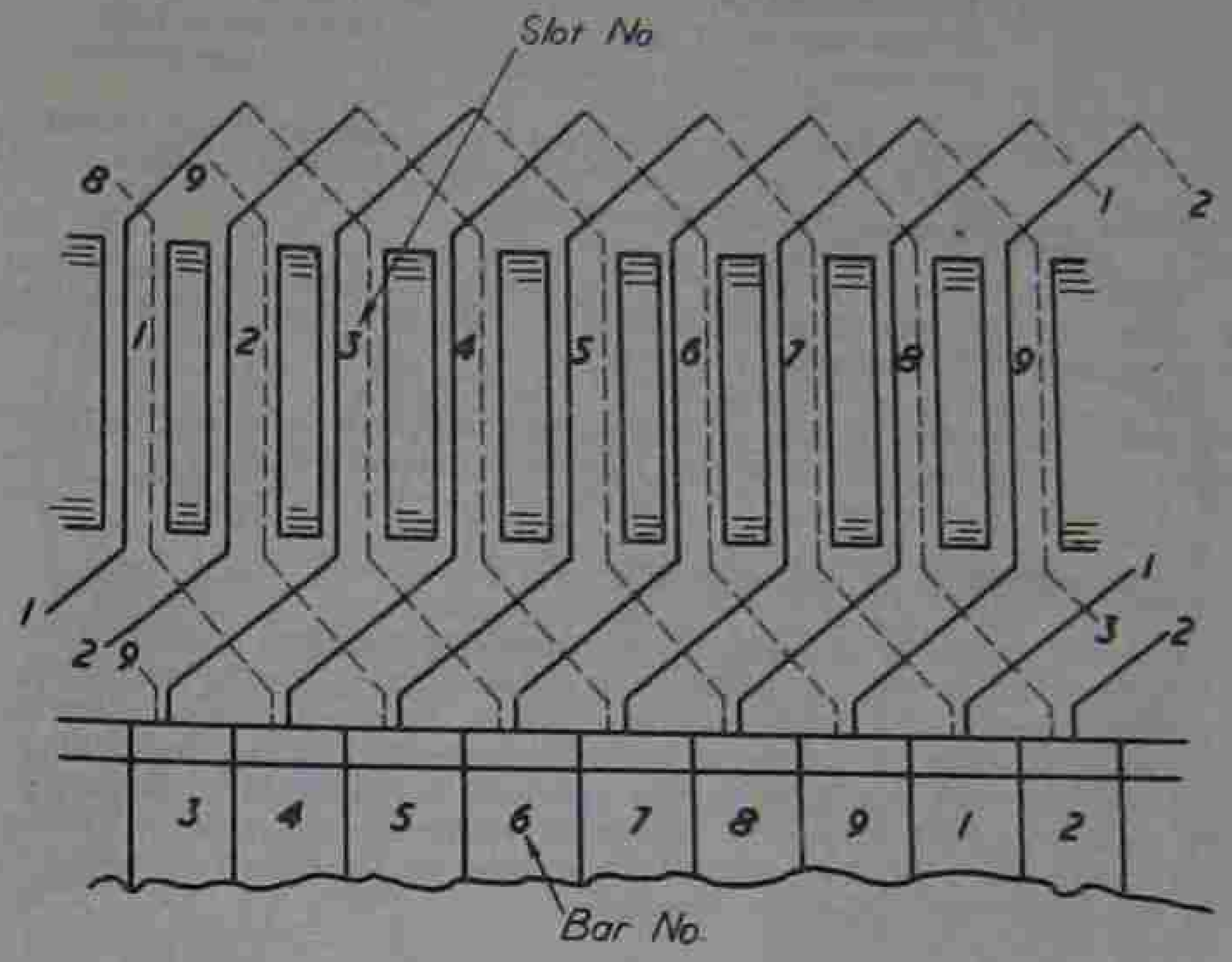
Figure 2.4 shows a simplex wave wound armature where S = 9, p = 4, number of commutator bars = 9.

$Y_s = \frac{9}{4} - \frac{1}{4} = 2;$ slot 1 to slot 3.

$Y_c = \frac{9 + 1}{2} = 5;$ bar 1 to bar 6.

Alternatively

$Y_c = \frac{9 - 1}{2} = 4;$ bar 1 to bar 5.



WAVE WINDING

—— Coil side occupies top half of slot

- - - Coil side occupies bottom half of slot

Figure 2.4

2.6 ARMATURE WITH MORE SEGMENTS THAN SLOTS

When the number of conductors required for a given output has been calculated, the number must be subdivided into a number of coils. There are the same number of slots as coils.

The number of slots chosen takes into account the following points:

(1) The flux density in the teeth must be below saturation level; hence, the teeth must have a certain minimum area in respect to the total flux per pole.

(2) The greater the number of slots the more the total insulation on the armature and thus the less space available for the copper.

(3) Too few slots on motors can cause uneven running.

(4) The teeth must be strong enough mechanically.

It is often necessary and advantageous to divide the coils into a number of elements reducing the number of turns per element for the following reasons:

(a) The commutation reactance voltage varies with the square of the number of turns in each element and a high reactance voltage gives unsatisfactory commutation.

(b) Each element is connected to a commutator bar (except where a dummy coil is used) and there is a limit to the maximum voltage between bars.

There is a practical limit to the number of bars in a commutator as the number of bars cannot be increased to such an extent that they are too small to take the armature conductor.

Thus the number of slots, number of commutator bars and turns per element become a compromise of all the above considerations.

2.7 DUMMY ELEMENTS IN WAVE WINDINGS

$Y_c = \frac{C \mp 1}{P/2}$

In wave windings the number of commutator segments (and coil elements) and the number of poles on a given machine may be such that if equation 2.3 is used the result may not be an integer. To overcome this, one or more of the elements are not connected to the commutator electrically but are retained on the armature for mechanical balance. Where, in the initial state the number of elements and segments is the same, this may also involve shorting two adjacent commutator segments to reduce the effective number of segments.

Example

4 poles, 37 slots, 4 elements per slot, 1 turn per element

total number of elements on winding = 37 x 4 = 148.

$$Y_c = \frac{148 \pm 1}{2} = \frac{149}{2} \text{ or } \frac{147}{2}$$

neither of which answers is an integer. If one element is made a dummy element then:

total number of active elements on winding = 148 - 1 = 147.

Assuming segments = active elements, Equation 2.3 will give:

$$Y_c = \frac{147 \pm 1}{2} = 73 \text{ or } 74$$

The element that is not connected is called the "dummy element". By fitting it and not connecting it, all the coils are then made the same and this assists in the mechanical balance of the armature. Also, if the fitting of the dummy element were omitted, some form of slot packing would be required in the two half-slots the coil fits in.

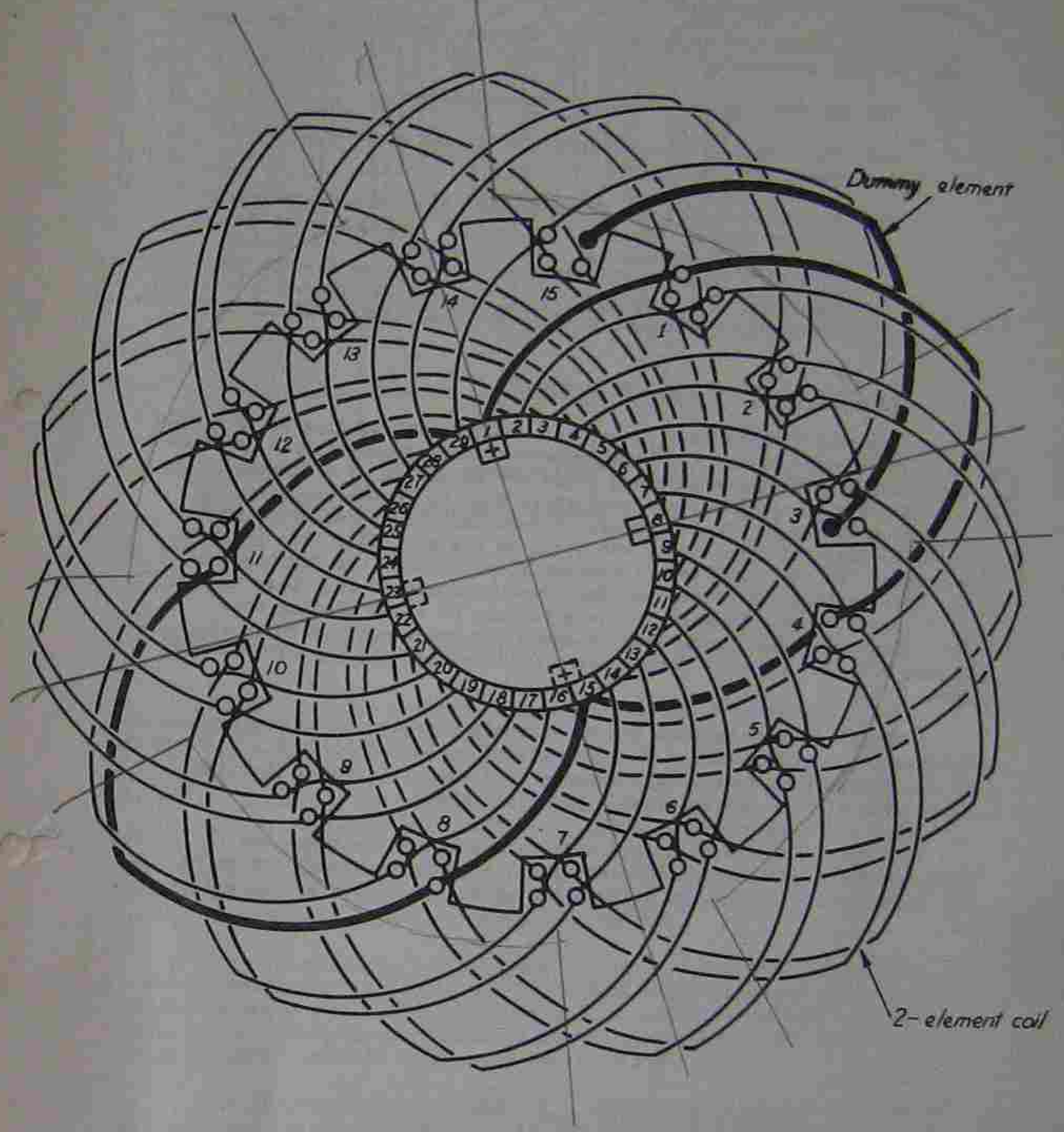


Figure 2.5 - Simplex wave winding with "dummy" element.

SISKIN FIG 24. P29.

$Y_c = \frac{29 \pm 1}{2} = \frac{28}{2} = 14$ Segs (1-15-29)

29 Com Segs
15 Slots
4 Pole
2 Elements/Coil

The general rule about whether a wave winding will have a dummy element is that $Y_c = \frac{C \pm 1}{P/2}$ must be an integer and if this is not possible by using the total number of elements then one or more elements must be left unconnected.

The following points should be emphasized:

(a) The dummy coil is not connected to the commutator and is therefore inactive.

(b) By commencing at bar 1 and tracing through the winding to slot 1, slot 4, bar 15, slot 8, slot 11 and then to bar 29, the armature surface has been traversed once by passing through p (pair of poles) coils. By tracing through the remainder of the coils from bar 29, the winding will eventually close on itself at its commencement at bar 1.

2.8 PARALLEL PATHS IN ARMATURE WINDINGS

Figure 2.6 shows what is termed a "developed" winding for a 4-pole 12 slot armature having the same number of commutator segments as slots. As the conductors under adjacent poles are in fields of different polarity the current in these conductors will be in the opposite direction as shown. Consequently, as each individual conductor passes from the field of one pole to the field of the next pole this involves a reversal of the direction of current flow. One of the functions of the brushes is to short-circuit the armature coils as they pass through this neutral zone. Because of the structure of a lap winding this necessitates as many brush sets as there are poles and, as shown in Figure 2.6, for a 4-pole machine this will involve the use of 4 brush sets.

The diagram shows that for the instant represented by the developed winding the instantaneously short-circuited coils are coils 11, 2, 5 and 8. In addition, if an active coil diagram is drawn, this shows that the armature coils are divided into 4 parallel groups.

It can be stated as a rule that in lap wound armatures the conductors are divided into as many parallel paths as there are poles and brush sets. The number of parallel paths is denoted by the symbol "a".

Figure 2.6 on next page.

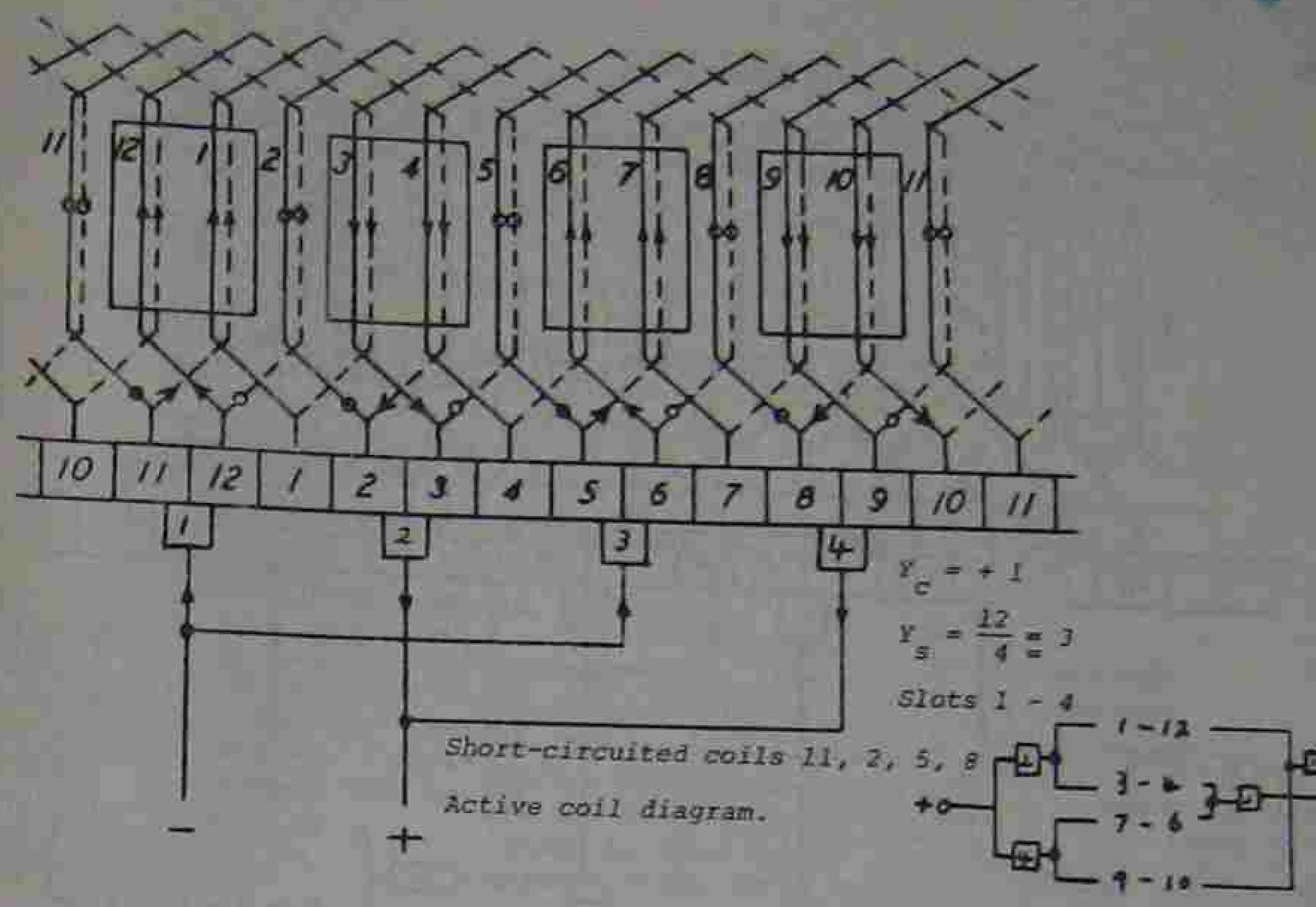
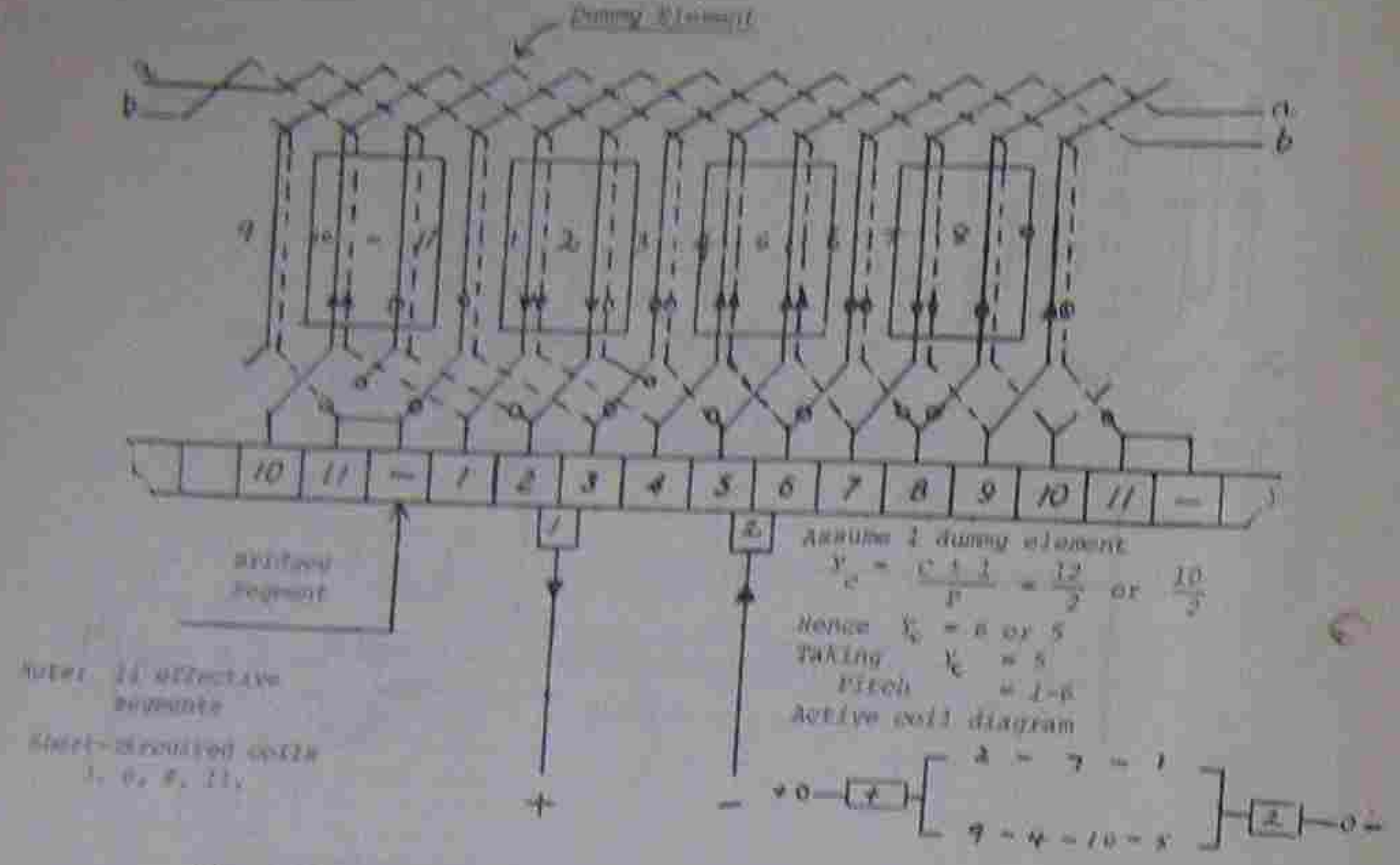


Figure 2.6 - Developed Winding Diagram, Four-pole Simplex Lap.

Figure 2.7 shows the same armature as was used in Figure 2.6 developed as a 4-pole wave winding. From the winding details shown in Figure 2.7 it will be observed that in order to develop this as a wave winding it has been necessary to reduce the number of active elements to eleven involving the removal of one element from the circuit and, as a consequence, the shorting together of two adjacent segments to reduce the effective segments to eleven as it is necessary that the number of segments and elements be equal. It may also be observed that the dummy element has still been retained in the winding where in practice it serves to assist in obtaining mechanical balance.

In a wave winding, as there are p coils in series between two adjacent commutator segments, one brush will simultaneously short-circuit 2p coil sides or, as shown in Figure 2.7, a coil side in each neutral zone. As a consequence, regardless of the number of poles, in wave wound machines only two brush sets are required.

Thus if the short-circuited coils for the particular instant shown are recorded and the active coil diagram drawn, it can be seen that the coils are formed into only two parallel groups compared to the four groups formed when the winding was lap wound.



Shifted Segment

Note: 11 effective segments

Short-circuited coils 3, 6, 8, 11.

Assume 1 dummy element

$Y_c = \frac{C \pm 1}{P} = \frac{12}{2}$ or $\frac{10}{2}$

Hence Y_c = 6 or 5

Taking Y_c = 5

Pitch = 1-6

Active coil diagram

$$+0-\boxed{1}\left[\begin{matrix} 2 - 7 - 1 \\ 9 - 4 - 10 - 5 \end{matrix}\right]\boxed{2}-0-$$

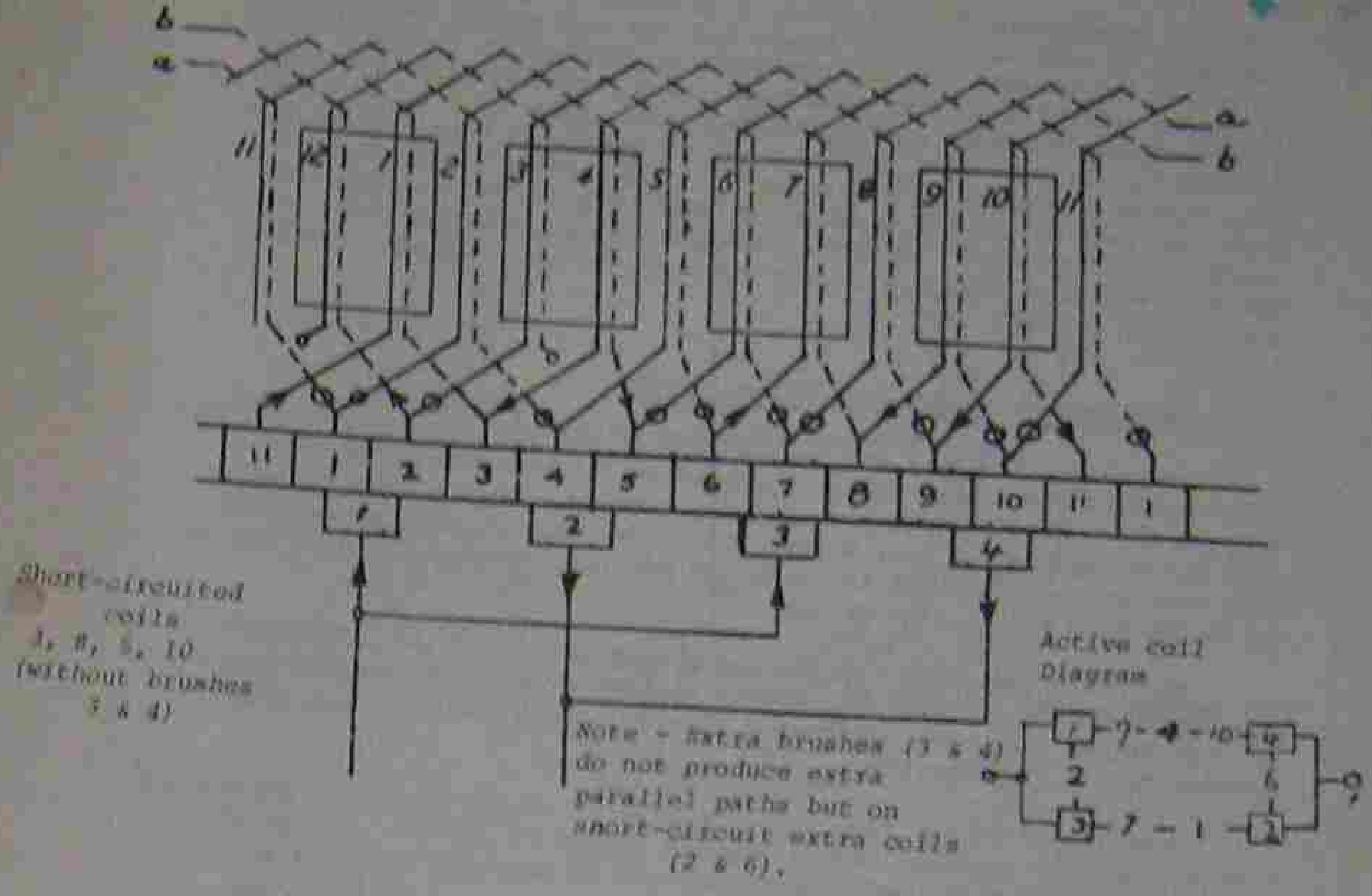
Figure 2.7 - Developed Winding Diagram, Four-pole Simplex Wave.

Alternatively, if the four brush sets were retained as illustrated by the developed winding shown in Figure 2.8 the result is not four parallel paths as may have been expected but the two path winding structure has been retained, the only significant difference being in the fact that one extra coil has been short-circuited.

The conclusion reached,therefore,is that in a simplex wave winding only two parallel paths are formed on the armature regardless of the number of poles or brush sets.

It should be emphasized that the armature used as an example would be most unlikely to be met with in practice but that the conclusions reached are valid regardless of the number of armature slots or the slot to segment ratio.

See Figure 2.8 on next page.



Short-circuited coils 3, 8, 5, 10 (without brushes 3 & 4)

Note - Extra brushes (3 & 4) do not produce extra parallel paths but on short-circuit extra coils (2 & 6).

Active coil Diagram

Figure 2.8 - Developed Winding Diagram, Four-pole Simplex Wave.

2.9 EQUALISER CONNECTIONS IN LAP WINDINGS

By examining the developed diagrams and their associated active coil diagrams for both lap and wave windings it will be observed that in wave windings the series connected coils contributing to the e.m.f. between the two brushes come under the influence of all poles and any lack of uniformity in the fluxes of the individual fields will have little effect on the magnitude of the e.m.f. produced in the separate parallel paths.

As a contrast, in lap windings, the series connected coils between two brushes come under the influence of only two adjacent fields. Consequently, where there is an inbalance or variation in the flux in the region of one pole the e.m.f. produced in two parallel connections will differ. In some instances, these unbalanced e.m.f.'s will cause circulating currents in the armature circuit which, in turn, can cause such disadvantageous effects as localized armature heating and faulty commutation. The flux inbalance that would such cause such unbalanced e.m.f.'s could be caused by electrical factors such as unequal field turns or shorted field turns which would reduce the m.m.f. produced by the fields or by mechanical factors such as varying grades of steel in the different poles or differing airgap widths both of which would vary the reluctance of the flux path and vary the flux for a given m.m.f.

Hence in large multipolar lap machines some means must be employed to ensure the minimization of these circulating e.m.f.'s.

In an armature winding there is no means available of rectifying the cause of unbalanced field fluxes and the only avenue available is to remedy the effect. This is achieved in practice by what are termed equalizer connections which join together all conductors in the same relative position under all poles of the same polarity. In this way any circulating currents will pass through the equalizer connection rather than through the windings or across the commutator. Figure 2.9 (a) shows the path of the circulating currents in a 4-pole uncompensated winding and Figure 2.9 (b) shows the addition of a compensating winding and the resultant variation in the paths of the circulating currents achieved by its addition.

2.10 PROBLEMS ASSOCIATED WITH S.C.R. DRIVES

As the availability and reliability of silicon controlled rectifiers have improved there has been an increase in the use of such devices to provide the d.c. power for use with d.c. motors. The increasing use of such S.C.R. drives for d.c. motors introduces certain design restraints that must be observed when the machines are specifically intended for use in conjunction with S.C.R. drives.

The basic design restraints are a consequence of the differences in the nature of the supply. The supply derived from S.C.R. sources having a lower ripple frequency and larger ripple voltage than the d.c. supply derived from d.c. generators.

This is due to the fact that the highest ripple frequency obtainable from a rectifier supplied from a 3-phase system is 300 Hz. On the other hand, a 4-pole generator with approximately 80 segments rotating at 1500 r.p.m. would have a ripple frequency of approximately $\frac{80 \times 1500}{60}$ or 2000 Hz with the consequent reduction in ripple voltage. It is the high ripple voltage in S.C.R. drives that cause the majority of problems such as winding overheating and sparking at the commutator. Although controlled rectifier drives using thyratrons and controlled mercury arc rectifiers have been in use for a number of years it is only the more recent availability of silicon controlled rectifiers that has made this type of drive more suitable for situations with an inherent vibration problem and led to the rapid increase of industrial applications.

Other important reasons for the use of S.C.R. drives are common with any controlled rectifier drives, namely the advantages of what is in effect voltage control of speed coupled with the ease of both transmitting and generating a.c. power.

Although the actual circuitry and control techniques employed with S.C.R. drives belong more properly to a course with an emphasis on industrial electronics some work will be done on these aspects of the course in later units. At this stage, however, mention will be made of the fact that the control of voltage comes not from varying the magnitude of the a.c. wave but from varying the conduction period as shown in Figure 2.11.

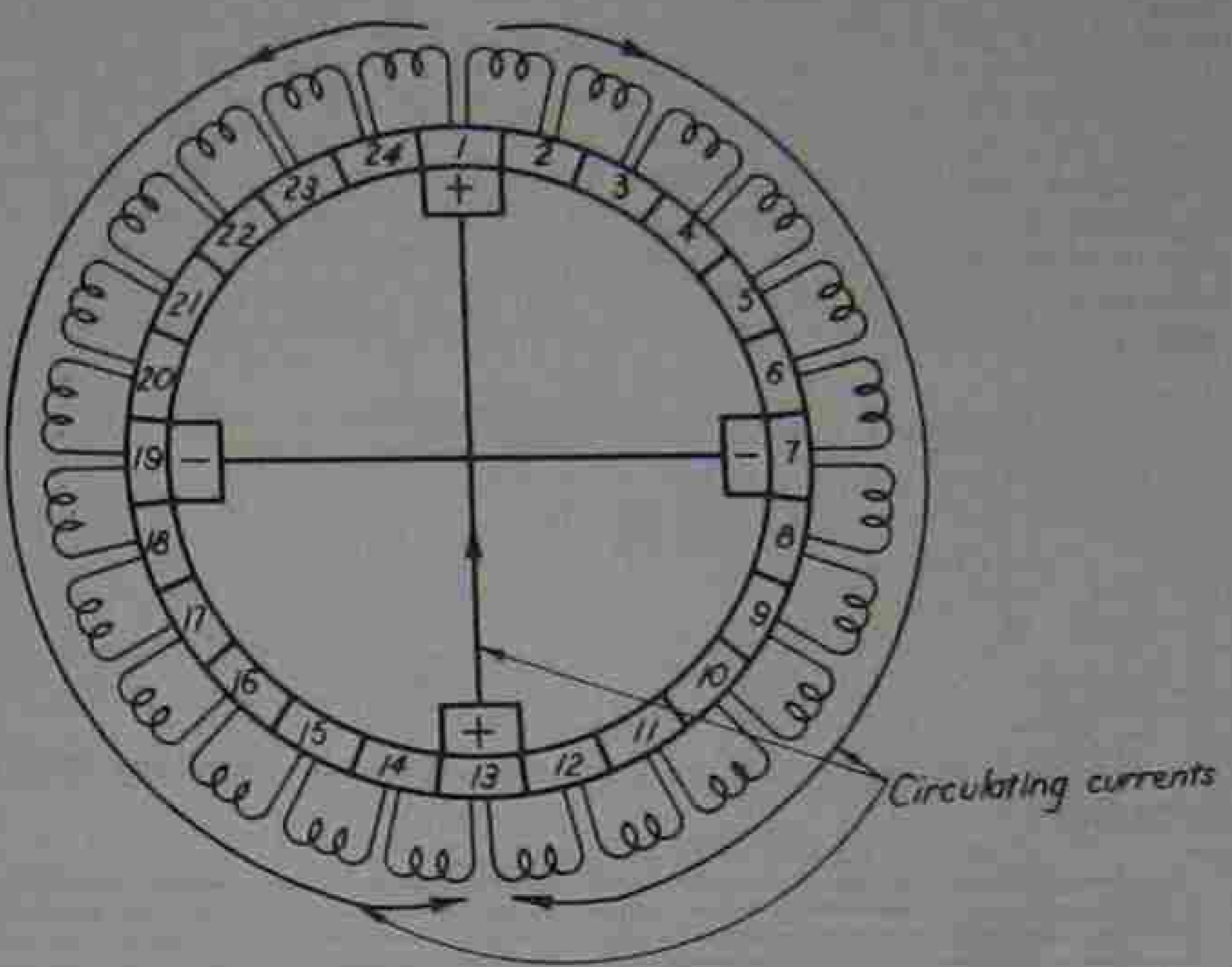


Figure 2.9 (a)

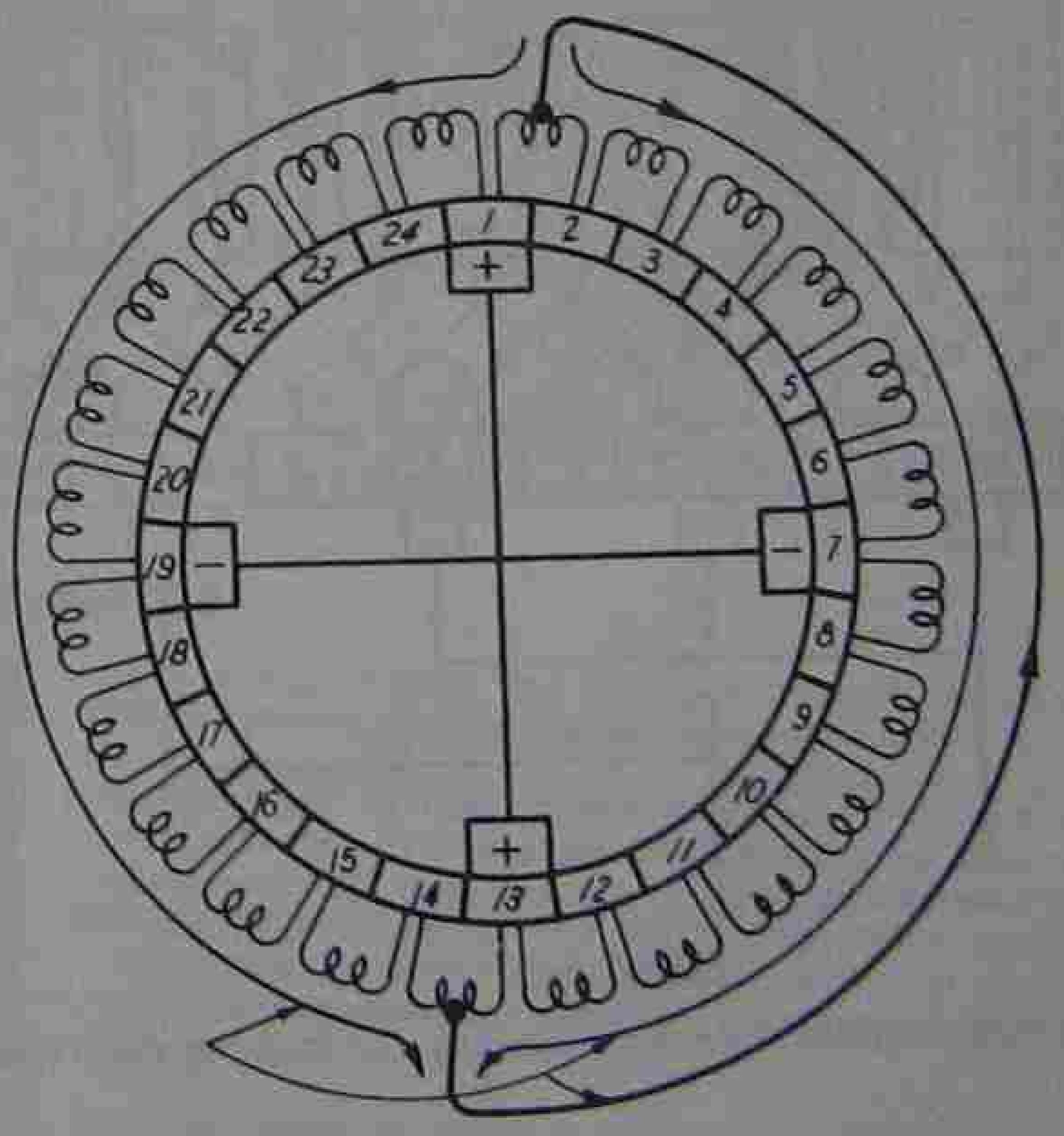


Figure 2.9 (b) - Circulating currents in equaliser connections.

The number of equalizer connections required on a given armature depends on the total number of coils and the number of poles. For example, in the winding represented by the developed diagram of Figure 2.6 there are four poles and twelve coils. At any one instant four coils are short-circuited, two coils by brushes of negative polarity which should be interconnected and two coils by brushes of positive polarity. These last two coils should also be interconnected. This leads to the statement that if an armature is to be fully equalized an armature must have sufficient equalizer connections to enable all coils with a separation of 2 pole pitches to be joined to a common connection. Referring to Figure 2.6 the total number of equalizer rings would be:

$$\text{Equalizer rings} = \frac{\text{coils (elements)}}{P/2} \qquad - \quad 2.4$$

$$= \frac{12}{2}$$

$$= 6$$

Figure 2.10 shows Figure 2.6 modified by the addition of 6 equalizer connections.

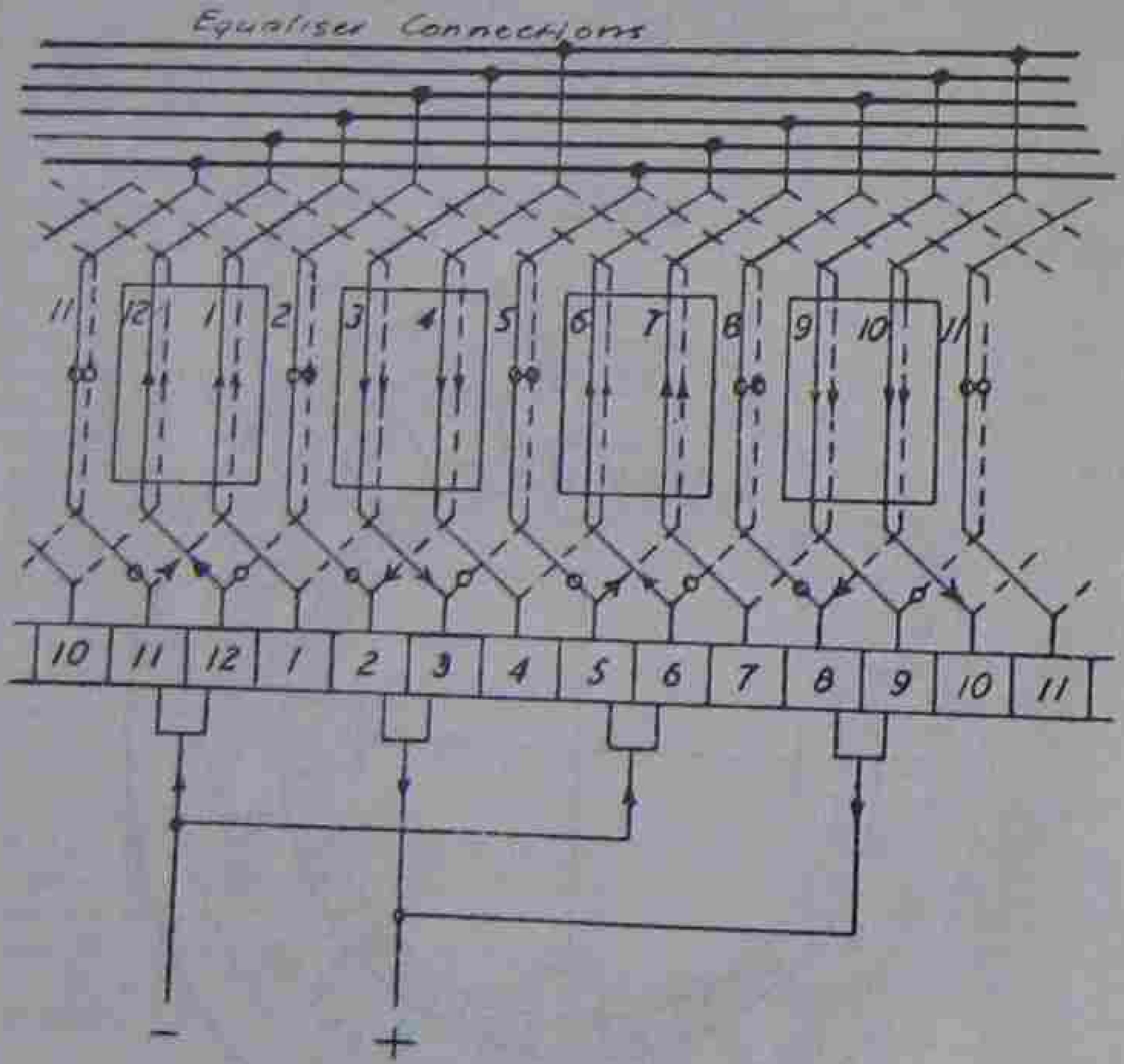


Figure 2.10

Developed Winding Diagram, Four-pole Simplex Lap Showing Equalizer Connections.

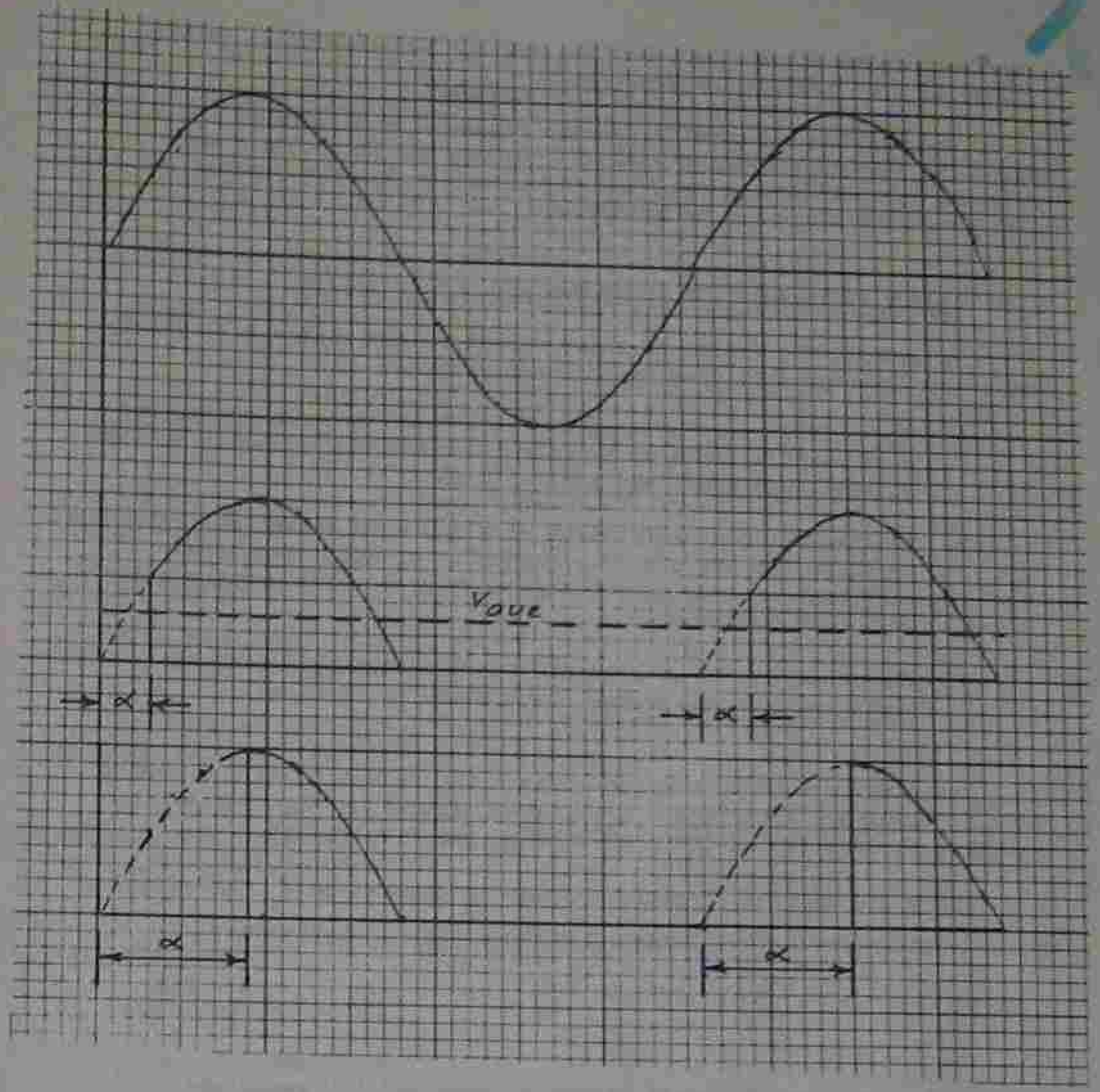


Figure 2.11 - Wave forms for S.C.R. Drives.

As a result of this gating action the sharply rising wave front leads to high induced e.m.f.'s and the associated transients produce a significant proportion of the problems associated with S.C.R. drives.

2.11 VOLTAGE SELECTION

The choice of a voltage rating for machines intended for S.C.R. drives is a compromise between the following considerations.

Firstly, from the point of view of the designer of the S.C.R. drive the preference is for voltages of the order of 500 volts as this voltage does not require an excessively high reverse voltage characteristic of the S.C.R. and this higher voltage reduces the current for a given power requirement and reduces the necessity for parallel operation of S.C.R.'s with the attendent problems associated with the simultaneous firing of 2 parallel connected devices.

Secondly, from the point of view of the motor designer the lower the voltage the less turns on the armature and the lower the inductance. As the coil inductance is an important factor to be considered when improving commutation, the lower the voltage the lower will be the probability of commutation problems.

The tendency is towards the use of ~~240~~ 400V V as a standard for S.C.R. drives as this is already a standard voltage and as a result many existing machines can be used in conjunction with S.C.R. drives provided the other conditions can be satisfied.

2.12 DESIGN RESTRAINTS FOR ARMATURES FOR S.C.R. DRIVES

In general the design of a d.c. armature and windings is mainly concerned with the following basic considerations:

1. The provision of an adequate number of turns in series for each parallel path to provide the necessary terminal voltage at the rated speed and available flux.
2. The provision of sufficient slot space to accept the conductors to allow for the use of a conductor of sufficient cross sectional area to give a satisfactory current density under full load conditions.
3. The selection of an armature tooth of sufficient cross sectional area to prevent saturation of the iron.

Other factors to be considered were the selection of a suitable value of turns per element and a suitable segment to slot ratio but the three factors listed above were of primary importance.

Where the machine terminal voltage is denoted by V_t the equation of the armature circuit voltage conditions can be written as:

$$V_t - L\frac{di}{dt} - iR = E_g \qquad - \qquad 2.5$$

In d.c. drives the small ripple voltage and the resultant variations in armature current are negligible and as a consequence the $\frac{di}{dt}$ term for normal drives can be neglected. In S.C.R. drives this term must be considered and one of the design restraints is to reduce the coil inductance by reducing the number of turns to a minimum since it will be recalled from earlier work on inductance the inductance of a circuit is proportional to the number of turns squared.

2.13 SPECIAL CHARACTERISTICS OF WINDINGS OF ARMATURES USED FOR S.C.R. DRIVES

The design of armature windings for machines specifically intended for S.C.R. drives must therefore consider the presence of the $L\frac{di}{dt}$ term of equation 2.5.

This term must be considered under two distinct sets of condition.

Firstly, under normal conditions when the $\frac{di}{dt}$ factor is due to current variations emanating from the source, that is, when the conductor is developing torque.

Secondly, under short circuit conditions when the coil is undergoing commutation during which time the $\frac{di}{dt}$ term is due to the reversal of current in the coil. In this instance the $\frac{di}{dt}$ term is a function of the coil parameters and is given by the expression:

$$\frac{di}{dt} = 2\frac{E}{L}\,\varepsilon^{-\frac{R}{L}t} \qquad - \qquad 2.6$$

where R and L are coil parameters

and E is the magnitude of the coil voltage before commutation.

Commutation will be covered more fully in the next unit but for this discussion it is sufficient to say that for good commutation the time constant of the coil circuit $(\frac{L}{R})$ must be approximately one fifth of the commutation period.

Therefore it is of primary importance that the coil inductance be reduced to a minimum by:

1. Reducing the number of turns per coil to a minimum, ideally one turn per coil.
2. Forming the slots in such a way that the coils are not deep in the iron but close to the surface, in this way increasing the leakage flux and reducing the coil inductance.

The limitations on these design techniques are that in the first case the number of conductors is fixed for a given flux and speed and if the turns per coil are reduced to too low a value this increases the number of segments necessary on the commutator with the consequent increase in the size and cost of the commutator.

In the second case, if the slots are too wide and shallow the tooth cross section is too small for mechanical strength and will have an increased tendency to saturate.

Both of these problems can be overcome by building the machine on a larger frame but this again will add to the expense of the machine.

REVIEW QUESTIONS

1) Suggest the main reasons for:

   a) multiple conductors on armatures;

   b) multiple elements in coils.

2) What is the most important factor that finally determines whether a particular winding is lap or wave?

3) What is the difference between progressive and retrogressive windings in:

   a) lap windings.

   b) wave windings?

4) Why are "dummy" elements sometimes necessary in wave windings? What is a "dummy" element?

5) How can the difference between a lap and a wave wound armature be determined by observation?

6) Explain the formation of parallel paths on:

   a) lap wound machines;

   b) wave wound machines.

7) What is the reason for using equalizer connections in lap wound armatures? Why are these connections not necessary on wave wound machines?

8) Explain how equalizer connections are fitted to lap wound machines.

9) What is meant by an S.C.R. drive and how is the voltage controlled?

10) What are the basic design considerations for d.c. armature windings and what extra design restraints are necessary for machines intended for use with S.C.R. drives?

ASSIGNMENTS

Marks

12 — 1) The average e.m.f. per conductor in a d.c. generator at rated speed is 0.5 volts and the generator is rated at 240 volts. Assuming the conductors to be grouped in 4 parallel groups, calculate the effective conductors required on the armature.

(Note: The reason for parallel grouping will be covered in Unit 3.)

$240 = (480)/$Gro

$Z_T = 480 \times 4$

$= 1920$ Cond

20 — 2) An armature winding is made up of 324 conductors arranged in 27 coils, 3 elements per coil. If the machine for which the armature is intended has a 4 pole field system, calculate:

   a) turns per coil; — $324 \div (2)(27)(3) = \frac{324}{54} = 6$ Tur
   b) turns per element; — $6 \div 3 = 2$ Turns
   c) number of slots; — 27
   d) coil pitch; — $Y_s = \frac{27}{4} = \cancel{6\frac{3}{4}}$ | $= \frac{27}{4} - \frac{3}{4} = 6$ | $= \frac{27}{4} + \frac{1}{4} = 7$
   e) pole pitch. — $P_P = \frac{27}{4} = 6\frac{3}{4}$ Slots

24 — 3) For the following 4 pole lap armatures calculate the coil span, commutator pitch and number of elements per coil.

   a) S = 29; C = 58.
   b) S = 32; C = 96.
   c) S = 47; C = 47.

24 — 4) For the following wave wound machines calculate the commutator pitch.

   a) P = 4; C = 39.
   b) P = 6; C = 68.
   c) P = 6; C = 61.

20 — 5) A 6-pole wave wound armature has 37 slots and each coil is made up of 3 elements. Calculate:

   a) the number of coils on the armature;
   b) the commutator pitch;
   c) the number of commutator segments.

In addition, draw a sketch of the commutator showing the start and finishing segments of three coils in series.

ELECTRICAL MACHINES I

Wk 3

UNIT No. 3

DIRECT CURRENT MACHINES

SUMMARY OF CONTENTS

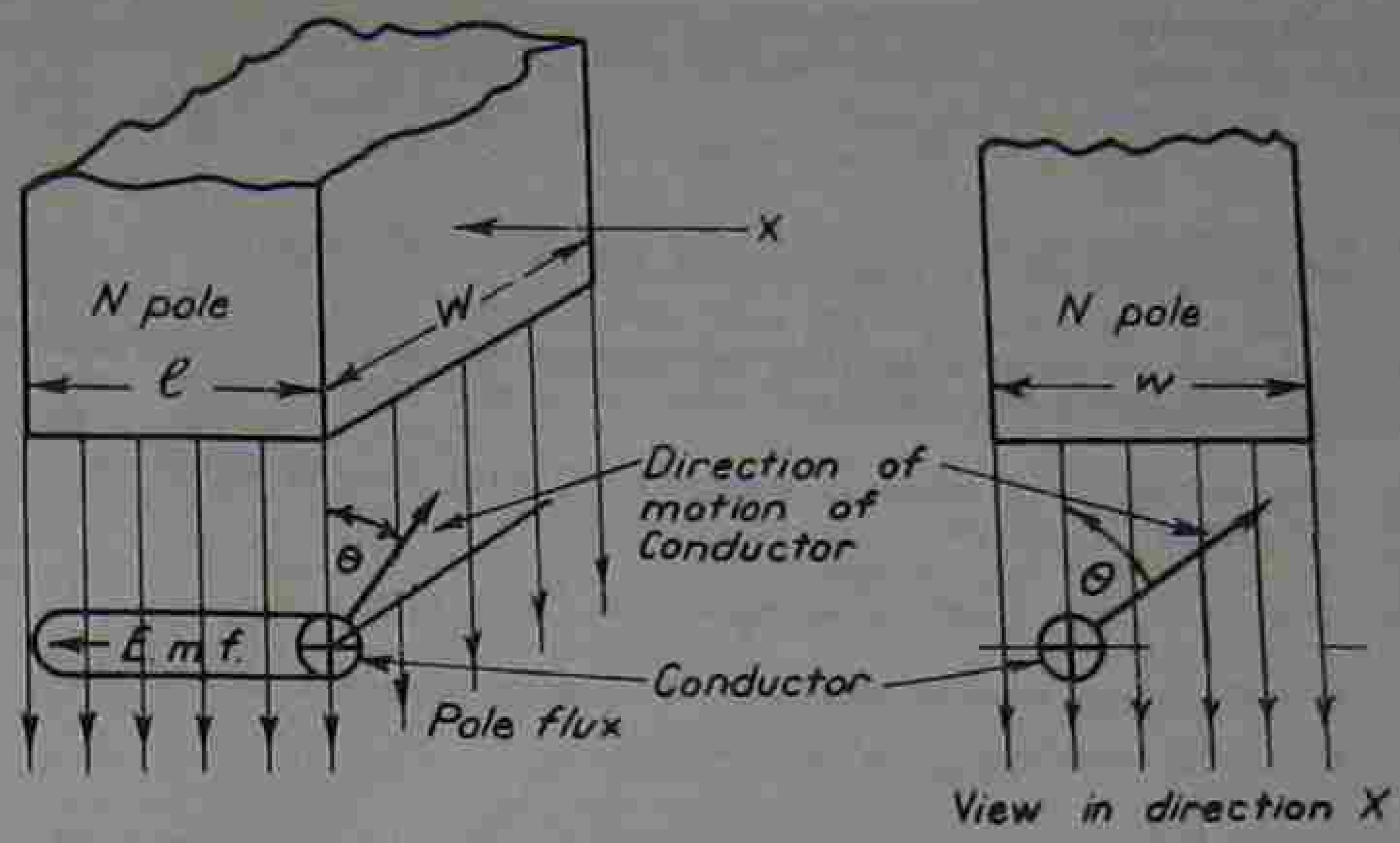
This unit will cover the following topics:

3.1 GENERATOR ACTION

Generator action is due to the fact stated in Unit 1 that when a conductor moves across a magnetic field an e.m.f. is induced in it. The value of which depends on:

1. The rate of movement across the magnetic field.
2. The total flux in the area swept by the conductor.
3. The sine of the angle between the direction of the magnetic field and the armature conductor motion.

The relationships outlined above are illustrated in the diagrams shown in Figure 3.1.



l = effective conductor length.

W x l = total flux area per pole swept by conductor.

θ = angle conductor makes the direction of main pole magnetic field.

Figure 3.1 - E.m.f. Induced in a Conductor passing through a Magnetic Field.

As, in d.c. machines, the conductor can be considered as always moving at right angles to the field, the sin θ term can be neglected.

Under these circumstances the relationship between the flux and the rate of cutting is such that the magnitude of the induced e.m.f. is numerically equal to the rate of cutting in webers per second.

Where one conductor cutting or intersecting one weber is termed a linkage, the general expression for induced e.m.f. is:

$$e = \frac{d\psi}{dt} \qquad - \qquad 3.1$$

where ψ is the symbol for linkages.

For one conductor induced e.m.f. per conductor

$$e = \frac{d\phi}{dt} \qquad - \qquad 3.2$$

where ϕ = magnetic field in webers

t = time (seconds).

For this expression there is no restraint as to whether the field moves relative to the conductor or the conductor moves relative to the field and equation 3.2 is equally applicable to generators or transformers.

Where the conductor is rotating at constant angular velocity as is the case in the steady state conditions in d.c. machines a more convenient form of the generated e.m.f. expression is that given in Unit 1, namely:

$$e = B\,l\,v$$

The derivation of this expression from equation 3.2 and Figure 3.1 presents no problems if it is appreciated that, for the conditions shown:

$$\frac{d\phi}{dt} = B\frac{dA}{dt} = Bl\frac{dW}{dt}$$

and $\frac{dW}{dt}$ can be written as v for constant velocity conditions.

To determine an expression that can be used for practical machines the following assumptions are made:

1. The conductor operates at constant velocity in a circular path of radius "r" metres.
2. The rotational speed is expressed as "N" r.p.m.
3. The effective area of each pole is $\frac{2\pi r l}{P}$ square metres and the total flux per pole is ϕ webers.

In terms of assumptions 1, 2 and 3 and for one conductor, the basic e.m.f. expression, equation 1, may be written as:

$$e = B l v$$

$$= \frac{\phi P}{2\pi r l} \times l \times \frac{2\pi N r}{60}$$

$$\text{or} \quad e = \frac{\phi P N}{60} \text{ volts} \qquad - \quad 3.3$$

Where the armature is wound with "Z" conductors arranged in "a" parallel paths the average e.m.f. produced by the armature is:

$$E = \frac{\phi P N}{60} \quad \frac{Z}{a} \qquad - \quad 3.4$$

This is the e.m.f. generated by an armature and can be denoted by the symbol E_g. If the machine terminal voltage is denoted by the symbol V_t the relationship between E_g and V_t can be written as:

$$E_g - (I_a R_a) = V_t \qquad - \quad 3.5$$

where $(I_a R_a)$ is the voltage drop in the armature circuit resistance.

Equation 3.5 can serve as a criterion for determining the direction of energy flow and whether the machine behaves as a motor or as a generator.

If $E_g > V_t$ the machine passes power to the external system and behaves as a generator.

If $E_g < V_t$ the machine absorbs electrical energy from the supply and behaves as a motor.

Where E_g is equal to V_t there is no power flow for under these conditions the current is zero. This condition is termed "floating".

The implications of these last three conditions are summed up in Lenz's Law which states that the direction of an induced e.m.f. is always such that it tends to set up a current opposing the motion or the change responsible for inducing that e.m.f.

Fleming's Right Hand Rule is one way in which the above law can be applied for generators. If the first finger of the right hand be pointed in the direction of the magnetic flux and the thumb in the direction of motion of the conductor relative to the magnetic field, then the middle finger held at right angles to both the thumb and first finger represents the direction of e.m.f.

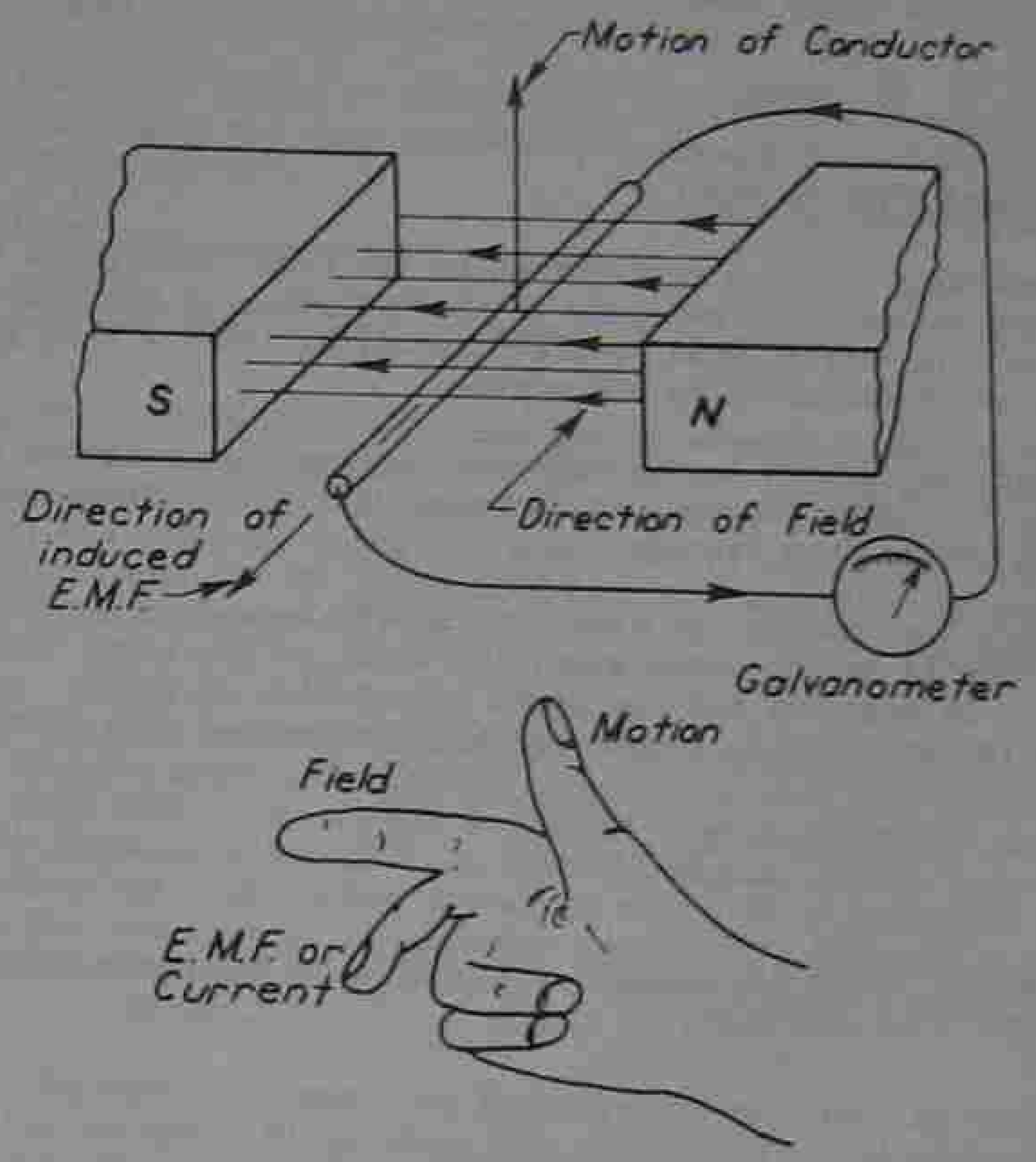


Figure 3.2

Fleming's Right Hand Rule for Generators

Figure 1.1 (a) and (b) showed all the possible combinations of direction of armature current, main field flux and rotation for a generator. Figure 1.2 (e) showed that the armature current was an alternating current which the commutator rectified to d.c. (see Figure 3.2). The direct current thus produced is, in fact, due to the sum of the e.m.f. induced in each conductor in one of the parallel paths on the armature.

Example 3.1

A six pole wave wound d.c. generator has 410 active conductors. If the generator is driven at 750 r.p.m. calculate the open circuit volts if the useful flux per pole is 0.03 Wb.

$Z = 410$ $\qquad\qquad \Phi = 0.03$ Wb

$P = 6$ $\qquad\qquad$ Speed $N = 750$ r.p.m.

$a = 2$

Solution

From equation 3.4

$$E = \frac{\Phi Z N}{60} \times \frac{P}{a} = \frac{.03 \times 410 \times 750}{60} \times \frac{6}{2}$$

$$= 461 \text{ volts.}$$

3.2 THE COMMUTATION PROBLEM

In Section 3.1 it was stated that in the time taken for a coil to pass from the influence of one pole to the influence of the next pole the armature coil current must reverse direction. During this process the coil is short-circuited by the brushes.

Whether the current in the coil can reverse and reach the correct value in the time that the coil is short-circuited will depend on the relationship between two factors.

Firstly, the commutation time. This will depend on the total number of segments on the commutator, the width of the brush in terms of the number of segments and the speed of rotation in r.p.m. Denoting the span of the brush by C_b (segments) the commutation time is then

$$t_c = \frac{60\, C_b}{N\, C} \text{ seconds} \qquad - \qquad 3.6$$

where C is the number of segments on the commutator
and N is the speed in r.p.m.

Example 3.2

A 240 segment commutator rotates at 1500 r.p.m. If a brush spans 3 segments, calculate the commutation time.

Solution

Using equation 3.6

$$t_c = \frac{60 \times 3}{1500 \times 240}$$

$$= \frac{1}{2000}$$

$$= 5 \times 10^{-4} \text{ seconds}$$

Secondly, the time constant of the armature circuit. This is given by the expression:

$$\tau = \frac{L}{R} \text{ seconds} \qquad - \qquad 3.7$$

Where L is the inductance of the armature coil.

and R includes the resistance of the coil and brush material and the brush contact resistance.

For ideal commutation the relationship between τ and t_c is such that

$$t_c \geqslant 5\,\tau \qquad - \qquad 3.8$$

In practice, particularly in higher speed machines this relationship is not readily realized. Consequently, some means must be found either to reduce L or alternatively to increase R.

The practical limits of reducing L by reducing the number of turns and increasing the flux leakage have already been covered. Methods used to increase R are:

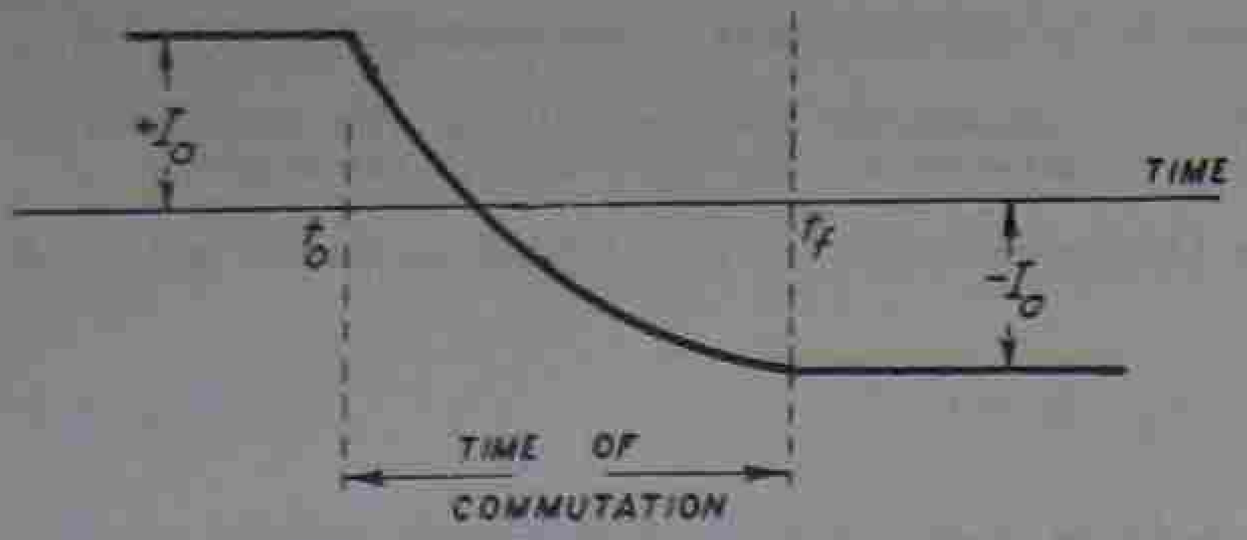
1. high resistance armature leads;
2. high resistance brush material.

One problem associated with too low an armature inductance is that, as a means of reducing the ripple in the current in the armature circuit, an inductive component in the armature circuit is desirable. As such a component in the armature coils has been seen to be undesirable the necessary inductance can be introduced into the armature circuit either by a series line inductance or by a transformer with a high leakage reactance.

Whatever steps are taken to reduce the inductance there will inevitably be some inductance in the armature circuit and this inductance will lead to a voltage component that opposes the change of current. To compensate for this an opposing e.m.f. can be injected into the coil undergoing commutation either by means of an auxiliary pole or by shifting the position of the brushes so that the commutated coil comes in the fringing flux and then the e.m.f. so induced will assist in the reversal of the current.

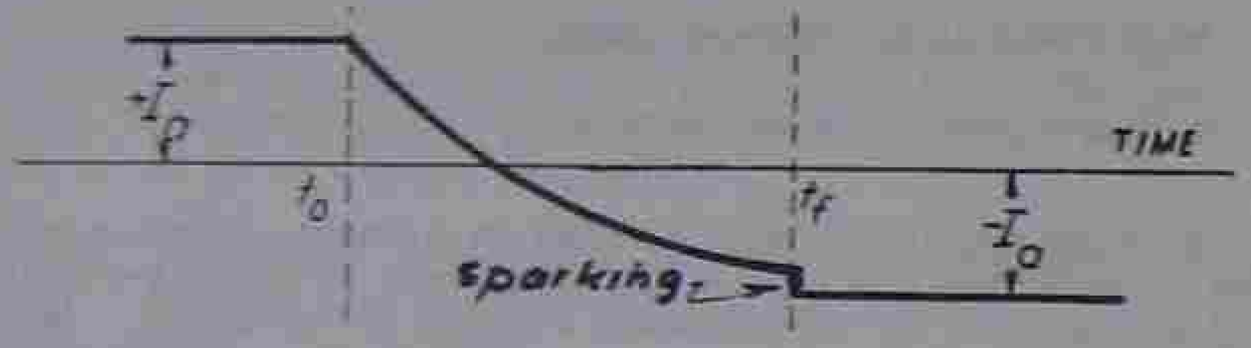
Where the current transition is correctly achieved as shown in Figure 3.3 (a) no sparking occurs. For other conditions either under - or over - commutation, there will be sparking at the commutator that can be harmful to the brushes and the commutator.

See Figure 3.3 on next page.



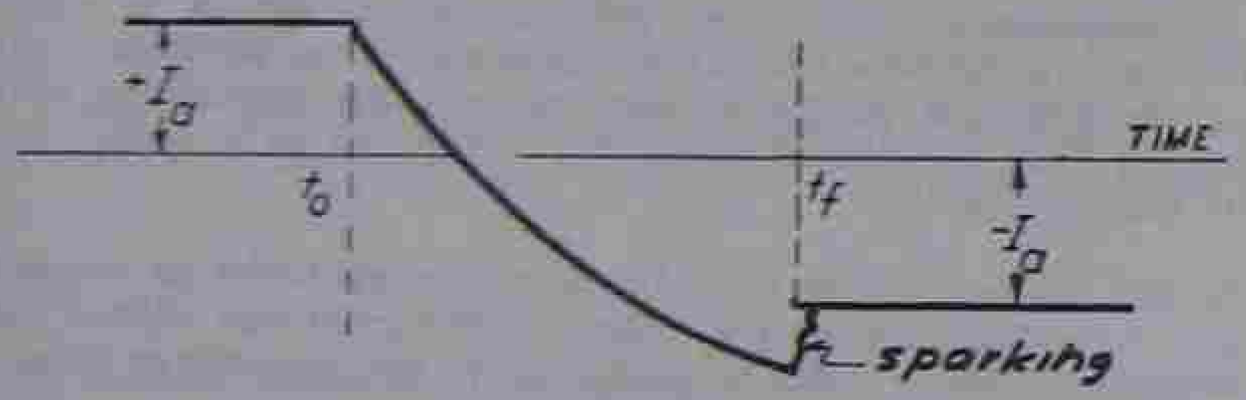
(a) IDEAL COMMUTATION

The current reverses without causing any visible sparking at the brushes or burning of the commutator.



(b) UNDER COMMUTATION

Where the process of commutation is not completed before the coil leaves the brush.



(c) OVER COMMUTATION

Where the current in the coil reverses too rapidly.

Figure 3.3

Current vs Time for Three Possible Types of Commutation

3.3 MAGNETIZATION CURVE

In Section 3.1, it was shown that the generated e.m.f. of a machine could be calculated from the expression,

$$E_g = \frac{P \phi Z N}{60 a} \text{ volts} \qquad - \qquad 3.4$$

For a particular machine where the number of poles, the number of active conductors and the parallel paths on the armature can be considered as being constant these may be denoted by a symbol K_o; that is,

$$K_o = \frac{P Z}{60 a} \qquad - \qquad 3.9$$

and in terms of this constant, equation 4 can be written as:

$$E_g = K_o \phi N \text{ volts} \qquad - \qquad 3.10$$

Equation 3.10 can now be used as a means of determining the manner in which the generated e.m.f. will vary for changes in flux and speed.

From equation 3.10 it can be observed that the magnitude of the generated e.m.f. is directly proportional to the field flux. The practical problem is to link this relationship to some readily measurable parameter in order that the generated e.m.f. under a certain set of conditions can be more readily predicted. The means chosen to provide this link is the magnetization curve which gives a graphical representation of the relationship:

$$E_g = \left[f(I_f) \right]_{\text{constant "N"}} \qquad - \qquad 3.11$$

When the main fields are excited the m.m.f. obtained produces a flux in the magnetic circuit, the strength depending mainly upon the combined reluctance of the various sections. However, due to the presence of different materials in the flux path, the relationship is neither linear nor easily calculable. It is these facts that make the graphical presentation essential. The reason for the problems associated with the calculation of the flux can be seen from the following discussion.

Each main pole magnetic circuit consists of two magnetic circuits in parallel (Figure 3.4 (a)}. It is the movement of the armature conductors through the air gap flux that causes an e.m.f. to be induced in the conductors.

The m.m.f. produced by the field must be equal to the sum of the m.m.f's required to produce the appropriate flux in the various sections of the magnetic circuit. Thus:

$$I_f N_f = (I N)_y + (I N)_p + (I N)_y + (I N)_t + (I N)_c \qquad - \qquad 3.12$$

I_f = field circuit.

N_f = total turns per pole.

$(I N)_y$ = ampere turns required for yoke section.

$(I N)_p$ = ampere turns required for pole section.

$(I N)_g$ = ampere turns required for gap section.

$(I N)_t$ = ampere turns required for teeth section.

$(I N)_c$ = ampere turns required for core section.

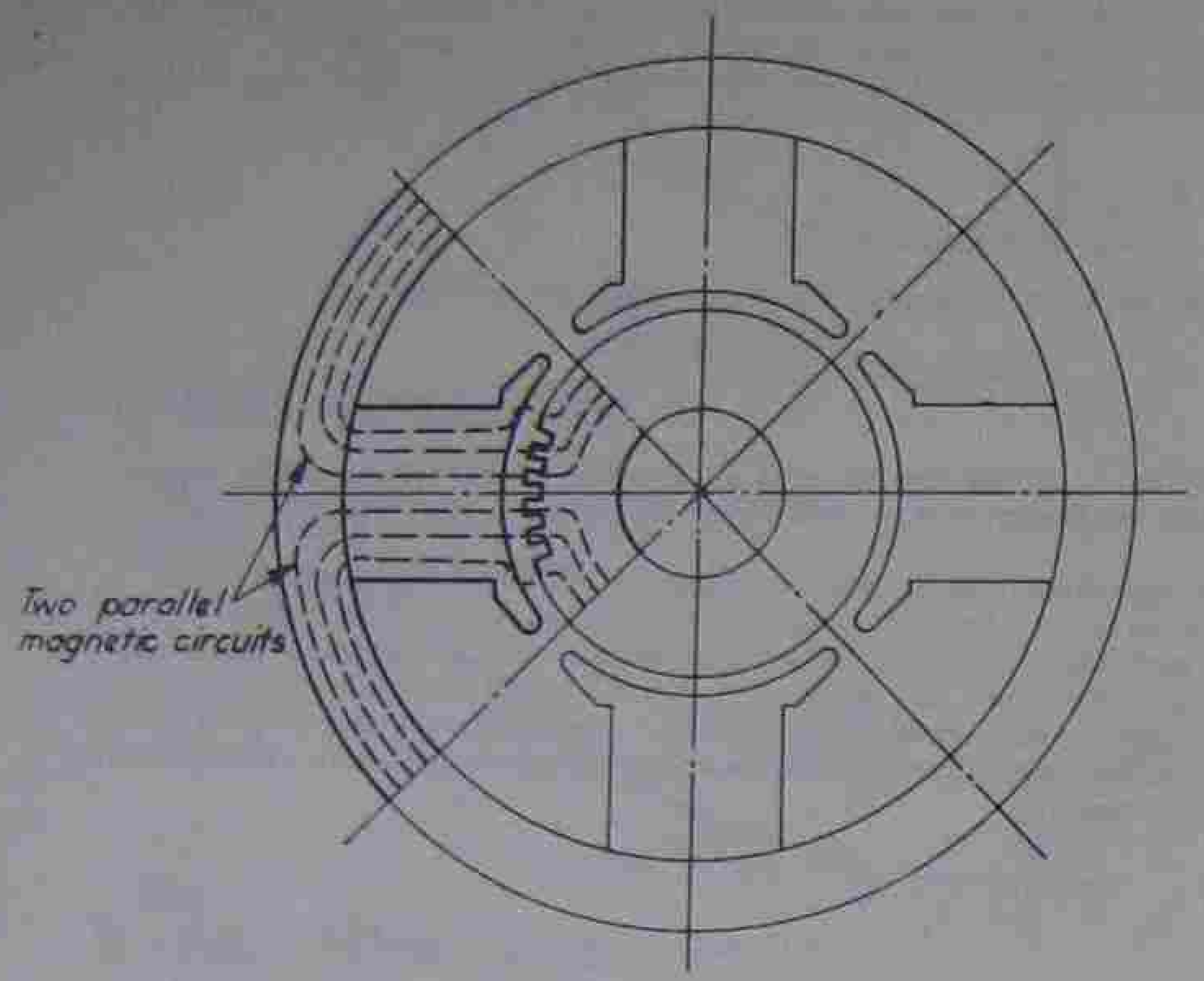


Figure 3.4 (a) - Typical magnetic circuit (4-pole machine).

Ignoring any stray flux the ampere turns necessary to produce the required flux for a given iron section are determined by obtaining the flux density ($\frac{\text{Flux}}{\text{Area of Section}}$) and using a curve giving the ampere turns per metre, flux density relationship for that material. This gives the magnetizing force in ampere turns per metre. Multiplying this by the length of the flux path in metres gives the required number of ampere turns.

In the case of the air gap:

for air $\frac{B_g}{H} = \mu_o$

$$\therefore \quad H = \frac{B_g}{\mu_o}$$

$$= \frac{B_g}{4\,\pi \times 10^{-7}} \text{ ampere turns per metre} \qquad - \qquad 3.13$$

$$(I\,N)_g = H \times l_g$$

$$= \frac{B_g\,l_g}{4\,\pi \times 10^{-7}} \qquad - \qquad 3.14$$

B = flux density (webers per metre ^{2}).

l_g = effective length of air gap, metres.

H = magnetizing force ampere turns per metre.

μ_o = permeability of free space.

Equation 3.14 can be simplified if the constant terms are denoted by K_g where

$$K_g = \frac{l_g}{4\,\pi \times 10^{-7}} \qquad - \qquad 3.15$$

Equation 3.14 then becomes:

$$(I\,N)_g = K_g B_g \qquad - \qquad 3.16$$

By making the above calculations for various values of flux it is possible to obtain a flux per pole versus ampere turns per pole curve, and if the value of K_o and the speed are known it is possible to calculate the e.m.f. This gives a curve of e.m.f. versus ampere turns per pole.

Examination of the flux per pole versus ampere turns per pole curve shows that the curve for all intent and purposes is coincident with the air gap line until saturation commences in various sections of the magnetic circuit, generally the armature teeth section. This shows that for low flux levels the major portion of the field m.m.f. is used in overcoming the reluctance of the air gap. The curve tends to level out as saturation increases. A typical breakdown of ampere turns for a modern machine would be 60% air gap, 30% teeth and 10% for other sections of the iron circuit.

Figure 3.4 (a) and (b) shows a typical magnetization curve and the magnetic circuit. It will be noted the machine has an output of E_r with the field unexcited. This is due to residual magnetism in the circuit. A more useful form of the curve simply shows the relationship between e.m.f. and the field current.

If the magnetization curve is taken with ascending value of field current and, when the maximum open circuit volts are reached decreasing the values of field current, the curves in Figure 3.5 are obtained. The reason for the difference in the curves is due to the hysteresis property of the iron.

See Figure 3.4 (b) on next page.

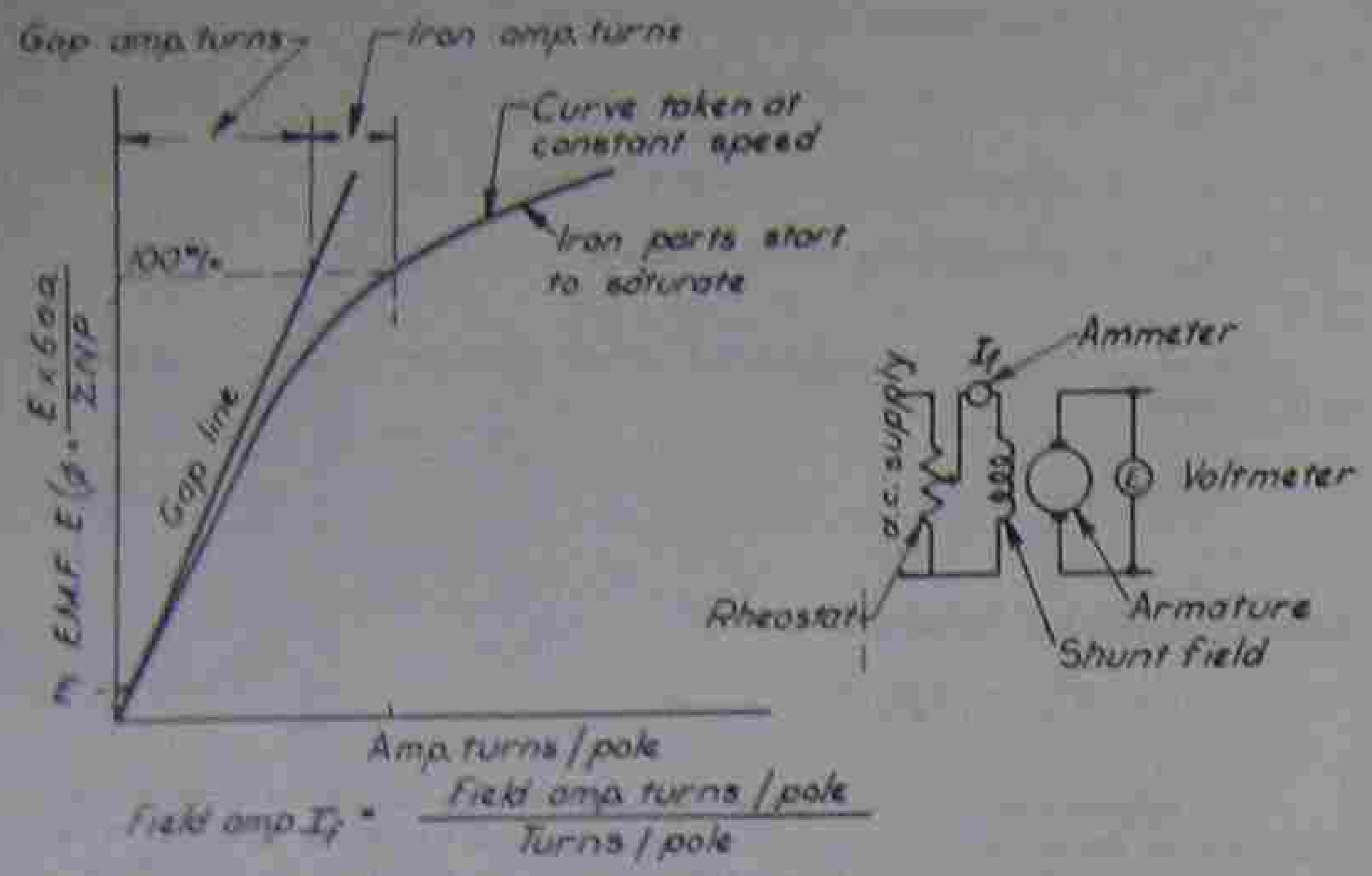


Figure 3.4 (b) - Typical Magnetization Curve.

As stated above, the circuit of Figure 3.4 (b) will give a different curve for both ascending and descending values of I_f. For this course it will be assumed that where a set of values is given they represent the mean of the two values.

See Figure 3.5 on next page.

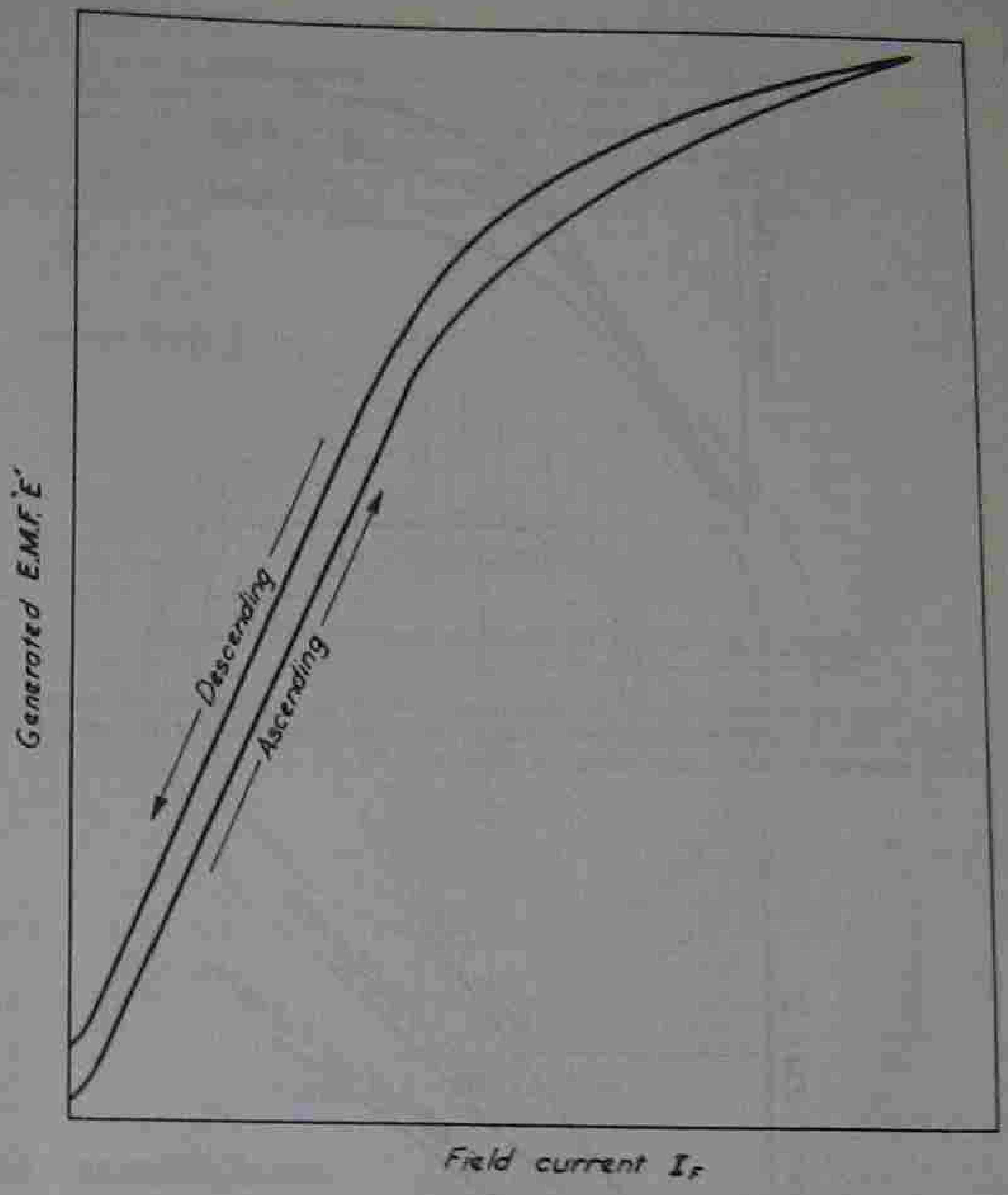


Figure 3.5 - Magnetization Curve Showing Hysteresis Effect.

3.4 EFFECT OF SPEED UPON VOLTAGE

If the field current is kept constant the flux will be constant and equation 3.10 can be written as:

$$E_g = K_2 N \qquad - \qquad 3.17$$

$$\text{where } K_2 = K_o \phi \qquad - \qquad 3.18$$

Thus for a given field current the generated e.m.f. is directly proportional to the speed leading to the family of curves shown in Figure 3.6.

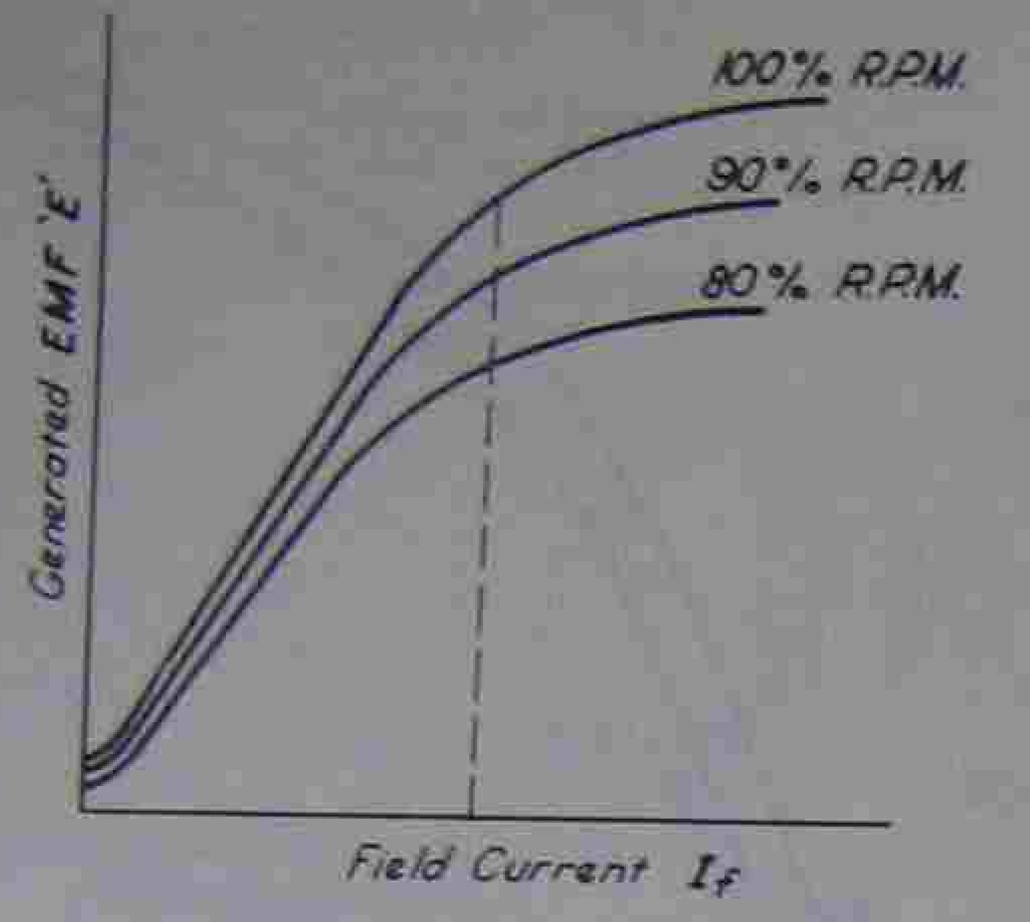


Figure 3.6 - Effect of Speed on Magnetization Curves.

From equation 3.10 it is also possible to plot a family of curves showing the relationship between e.m.f. and speed for different values of field current. These are shown in Figure 3.6.

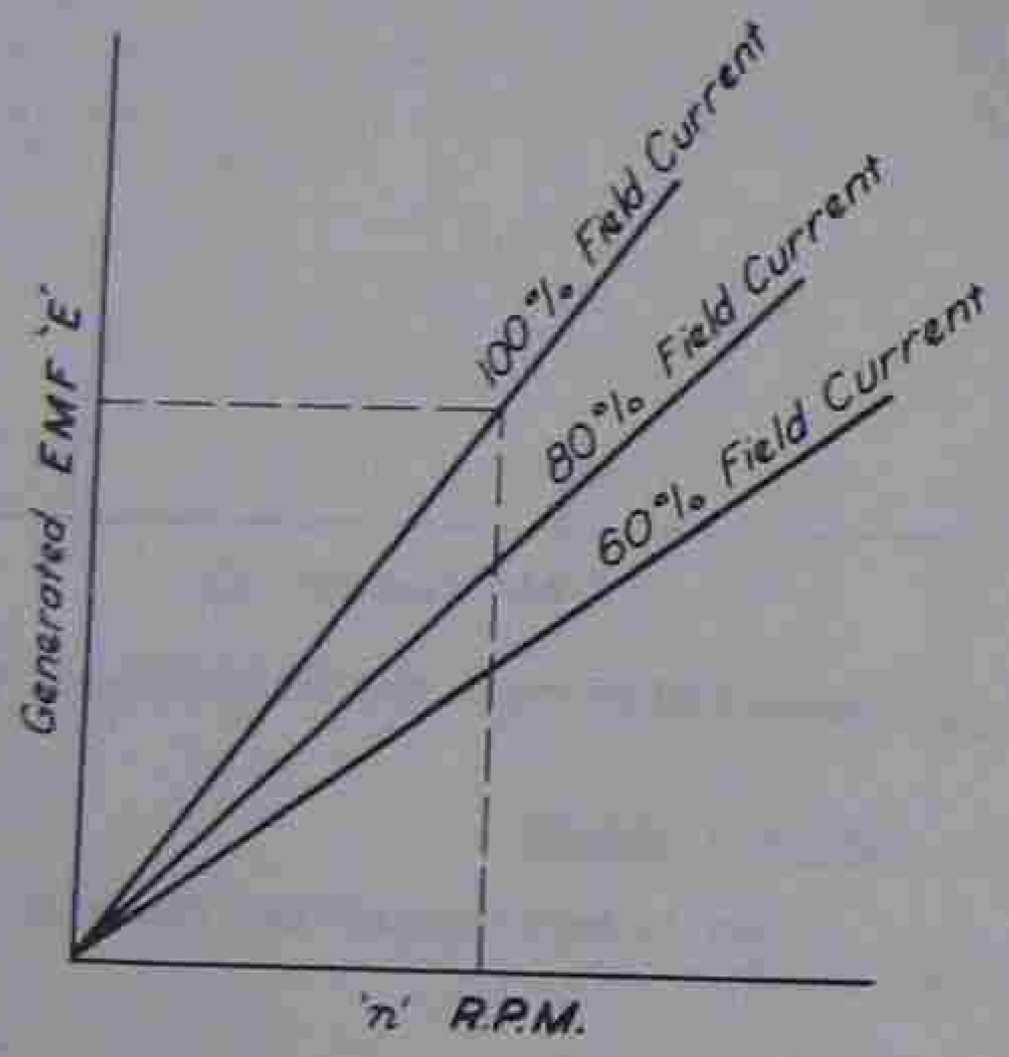


Figure 3.7 - Open Circuit Volts against r.p.m. for Varying Values of Field Current.

3.5 LEAKAGE FLUX

As with any magnetic device, all the magnetic flux produced by the main field does not keep within the iron circuit; a certain amount equal to between 10% and 20% of the useful flux by-passes the air gap and armature portion of the magnetic circuit, circulating only through the main pole and yoke portions of the magnetic circuit. This flux is called leakage flux ϕ_L and is shown diagrammatically in Figure 3.8.

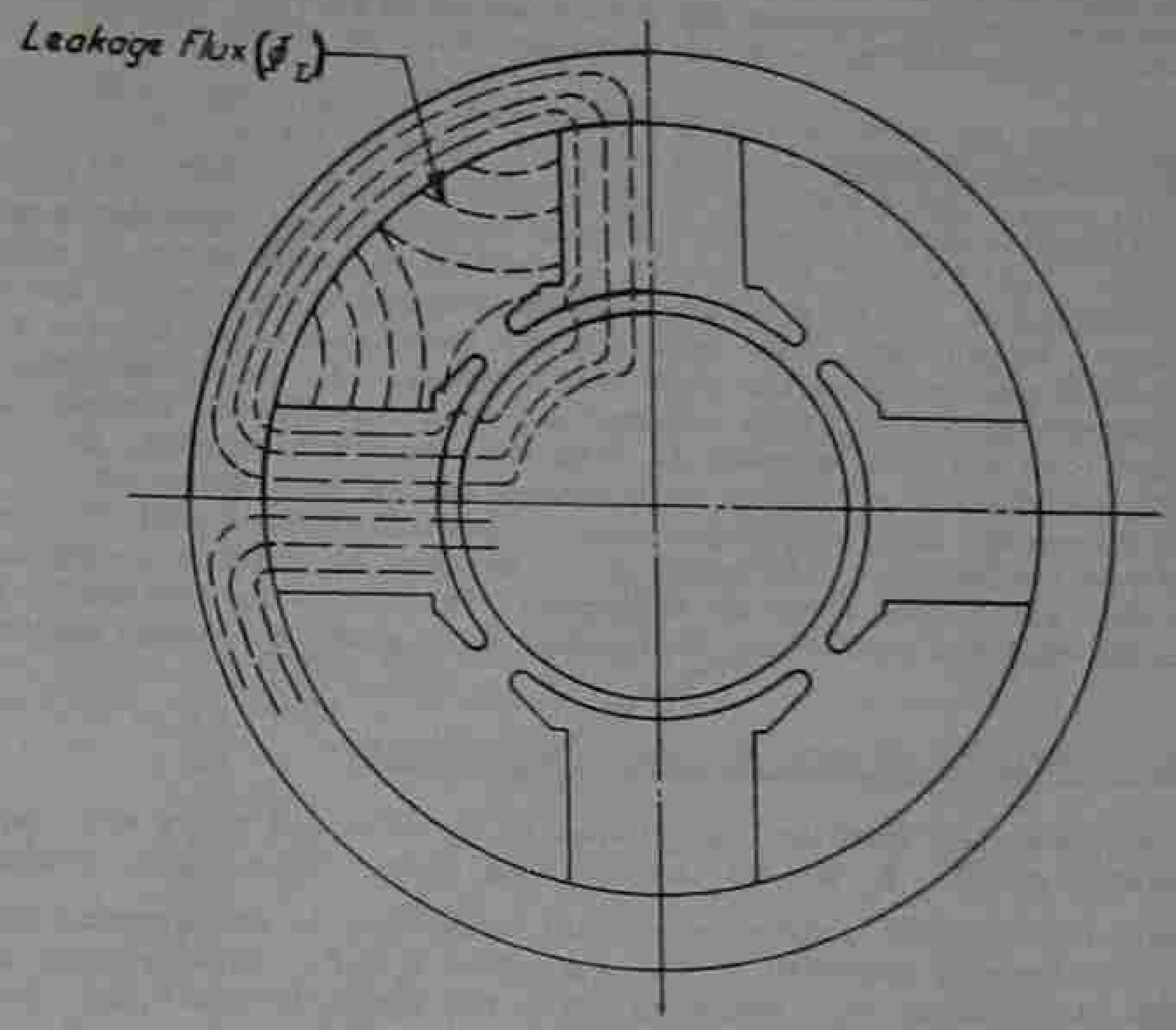


Figure 3.8 - Leakage Flux

3.6 EXCITATION METHODS

It will be apparent from the discussion on field systems that before a machine can function effectively some means must be found to produce this field. The two obvious methods are:

1. permanent magnet field;

2. electro-magnetic field.

Although the first alternative is used in some small machines and has the advantage of having no electrical losses the method has the marked disadvantage that the field is constant and this precludes any methods of field control.

The method almost universally used on all practical machines involves an electro-magnetic field system. This field can either be separately excited or self-excited.

3.7 SEPARATELY-EXCITED GENERATORS

In separately-excited machines the exciting current is derived from an external source which can be a small auxiliary generator termed an excitor, a d.c. bus system or, as is the case in some instances, a controlled rectifier unit. In this method of excitation there is no necessity for any link to exist between the machine generated voltage and the drop across the field system.

With regard to the analysis of the operation of separately-excited machines, this is generally less involved than the equivalent analysis of self-excited machines due to the fact that field current conditions are independent of the machine terminal voltage.

3.8 SELF-EXCITED MACHINES

In self-excited machines the exciting current comes directly from the armature. This type of machine is classed as either a shunt or series machine depending on the relationship between the exciting current and the load current. In practice, most machines are shunt connected and the field current is much smaller than the full load current. In series machines the load current is the exciting current and as a consequence increasing load current will give an increase in flux and, as a consequence, an increase in generated e.m.f. For this reason series excitation of generators is seldom used as a sole means of providing the field flux but can be used in conjunction with shunt field systems to provide a compensating factor in what are termed compound machines. The following discussion will therefore, be confined to factors associated with shunt connected machines.

3.9 VOLTAGE BUILD UP IN SELF-EXCITED SHUNT MACHINES

If the generator armature is rotated at rated speed there will be a small generated e.m.f. E_r due to the residual flux. This e.m.f. acting on the field circuit will produce a current resulting in an increase in flux with a consequent increase in the generated e.m.f. This process will continue and the machine will build up until the open circuit e.m.f. is equal to the drop in the field circuit. For if E_g is greater than $I_f R_f$ the tendency will be for I_f to increase which, in turn, will increase ϕ and E_g. If E_g is less than $I_f R_f$ the converse will be true.

Hence for equilibrium conditions

$$E_g = I_f R_f \qquad - \qquad 3.19$$

As shown in equation 3.10 the generated e.m.f. for a given machine may be written as

$$E_g = f\,(I_f, N) \qquad - \qquad 3.20$$

It is the simultaneous solution to these equations that gives the equilibrium value of E_g.

As the two expressions have four <u>unknown</u> variable terms, to obtain a solution it is necessary to impose restraints by specifying that two of the variables be considered as being constant. The two values specified are usually the field resistance and the speed. This leads to a solution for a given set of conditions. If either of these variables are altered the solution to the equation will vary.

In addition, as the relationship represented by equation 3.20 has been shown to be non-linear, an analytical solution is not practical and the problem must be solved graphically.

The procedure adopted to determine the equilibrium value of E_g for a given speed and field resistance is to plot the machine magnetization curve for the specified speed and on the same set of axes plot the relationship given by equation 3.19.

This last curve is termed the resistance line and, as shown in Figure 3.9, the solution to the problem which gives the equilibrium value of E_g is found from the intersection of the field resistance line and the magnetization curve.

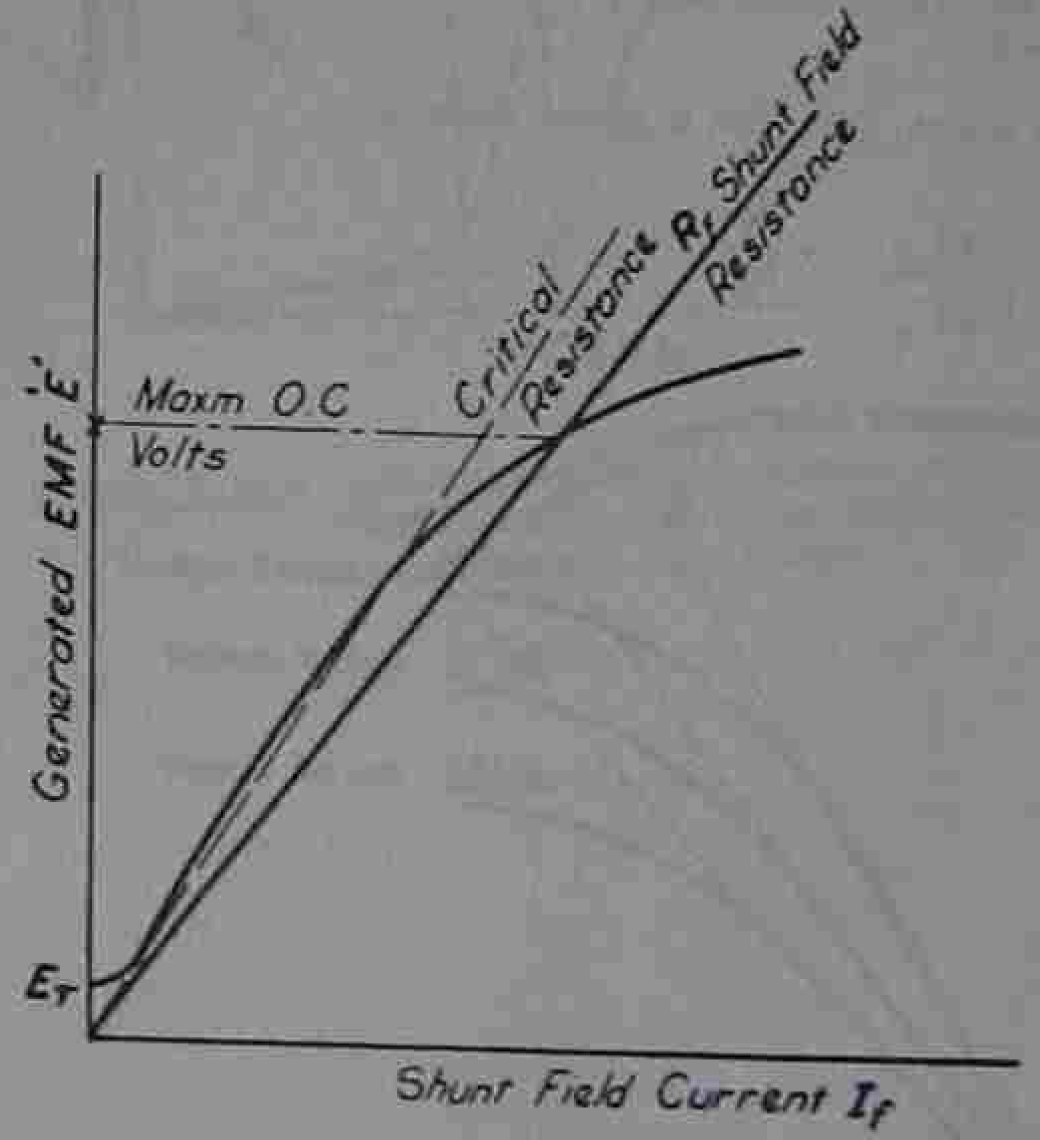


Figure 3.9 - Open Circuit Curve Self-Excited Generator showing Critical Resistance Line.

The build up mechanism can be more readily understood by referring to Figure 3.9 as it is apparent that, if for any value of I_f the generated e.m.f. is greater than the corresponding value of $I_f\,R_f$, the generated e.m.f. will continue to build up.

In practice, a machine may not build up for any one or more of the following reasons:

1. No residual magnetism, as stated, it is the residual magnetism that gives the build up process the initial impetus.

2. The current which flows in the field circuit as a result of the e.m.f. produced by the residual field may be in a direction such that the resulting field opposes the residual field. Under these conditions the machine is said to "build down".

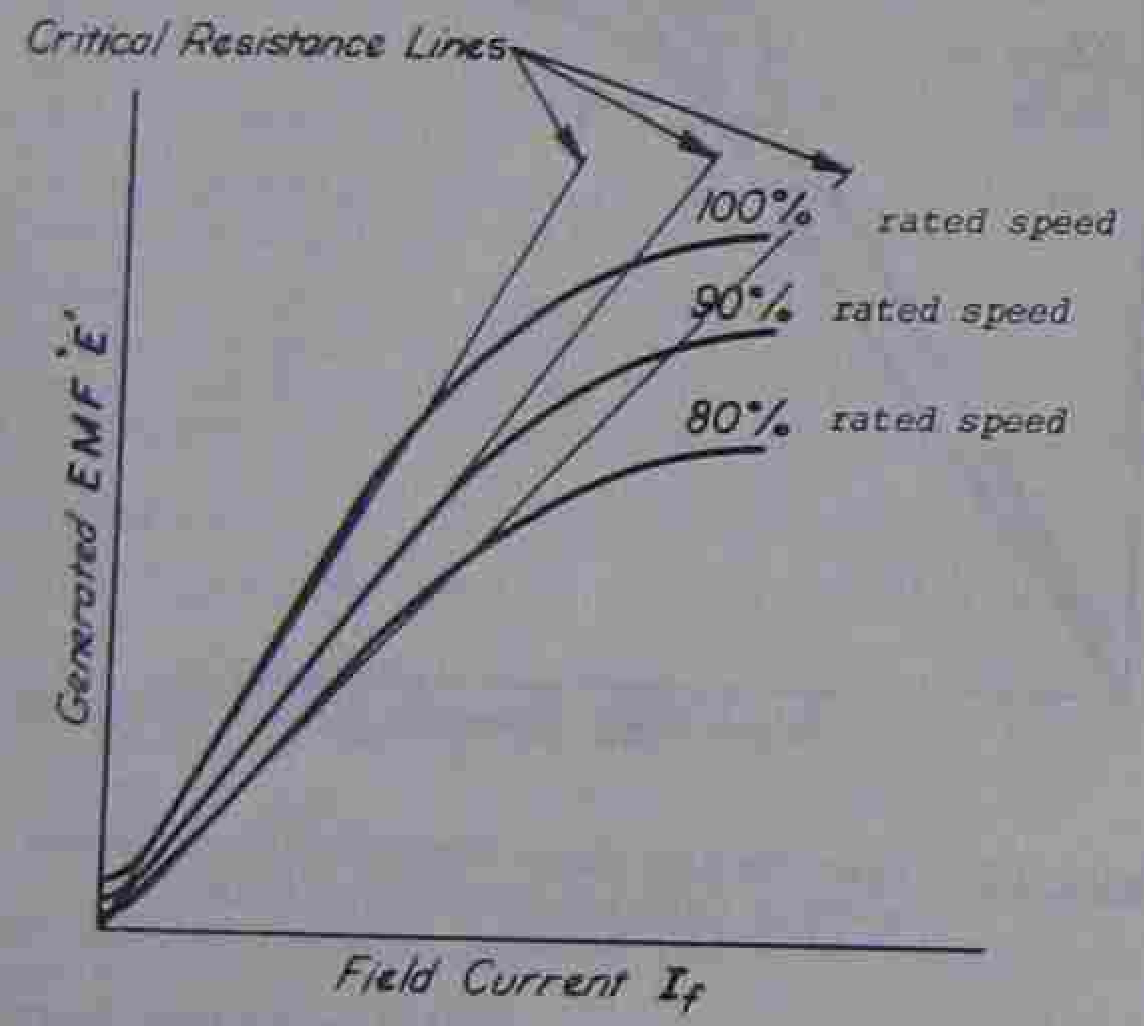
3. The resistance of the field circuit may be too high in which case the resistance line is rotated in an anti-clockwise direction and intersects the magnetization curve at too low a voltage. The highest value of resistance that prevents the e.m.f. build up is termed the critical resistance. This is shown in Figure 3.9.

An obvious, but trivial, special case of excessive field resistance is where the field circuit is open circuited. In this case, the resistance line coincides with the voltage axis intersecting the magnetization curve at E_r, the generated e.m.f. due to the residual flux.

As shown by Figure 3.10 the critical resistance value applies only at a stated speed.

It can be shown that for a given machine

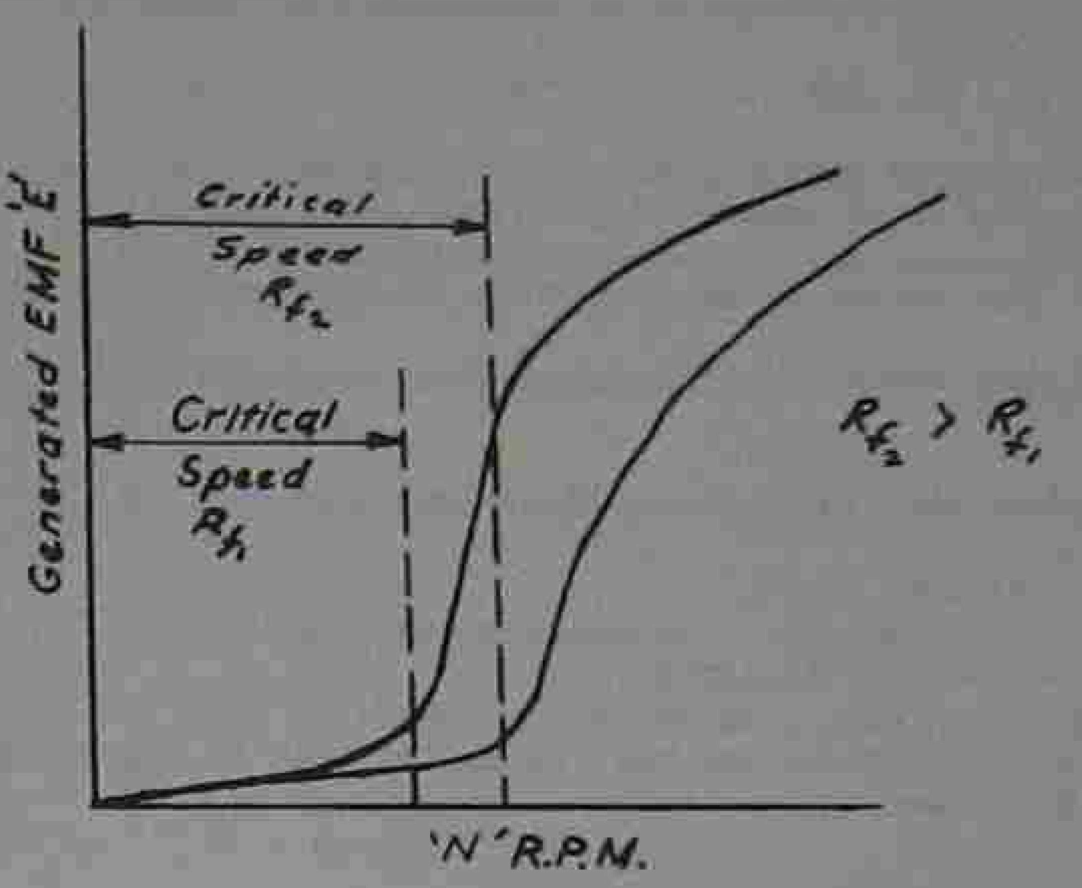
$$\frac{R_{critical_1}}{R_{critical_2}} = \frac{N_1}{N_2} \qquad - \qquad 3.21$$



<u>Figure 3.10</u> - Family of Magnetization Curves taken at various speeds showing there is a different critical resistance for each speed.

4. The speed of the machine is too low. As shown in Figure 3.10, if the machine was operating at 100% rated speed the critical resistance line would be line 1. If the field circuit resistance line was now line 2 the generated e.m.f. would reach the equilibrium value E_g'. If the speed now fell to

90% of rated speed the curve would change as shown and the machine would not build up as the resistance line 2 is now the critical resistance line for the 90% curve. The maximum speed at which build up will occur for a given field resistance is termed the critical speed (refer Figure 3.11). The trivial case is where n = 0 in which case the magnetization curve coincides with the I_f axis and $E_g = 0$.



<u>Figure 3.11</u> - Open Circuit Volts against r.p.m. for Self-Excited Generator with Constant Field Circuit Resistance.

REVIEW QUESTIONS

1) What factors govern the magnitude of the e.m.f. generated in a d.c. machine?

2) What condition prevents a mathematical analysis to determine the equilibrium voltage of an unloaded shunt connected self-excited generator?

3) Explain the build up process for the generated e.m.f. in a self-excited shunt connected generator specifically referring to:

a) the method of determination of the equilibrium voltage;

b) the factors that could prevent the build up process.

4) Explain what is meant by the terms:

a) critical speed,

b) critical resistance,

with reference to any restraints implicit in the definitions of the terms.

5) What factors are considered when determining the m.m.f. required to produce a given field flux and which of these factors require the greatest proportion of the available ampere turns?

6) What is meant by the term commutation and how is this achieved?

7) Commencing with the expression

$$e = B\,l\,v$$

derive the expression

$$E = \frac{\Phi Z N P}{60\,a}$$

8) State Fleming's Right Hand Rule for generators.

9) Give the relationship between the speeds and critical resistance values for self-excited d.c. generators.

ASSIGNMENTS

Marks

10 1. The following set of values are the open circuit test results for a self-excited shunt connected generator running at rated speed. Nrated 1500

Volts:	8	40	75	110	148	177	192	205	212
Field Current	0	.4	.8	1.2	1.6	2.0	2.4	2.8	3.0

Draw the magnetization curve for the machine at 1500 r.p.m. and determine:

a) the open circuit e.m.f. for a field circuit resistance of 80 Ω;

b) the terminal e.m.f. for an open circuit field.

20 2. For the machine of question 1, determine:

a) the critical resistance at a speed of 1000 r.p.m.;

b) the open circuit e.m.f. for this value of resistance at a speed of 1280 r.p.m.

40 X 3. By drawing a nest of magnetization curves for the machine of question 1 at speeds of 250, 500, 750, 1000, 1250, 1500 and 1750 r.p.m., plot the curves of e.m.f. against speed for field circuit resistance value of 60, 80 and 100 ohms and determine from these curves the critical speeds associated with these resistance values.

15 4. Each pole of a compound generator has 1260 shunt field turns and 18 series field turns. If rated voltage is developed when the shunt field alone is separately excited, under which condition it takes 3.7 amps, how much current would it be necessary to supply to the series field for the same generated e.m.f.? (259A)

15 5. If it is assumed that the airgap m.m.f. represents 60% of the total m.m.f. for the flux path, calculate the ampere turns necessary to produce a flux density of 1.0 tesla (weber per square metre) in an airgap of effective length of 1 mm.

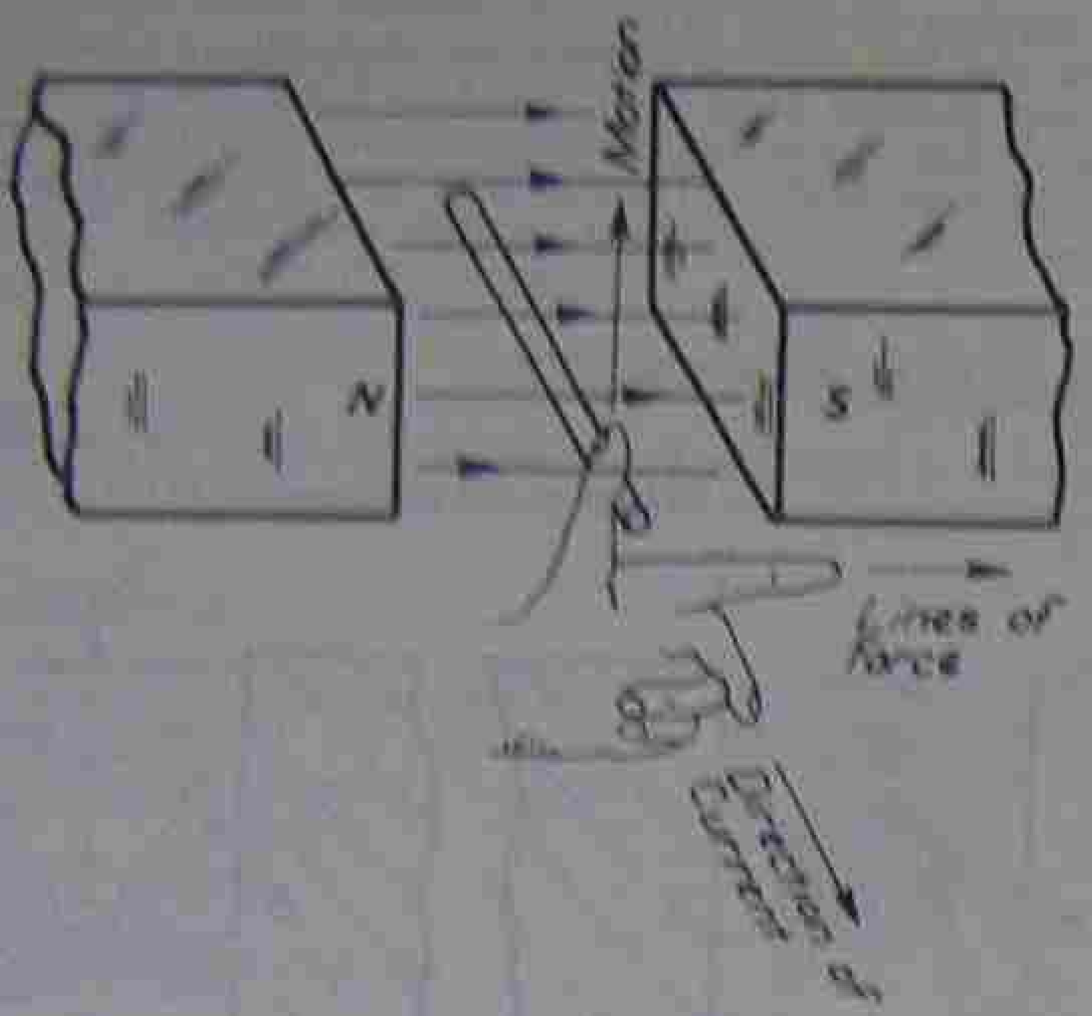


Figure 4.2

Fleming's Left-Hand Rule for motors.

One method of recalling this relationship is to use the following memory aid:

"F"irst finger - Field

Se"C"ond finger - Current

thu"M"b - Motion

The initial letters of field, current and motion only occur in the names of the finger (or thumb) that represents the positive direction of the quantity concerned and in this way it becomes a relatively simple matter to recall the association.

If the conductor of Figure 4.1 is formed into a coil as shown in Figure 4.3 the force exerted on the opposite sides of the coil will be opposite in direction and would appear to give a zero net force. However, if the coil is pivoted the torque produced by both sides of the coil will be additive and the direction of rotation will be as shown:

See Figure 4.3 on next page.

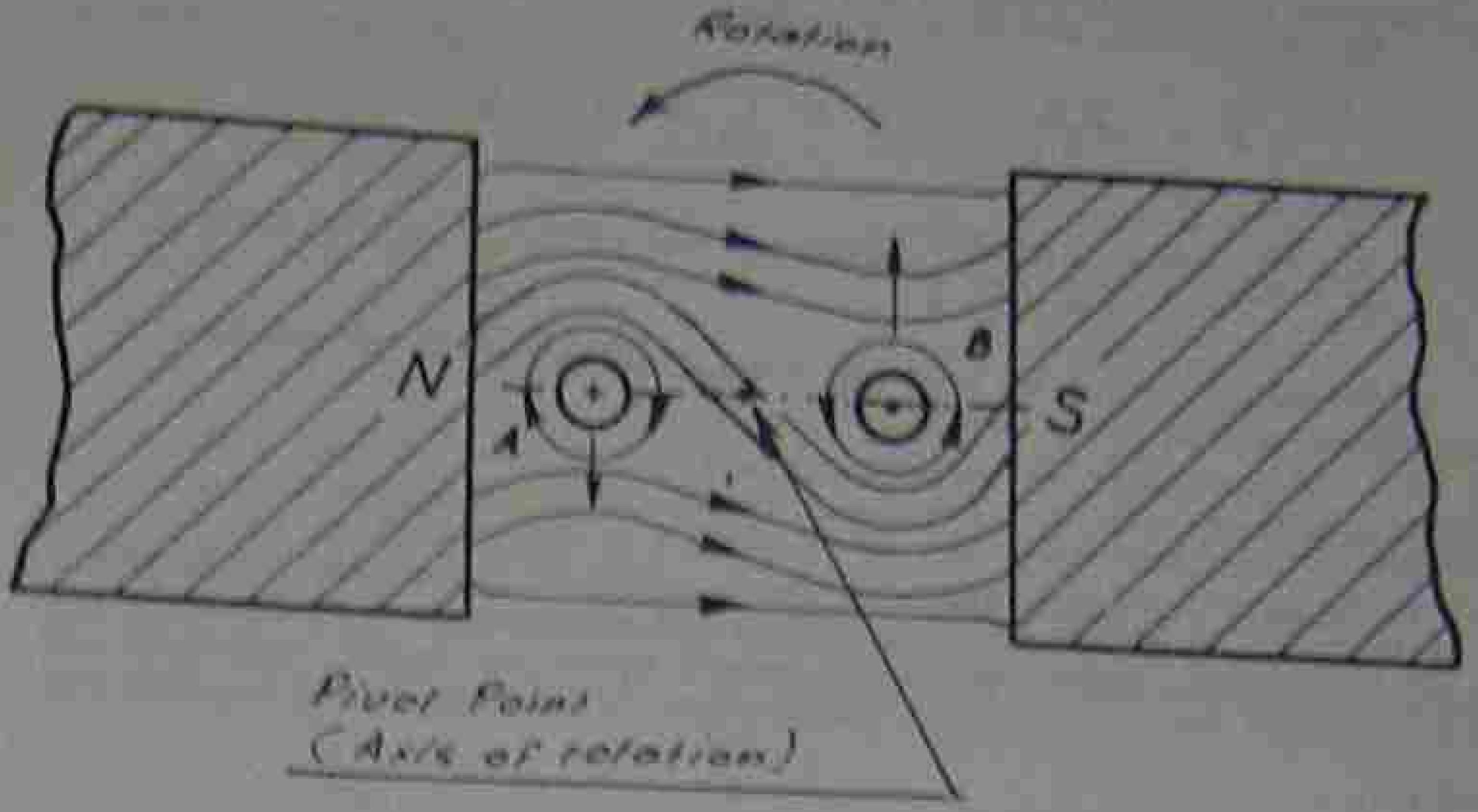


Figure 4.3

Motion of a current carrying coil in a magnetic field.

The expression

$$T = B\,l\,I\,r$$

refers only to one conductor and, as was the case with d.c. generators intended for practical applications, the torque developed by one single conductor is of little practical use and armatures are generally wound with many conductors.

Where the armature winding comprises many conductors, once again denoted by the symbol "Z" and these are arranged in "a" parallel paths, for a given armature current, Ia, the total torque developed by an armature is given by the expression:

$$T = Z\,B\,l\,\frac{I_a}{a}\,r \text{ Nm}$$

where Z is the effective armature conductors

a the number of parallel paths

and I_a the armature current in amperes.

In terms of the flux per pole, which is readily obtainable for a given field current using the methods of Unit 3, and the physical dimensions of the machine the flux density, B, can be written as:

$$B = \frac{\phi}{\text{pole area}}$$

$$= \frac{\phi}{2\,\pi\,r\,l_{/P}}$$

$$\text{or} \quad B = \frac{P\,\phi}{2\,\pi\,r\,l} \qquad - \quad 4.2$$

The torque can now be written as

$$T = \frac{P\,\phi}{2\,\pi\,r\,l} \times l \times \frac{I_a}{a} \times Zr$$

or $$T = \frac{1}{2\,\pi}\;\frac{\phi\,Z\,P\,I_a}{a} \qquad - \qquad 4.3$$

It should be noted that the torque developed by an armature is independent of the motor speed.

Example 4.1

A 4-pole lap wound armature has a total of 720 active conductors. If the flux per pole is 0.04 webers and the armature current is 31.4 amperes, calculate the torque developed.

Solution

From equation 4.3

$$T = \frac{1}{2\,\pi}\;\frac{\phi\,Z\,P\,I_a}{a}$$

$$= \frac{1}{3.14} \times \frac{0.04 \times 720 \times 4 \times 3.14}{2 \times 4}$$

$$= 144 \text{ Nm.}$$

In terms of the above expression for torque, the power developed by the armature can be obtained from the expression

$$P_{dev.} = \frac{2\,\pi\,N\,T}{60}$$

$$= \frac{2\,\pi\,N}{60} \cdot \frac{1}{2\,\pi}\;\frac{\phi\,Z\,P\,I_a}{a}$$

or $$P_{dev.} = \frac{\phi\,Z\,N\,P}{60a} \cdot I_a \qquad - \qquad 4.4$$

Example 4.2

Assuming that the armature of Example 4.1 was rotating at 1500 r.p.m. and that the current was increased to 50 amperes, calculate the power output of the machine.

Solution

From equation 4.4

$$P_{dev.} = \frac{\phi\,Z\,N\,P}{60a} \times I_a$$

$$= \frac{0.04 \times 720 \times 1500 \times 4 \times 50}{60 \times 4}$$

$$= 14.4 \times 25 \times 10^2$$

$$= 36 \text{ kW}$$

In Unit 3, it was seen that the e.m.f. generated by an armature, E_g, was given by the relationship

$$E_g = \frac{\phi\,Z\,N\,P}{60\,a} \qquad - \qquad 3.4$$

Substituting E_g into the expression 4.4 will give:

$$P = E_g\,I_a \text{ watts.}$$

This is, in terms of the electrical quantities associated with the armature, the magnitude of the power developed. It will be appreciated that not all of this power is available at the shaft but a percentage is absorbed in overcoming frictional losses. In addition, losses occur in the armature iron circuit due to the alternating nature of the flux in the armature. Where all these losses, which are termed rotational losses, are denoted by the symbol "W" the mechanical output of the armature becomes:

$$P_{out} = E_g\,I_a - W \qquad - \qquad 4.5$$

Example 4.3

The e.m.f. generated in a motor armature is 250 volts and the armature current is 40 amperes. If the rotational loss is 500 watts, calculate the power available at the shaft.

Solution

From equation 4.5

$$P_{out} = E_g\,I_a - W$$

$$= 250 \times 40 - 500$$

$$= 9.5 \text{ kW}$$

Example 4.4

If the armature of example 4.3 was rotating at 1 000 r.p.m. calculate the available shaft torque.

Solution

From equation 1.11

$$P = \frac{2\,\pi\,N\,T}{60}$$

hence $$T = \frac{60\,P}{2\,\pi\,N}$$

$$= \frac{60 \times 9500}{6.28 \times 1000}$$

$$= 91 \text{ Nm}$$

As both E_g and I_a can be obtained by measurement and a knowledge of the resistance of the various motor circuits this gives a convenient method of determining the rotational losses.

If the machine is operated at no load equation 4.5 becomes:

$$P_{out} = 0 = E_g I_a - W$$

from which

$$E_g I_a = W \qquad - \qquad 4.6$$

Thus it may be stated that at no-load the power developed by the armature is equal to the rotational losses.

It should be noted that as rotational losses are dependent on speed that this particular loss will only apply at a specified speed.

Under load conditions the armature conductors carry a considerable current and this current produces a flux pattern as shown by Figure 4.4. Although the individual conductors are constantly moving, for any given position on the armature, there is always one conductor carrying current in a constant direction. As a result the armature field will be constant in magnitude and stationary in space.

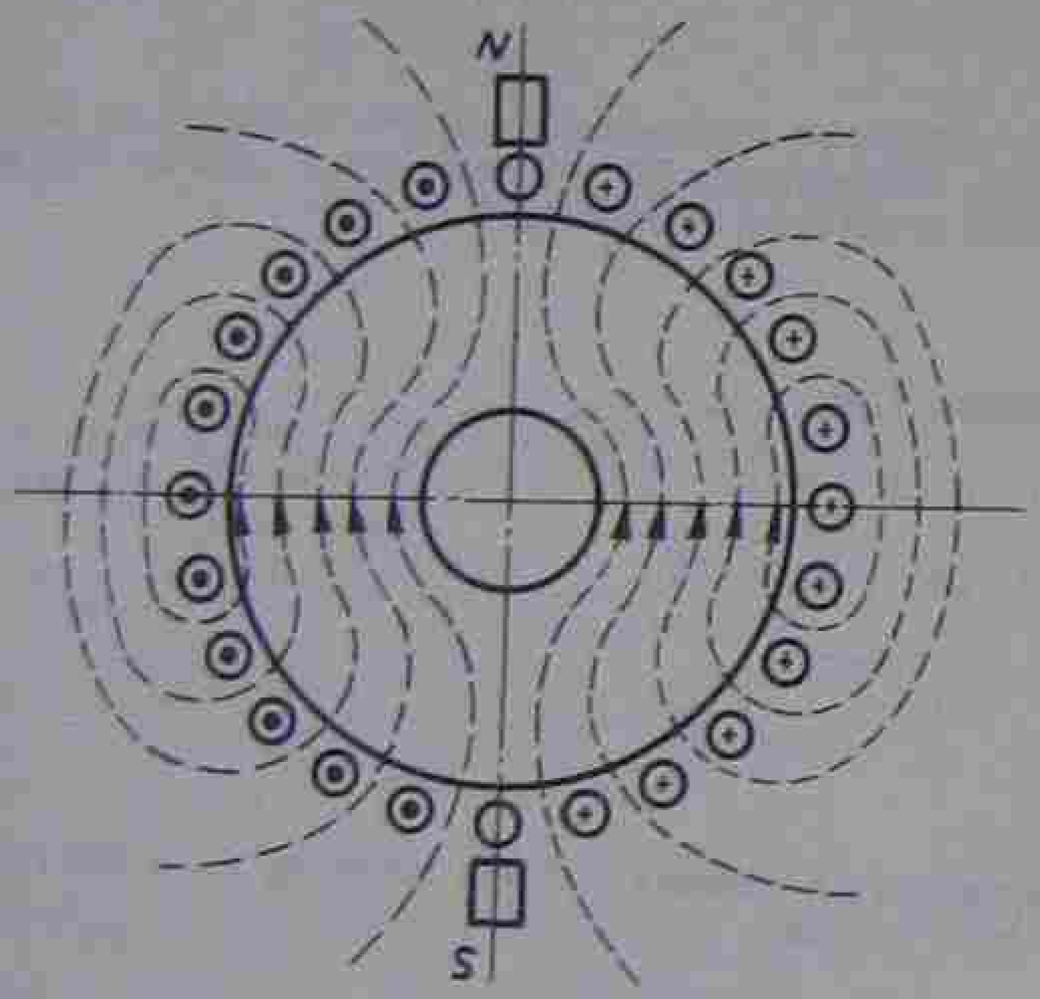


Figure 4.4 - Flux distribution due to Armature Field.

Considering the main and armature fields together:

1. The current in the armature produces poles, the axes of which are in the inter main field gaps. Figure 4.5

See Figure 4.5 on next page.

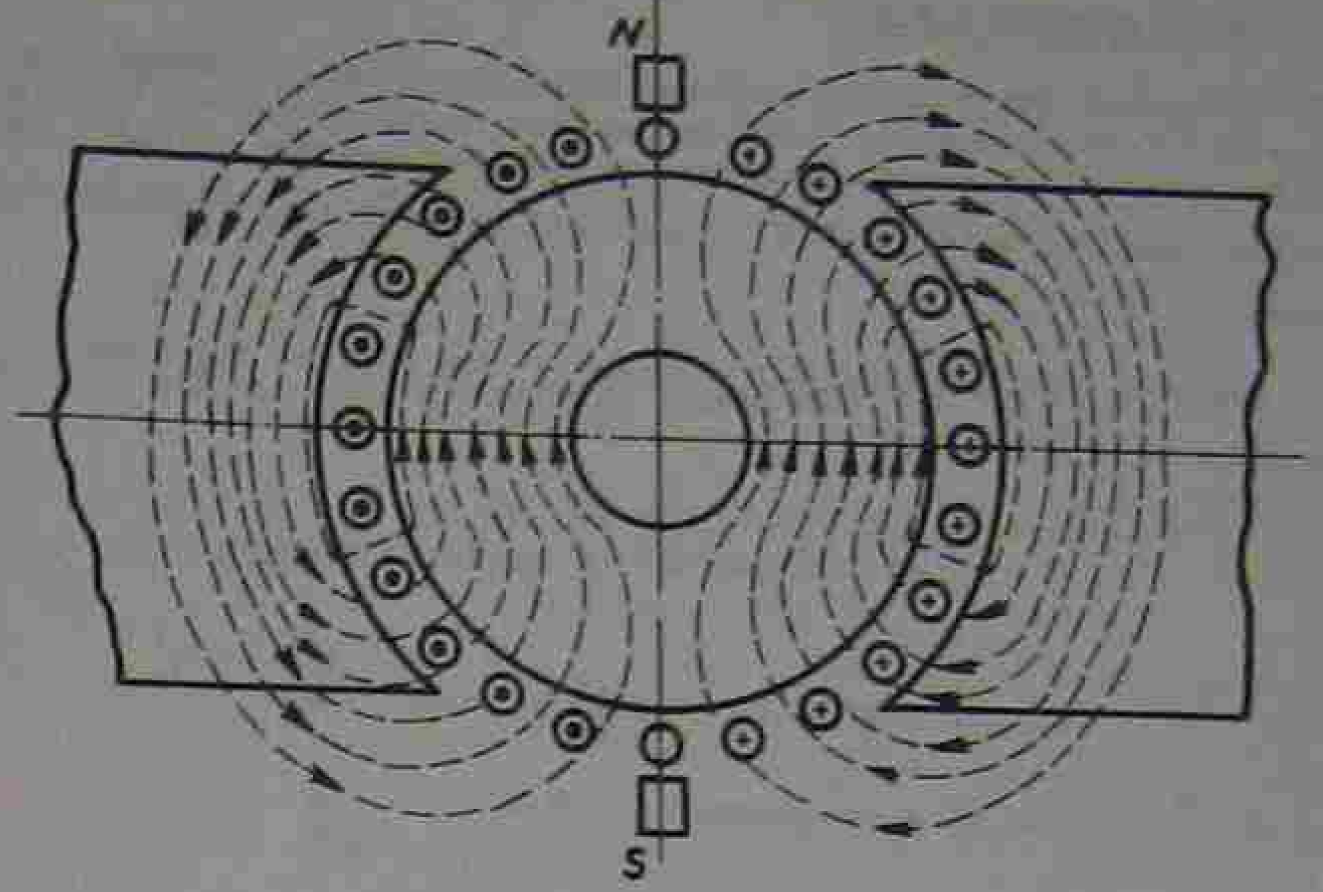


Figure 4.5 - Relative position of Main and Armature Poles.

2. The field produced by the armature conductors lies approximately one half of a pole pitch from the main pole of the same (and also opposite) polarity.

3. The net result is that the armature will tend to rotate due to the simultaneous repelling and attracting effect of the main poles of like and opposite polarity to the armature poles.

This is an alternative method of explaining how rotation is produced in an armature.

Figure 4.6 shows the resulting flux pattern due to the interaction of the main and armature fields and the consequent shift in the magnetic neutral axis. As current will flow in the armature conductors when the machine is operating both as a motor and a generator the direction of conductor rotation for both cases is shown.

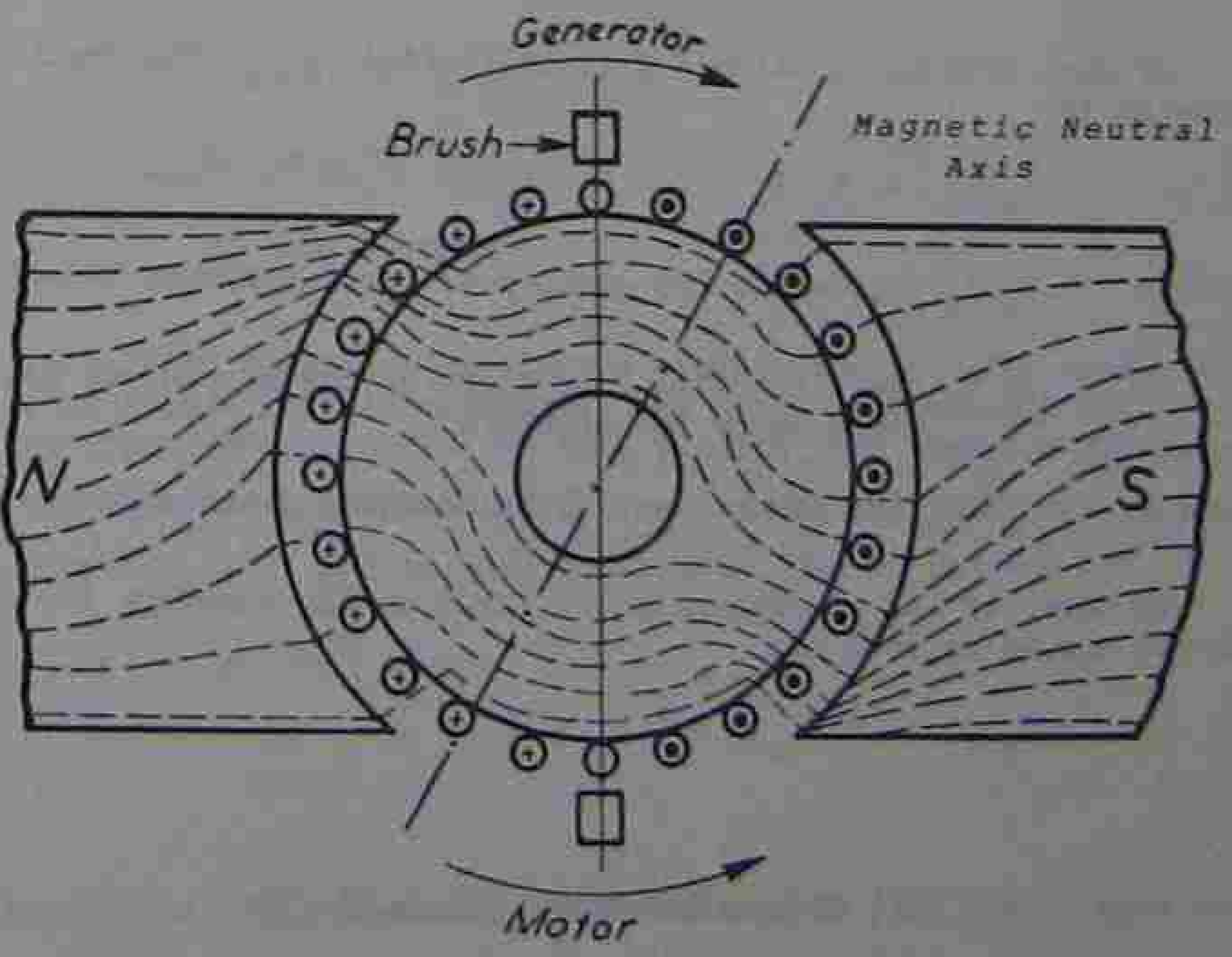


Figure 4.6 - Effect of Armature Field on Main Field.

4.3 MOTOR COUNTER E.M.F.

In motors the e.m.f. generated in the armature is termed the "back e.m.f." or "counter e.m.f.". For convenience, however, this will still be referred to as the generated e.m.f. and denoted by the symbol E_g to prevent any confusion with E_c (commutation e.m.f.) or V_b (brush drop voltage).

Using V_t for the terminal voltage of the machine the equation for the armature circuit becomes:

$$V_t - E_g - V_b - L\frac{di}{dt} - I_a R_a = 0 \qquad - \qquad 4.7$$

where

V_t is the supply (terminal) voltage

E_g the back or generated e.m.f.

V_b the brush drop

$L\frac{di}{dt}$ the armature inductive voltage

and $I_a R_a$ the voltage drop due to the resistance of the armature winding.

Since E_g has been used to represent the back e.m.f. this equation is now equally applicable to both motors and generators.

For steady state conditions the $L\frac{di}{dt}$ term can be ignored and, if, for simplicity, the brush drop is allowed for by being included in the armature circuit resistance, equation 4.7 simplifies to

$$V_t - E_g - I_a R_a = 0$$

$$\text{or} \quad V_t = E_g + I_a R_a \qquad - \qquad 4.8$$

If each term in equation 4.8 is multiplied by I_a the resulting expression is

$$V_t I_a = E_g I_a + I_a^2 R_a \qquad - \qquad 4.9$$

where $V_t I_a$ represents the electrical power input to the armature

$E_g I_a$ the electrical equivalent of the mechanical power produced by the armature

and $I_a^2 R_a$ the power loss in the armature resistance.

In terms of the electrical power input to the armature the output power can now be written as:

$$P_{out} = V_t I_a - I_a^2 R_a - W \qquad - \qquad 4.10$$

Example 4.5

The input current to a shunt connected 240 d.c. motor on no load is 6 amperes. If the winding resistances are:

$$R_a = 0.1\ \Omega$$

$$R_f = 240\ \Omega$$

determine the value of the rotational losses (W).

Solution

The field current is given by the expression

$$I_f = \frac{V_t}{R_f}$$

$$= \frac{240}{240}$$

$$= 1 \text{ ampere.}$$

The armature current I_a is then

$$I_a = I - I_f$$

$$= 6 - 1$$

$$= 5 \text{ amperes.}$$

For no load conditions

$$V_t I_a - I_a^2 R_a - W = 0 \qquad \text{(from equation 4.10)}$$

$$\text{or} \quad W = V_t I_a - I_a^2 R_a$$

$$= 240 \times 5 - 5^2 \times 0.1$$

$$= 1200 - 2.5$$

$$= 1197.5 \text{ watts}$$

Note: It will be observed that in the above example if the armature no load copper loss is neglected, the error in the value of W will be approximately 0.2%. As this is much less than the accuracy of the meter readings the $I_a^2 R_a$ loss can be neglected and in practice equation 4.10, for no load conditions, can be reduced to:

$$V_t I_a = W \qquad - \qquad 4.11$$

4.4 THE EFFECT OF LOAD

When the load torque applied to a motor is increased the motor developed torque must also increase in order to maintain equilibrium. As the main variable component of the torque expression is the armature current, I_a, it is this factor that must increase. From equation 4.8 it can be seen that

$$I_a = \frac{V_t - E_g}{R_a}$$

To increase I_a it is therefore necessary to decrease the value of E_g as both V_t and R_a can, for the purpose of this analysis, be considered as being constant. As the obvious means whereby the machine can automatically increase I_a is to decrease E_g by reducing the speed, the net result of an increase in load is to reduce the speed. The actual relationship between load and speed is covered in Section 4.6

4.5 MOTOR TORQUE RELATIONSHIPS

Considering the terms in equation 4.3 that can be taken as being constant the expression becomes:

$$T = K \phi I_a \qquad - \qquad 4.12$$

where

$$K = \frac{1}{2\pi} \frac{Z}{a} \qquad - \qquad 4.13$$

This relationship (4.12) can now be used to obtain torque-armature current relationships for the various machines.

1) Shunt Machines

In shunt motors the flux, being a function of V_t, can be assumed to be constant and equation 4.12 becomes:

$$T \propto I_a \qquad - \qquad 4.14$$

This is a linear relationship and, as a result, for shunt machines the torque-armature current curve is linear. (Refer Figure 4.7.)

See Figure 4.7 on next page.

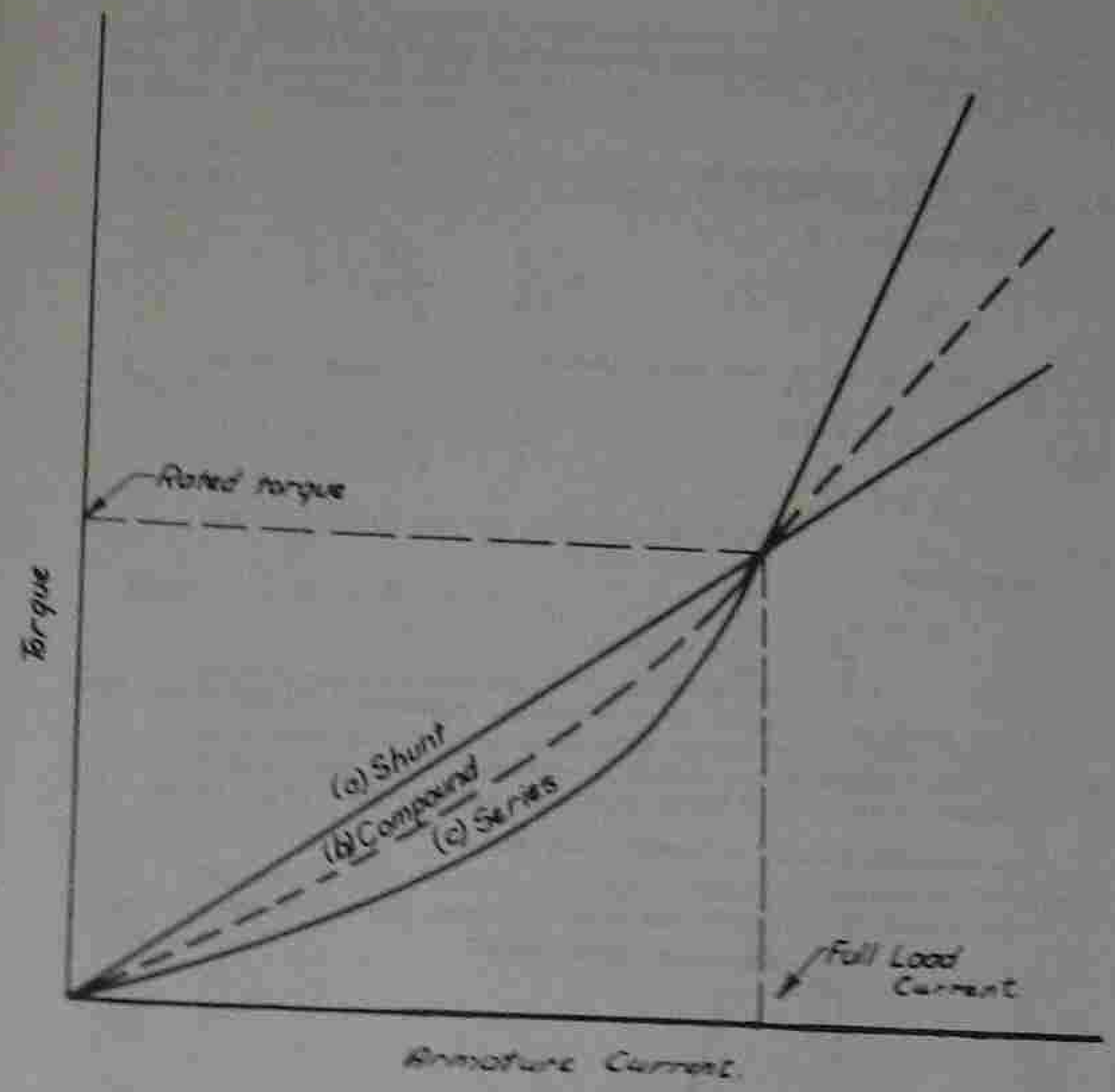


Figure 4.7 - Motor Current-Torque Curves for Shunt

(a) Shunt.

(b) Compound.

(c) Series.

2) Series Machines

Neglecting the effects of saturation, in a series machine

$$T \propto I_a^2 \qquad - \qquad 4.15$$

$$\text{since } \phi \propto I_a \qquad - \qquad 4.16$$

As a result, the relationship between torque and armature current is parabolic.

3) Compound Machines

The characteristics of compound machines lie midway between those for shunt and series machines. The actual characteristic depends on the ratio between the shunt m.m.f. and series m.m.f. at a particular load. (Refer Figure 4.7.)

4.6 MOTOR SPEED RELATIONSHIPS

From equation 4.8

$$E_g = V_t - I_a R_a \qquad - \quad 4.17$$

Substituting for E_g the relationship

$$E_g = k \phi N \qquad - \quad 4.18$$

$$k \phi N = V_t - I_a R_a$$

from which

$$N = \frac{V_t}{\phi k} - \frac{R_a}{k\phi} \cdot I_a \qquad - \quad 4.19$$

For a shunt motor where ϕ is constant, equation 4.19 takes the form

$$N = a - b I_a$$

the standard form of a linear equation.

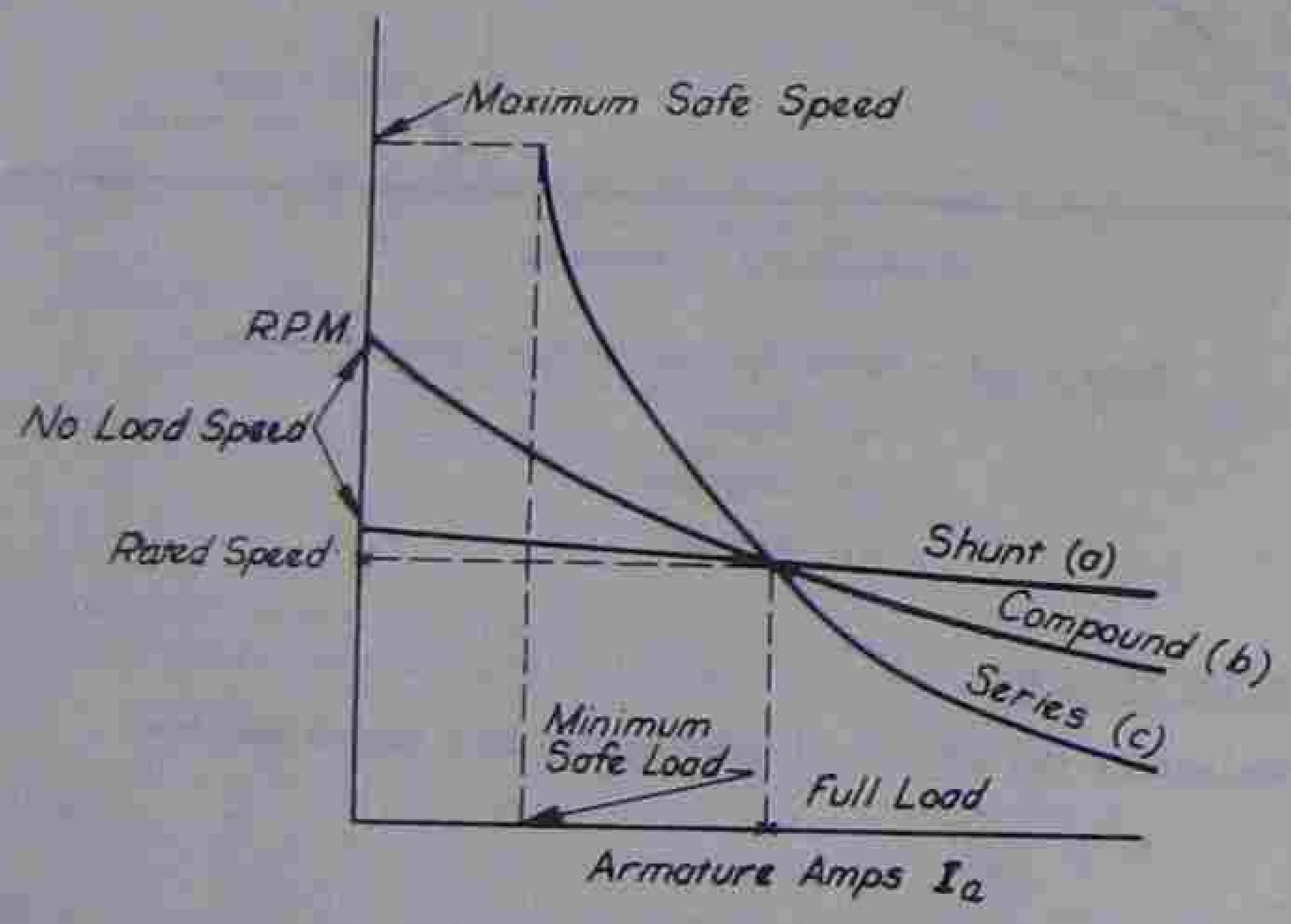


Figure 4.8 - Motor Current Speed Curves for Shunt.

(a) Shunt.
(b) Compound.
(c) Series.

As shown in Figure 4.8, the speed-load relationship for the shunt motor is linear, the speed gradually decreasing as the load increases. This is in accordance with the findings of section 4.4 but gives a more precise definition of the relationship.

For a series motor, if the effects of saturation are again neglected, the relationship of 4.14 again applies. Expression 4.19 now becomes of the form

$$N = \frac{V_t}{k I_a} - \frac{R_a I_a}{k I_a}$$

which becomes

$$N = \frac{V_t}{k I_a} - \frac{R_a}{k} \qquad - \quad 4.20$$

The expression has the mathematical form:

$$N = \frac{a}{I_a} - b$$

This inverse relationship is shown in Figure 4.8.

As a consequence, the speed of a series motor rises rapidly as the load decreases and in practice a series motor should never be allowed to run at light loads as the excessive speed may result in damage to the machine.

The speed-load relationship for a compound machine falls between that of the series and shunt machines depending on the degree of compounding.

REVIEW QUESTIONS

1) What is the basic expression for developing the torque relationships of a motor?

2) Explain how motion is produced in a d.c. motor.

3) State Fleming's ~~Right~~ LEFT Hand Rule for d.c. motors.

4) Derive the torque relationship for d.c. motors.

5) What is meant by the counter e.m.f. of a d.c. motor and what is the importance of this e.m.f. when determining:

   a) the speed load characteristics;

   b) the torque armature current characteristic;

   c) the output of a d.c. motor?

6) Describe a method of determining the rotational loss of a d.c. motor.

7) Derive the expressions for the speed load characteristics of a d.c. motor. (Shunt only)

8) State the effects of the armature field on the main field.

ASSIGNMENTS

Marks

15 1. The following information is given in connection with a certain motor: arm.dia.- 15 cm, B - 0.8 wb./metre^2, Z - 258, I_a - 120 amps, l - 18 cm. Wave Wound, four - pole. Calculate the torque developed.

20 2. A 4-pole machine operates at a full load speed of 1500 r.p.m. If the armature contains 432 conductors arranged in a 4-pole lap winding and the main field flux is 0.0412 webers, calculate:

   a) the torque developed for an armature current of 150 amperes;

   b) the output power if the full load current is 200 amperes.

25 3. The full load speed of a 240 volt shunt d.c. motor is 1500 r.p.m. and under these conditions the armature current is 100 amperes. If the armature current on no load is 5 amperes and the armature resistance is 0.024 ohms., calculate the no load speed. Assume that the brush drop is 5 volts on full load and 2 volts at no load. (Neglect any change in field.)

25 4. When run on no load, the input to a shunt d.c. motor was 10 000 watts. If the motor has a rated voltage of 500 volts a shunt field resistance of 125 ohms and an armature circuit resistance of 0.01 ohms, calculate:

   a) power input to the armature;

   b) the back e.m.f.;

   c) the armature copper loss;

   d) the output power;

   e) the rotational loss.

15 5. A d.c. motor develops a full load torque of 100 Nm for an armature current of 60 amperes.

   a) For a shunt connected motor calculate the torque for:

      i) I_a = 30 amperes;

      ii) I_a = 60 amperes.

   b) For a series motor, assuming that the magnetization curve can be approximated by a linear relationship, calculate the torque when:

      i) I_a = 20 amperes;

      ii) I_a = 80 amperes.

ELECTRICAL MACHINES I

UNIT No. 5

WHS

DIRECT CURRENT MACHINES

This unit will cover the following topics:

- 5.1 Magnetic action of armature field distortion.
- *5.2 Demagnetizing effect of cross magnetizing armature reaction.
- *5.3 Brush shifting.
- 5.4 Voltage of self induction.
- 5.5 Interpole and compensating windings.
- 5.6 Interpoles for d.c. generators.
- 5.7 Sparking at commutator with S.C.R. drives.

Review questions.

Assignments.

* These subjects are non-examinable but are included for reference purposes only.

5.1 MAGNETIC ACTION OF ARMATURE FIELD DISTORTION

In the shunt motor and machines where the field and armature are supplied from different sources, the main field m.m.f. is constant. Conversely the magnetic field produced by the armature varies directly with the armature current. The interaction of the main field flux and the flux produced by the armature field has two effects:

1. It strengthens one half of the pole and weakens the other half of the pole (see Figure 5.1). Due to iron saturation the overall effect is to demagnetize, that is, to reduce the main field strength. This can be seen from Figure 5.1 where the effect of the armature m.m.f. can be defined in terms of the main field m.m.f. as producing a change in the main field current of ΔI_f. In the section of the pole where ΔI_f assists the main field there will be an increase in flux and E_g represented by the distance a-b. Where ΔI_f opposes the main field the decrease will be represented by d-c. As d-c is greater than a-b the net effect is an overall reduction in t total flux per pole.

See Figure 5.1 on next page.

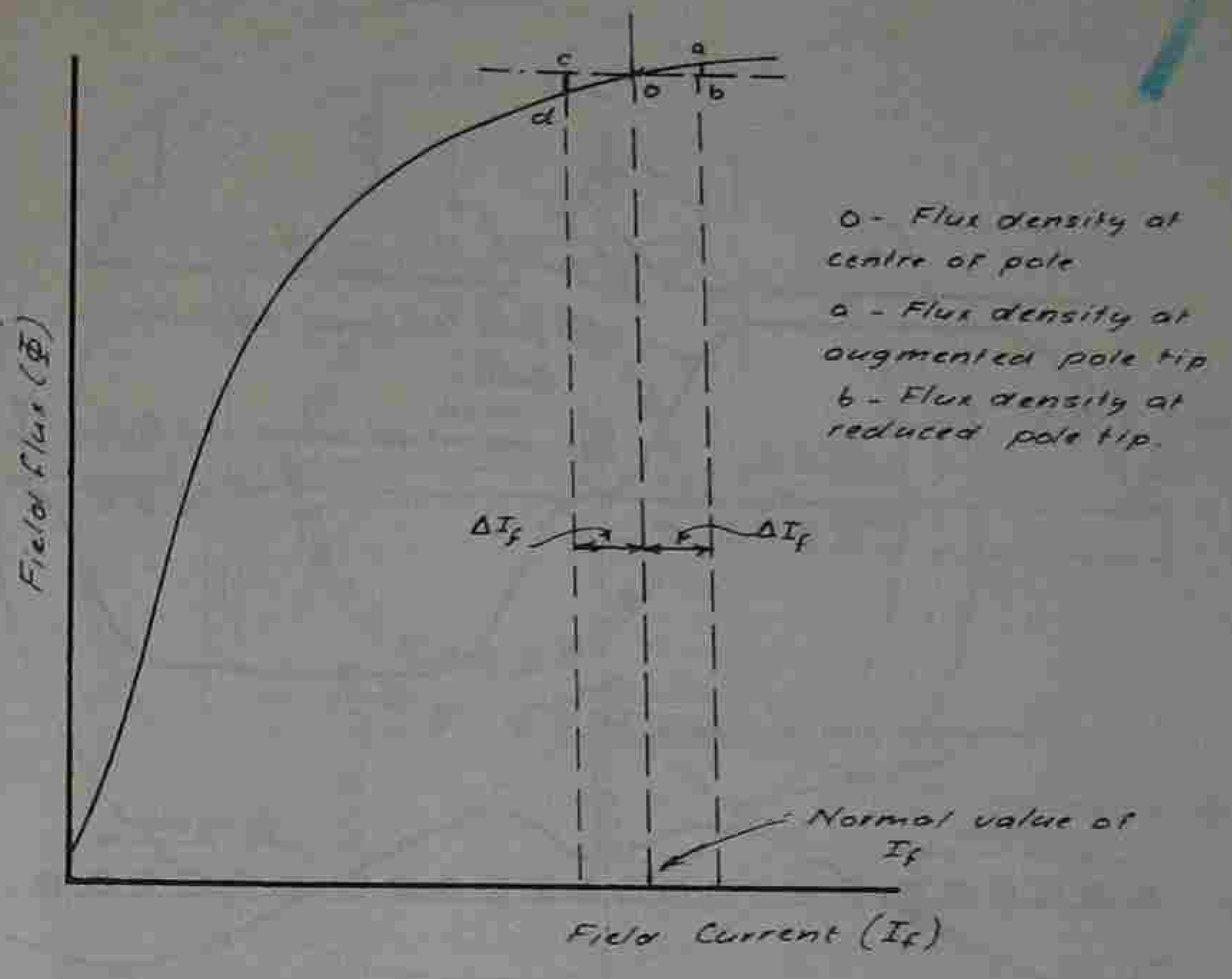


Figure 5.1 - Effect of armature field on Total field flux.

2. As a further consequence the main field is distorted; that is, the neutral axis of the main field is displaced from the geometrical neutral axis by a small angle. Figure 5.2 shows how the net result is a distortion of the main field and a shift of the magnetic axis.

To overcome the above two effects a further auxiliary pole is added between each pair of poles. Such poles are called interpoles or commutating poles. They are narrower than the main poles and carry a winding excited by the armature current. On the larger size of machines a further winding called a compensating winding is sometimes used. This winding is fitted in slots in the main pole shoe and is also excited by the armature current. Both the interpole and the compensating winding are connected in series with the armature circuit. As a result of this, both interpole and compensating winding field strength vary directly with armature current. In this way variations in the armature m.m.f. and field are automatically compensated for as the load varies.

Theoretically the armature conductor current should reverse where there is no field, namely in the magnetic neutral zone, and these windings endeavour to bring this about. The above windings are illustrated in Figure 5.2.

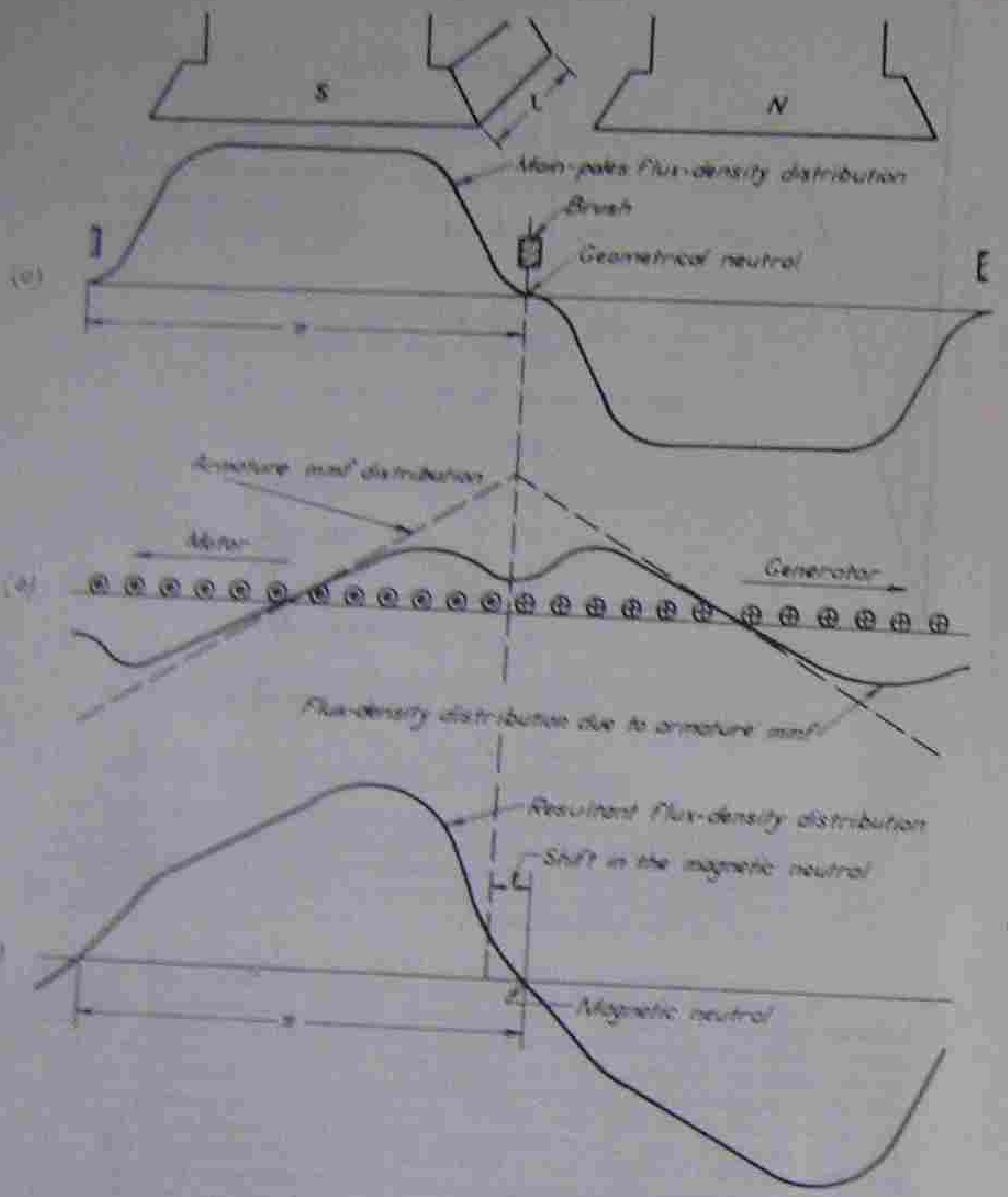


Figure 5.2

Displacement of Magnetic Neutral.

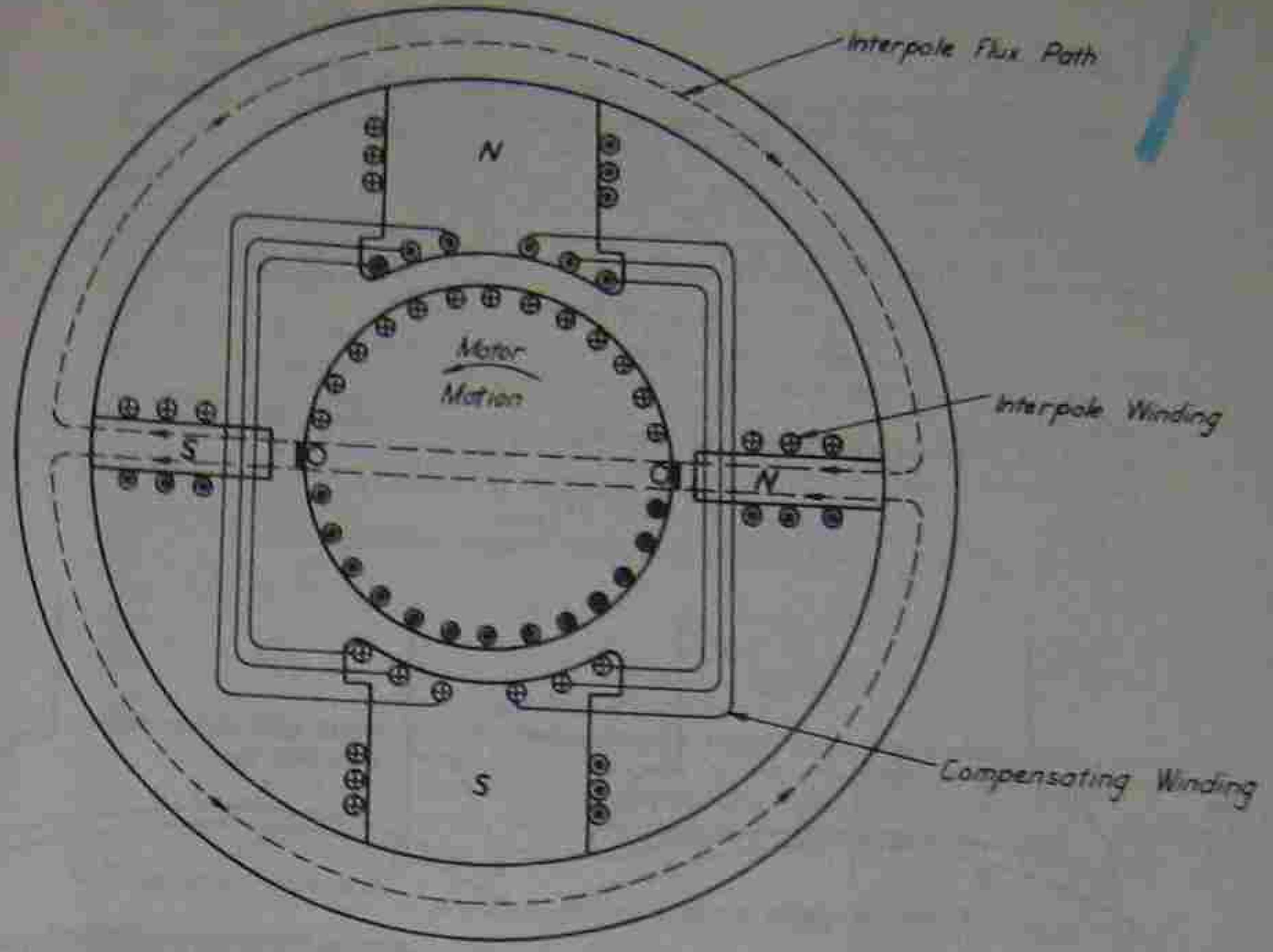


Figure 5.3

5.2 DEMAGNETIZING EFFECT OF CROSS MAGNETIZING ARMATURE REACTION

In machines where the brushes are not shifted to compensate for the shift of the magnetic neutral as would be the case where the presence of interpoles and compensating winding minimize the shift the armature magnetic field is called the cross magnetizing armature reaction. The magnitude of this effect is given by:

$$\text{The cross magnetizing ampere turns/pole} = \frac{\tau Z I_a}{2aP} \qquad \ldots 5\cdot 1$$

where

$$\tau = \frac{\text{polar arc}}{\text{pole pitch}} \qquad - \quad 5.2$$

I_a = armature conductor current

Z = armature conductors

a = parallel circuits on armature

P = number of poles.

Example 5.1 LAP

An armature 0.5 metres diameter of a six-pole generator has 378 conductors, carries 800 amperes and has a pole arc of 0.17 metres. Calculate the cross magnetizing armature reaction ampere turns.

Solution

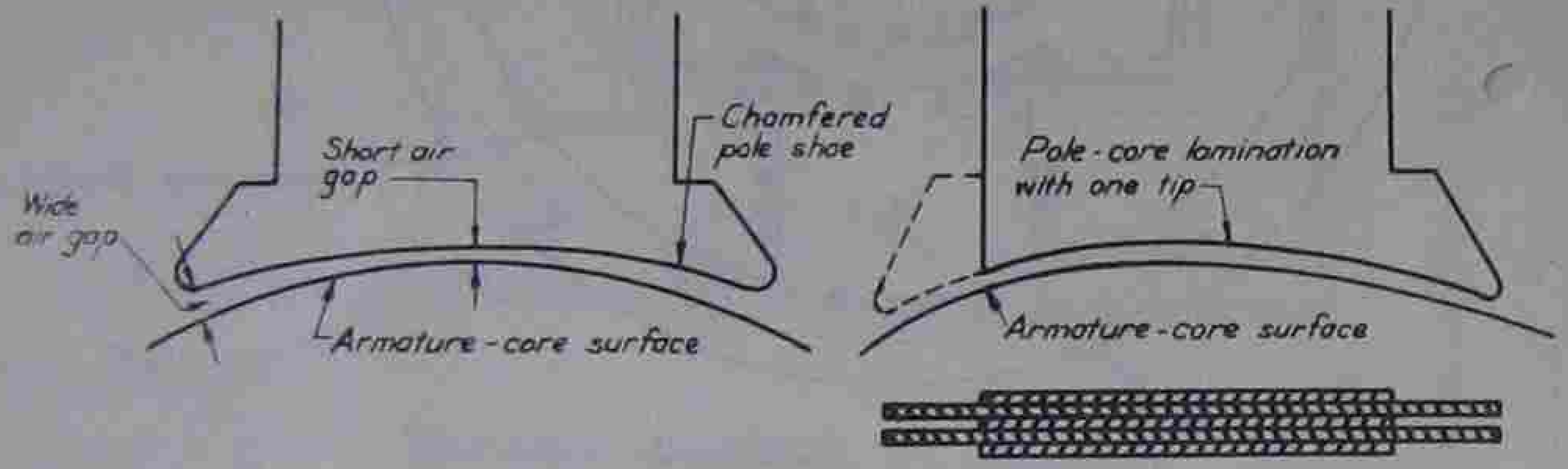
i) From equation 5.2

$$\frac{\text{polar arc}}{\text{pole pitch}} \quad \tau = \frac{0.17}{\pi/6 \times 0.5} = 0.65$$

ii) From equation 5.1

$$\text{cross magnetizing ampere turns/pole} = \frac{0.65 \times 378 \times 800}{2 \times 6 \times 6}$$

$$= 2740 \ \text{At}_{/\text{pole}}$$



(a) Chamfered-pole design (b) Lamination with one pole tip

Figure 5.4

Since modern machines operate in the saturated region of the magnetization curve, the armature field additive effect is less than its demagnetizing effect as shown in Section 5.1.

The demagnetizing ampere turns are strongest at the main pole tip, decreasing to the pole centre. To counteract this effect the reluctance of the armature field flux path may be increased at the pole tips by either of the two alternative methods illustrated in Figure 5.4.

These methods may be described as:

1. Increase the gap gradually from the centre of the pole to its tip. The ratio of the air-gap at the edge of the pole to the air-gap at the centre of the pole is between 2.5 and 3.5 to one.
2. Use pole laminations with only one tip and alternate that tip, first on one side of the pole and then the other.

Both of these methods increase the reluctance of the flux path at the pole tips.

5.3 BRUSH SHIFTING

It was seen how field flux distortion causes the magnetic neutral position to shift when no precautions are taken to overcome this. (Figure 5.2.) If the brushes are moved to the magnetic neutral, the armature field axis is no longer at right angles to the main field. The armature conductors can now be divided into two distinct groups, each group producing a component of the armature field with an axis having a definite relationship to the main field axis. These groups of coils and the effect they produce are:

1. The demagnetizing ampere turns. These produce a field with the same axis as the main field but opposite in direction. The conductors that contribute to the m.m.f. producing this field are those conductors included in the angle 2 β where β is the brush shift angle. This is illustrated in Figure 5.5 where, for simplicity, a two-pole example is used.

$$\text{Demagnetizing ampere turns/pole} = \tfrac{1}{2} \times \tfrac{1}{2} \times \frac{4\,\beta}{360} \times \frac{ZI_a}{a} \qquad - \quad 5.3$$

$$= \frac{\beta\, ZI_a}{360 \times a}$$

2. The cross-magnetizating ampere turns which are formed from those conductors outside the 2 β arc in each interpolar space and which produce a field in quadrature with the main field. The resultant of these two component fields produces the actual armature field.

The number of cross-magnetizing ampere turns per pole is then found by the following method:

i) Total conductors producing field = $Z\left(\dfrac{360 - 2P\,\beta}{360}\right)$

ii) The current in each conductor will be $\dfrac{I_a}{a}$

Hence, the total cross-magnetizing ampere turns per pole become:

$$\text{Cross-magnetizing At}_{/\text{pole}} = Z\left(\frac{360 - 2P\,\beta}{360}\right)\frac{I_a}{a} \times \frac{1}{2P}$$

$$= \frac{ZI_a}{aP}\left(\frac{360 - 2P\,\beta}{720}\right) \qquad - \quad 5.4$$

In practice, if the coil span is made fractionally less than the pole pitch, some of the coils included both in the arc 2 β and also in the remainder of the winding do not carry current in the same direction and consequently the net effect in both cases will be less than the calculated effect.

Example 5.2 (*Non-examinable*)

0·4

If the brushes on a 0.5 metres diameter commutator are rocked 0.03 metres circumferentially, find (a) the demagnetizing ampere turns/pole and (b) the cross magnetizing ampere turns per pole (assume armature is lap wound).

Number of poles = 6, conductors (Z) = 378, current (I_a) = 800 amperes.

Solution

To find the magnitude of

$$\beta^\circ = \frac{0.03}{\pi \times 0.4} \times 360 = 8.60^\circ$$

(a) From equation 5.1

$$\text{demagnetizing ampere turns/pole} = \frac{\beta\ ZIa}{360a}$$

$$= \frac{8.60 \times 378 \times 800}{360 \times 6} = 1210\ \text{At}/_{\text{pole}}$$

(b) From equation 5.4

$$\text{cross-magnetizing ampere turns/pole} = \frac{ZIa}{aP}\left(\frac{360 - 2P\ \beta}{720}\right)$$

$$= \frac{378 \times 800}{6 \times 6}\left(\frac{360 - 12 \times 8.6}{720}\right)$$

$$= \frac{378 \times 800}{36}\left(\frac{256.8}{720}\right)$$

$$= 3000\ \text{At}/_{\text{pole}}$$

See Figure 5.5 on next page.

5.4 VOLTAGE OF SELF-INDUCTION

During the process of commutation, the current in an armature coil reverses its direction from + 100% to - 100%. Likewise the flux Φ_c produced by this current changes its direction. Assuming ideal, that is, linear commutation when the current and flux reverse, a constant voltage of self-induction is induced in the armature coil and according to Lenz's law opposes the changes of the current. Figure 5.6 illustrates an armature coil undergoing commutation. It will be noted that the flux path around the armature conductor is in iron rather than air and that the total change of flux is twice Φ_c.

$$\text{The voltage of self-induction } E_i = \frac{N\ 2\ \Phi_c}{t} \text{ volts} \quad - \quad 5.5$$

N = turns per coil short-circuited during commutation.

t = time during which current is reversing.

The local circuit around which E_i acts consists of the resistance of the turns in the short-circuited element, the carbon brush resistance and the contact resistance at the brush face. Because this resistance is comparatively low, heavy currents could develop causing arcing at the brushes which results in the commutator being damaged. However, as stated earlier, this can be minimized by using high resistance brush material.

The brush contact resistance plays a very important part in limiting the circulating current when the brush short-circuits the coil. From the above we can see that if an e.m.f. could be induced in the armature coil so that it counteracted the self-induced e.m.f. of the coil, there would be an improvement in the machine's commutating ability. In non-interpole machines this is achieved by moving brushes slightly until the coil undergoing commutation comes under the influence of the desired main pole flux. In practice, this means moving the brushes forward in the direction of rotation in a generator and backward in a motor. It is this movement of the brushes that produces the brush axis shift referred to in Section 5.3.

5.5 INTERPOLES AND COMPENSATING WINDINGS

Any d.c. machine operating on a fluctuating load would require continual movement of brush position to obtain reasonable commutation due to the armature field varying and moving the magnetic neutral.

See Figure 5.6 on next page.

Number of poles = 6, conductors (Z) = 378, current (I_a) = 800 amperes.

Solution

To find the magnitude of

$$\beta^\circ = \frac{0.03}{\pi \times 0.4} \times 360 = 8.60^\circ$$

(a) From equation 5.1

demagnetizing ampere turns/pole $= \dfrac{\beta\ ZIa}{360a}$

$$= \frac{8.60 \times 378 \times 800}{360 \times 6} = 1210\ \text{At}/_{\text{pole}}$$

(b) From equation 5.4

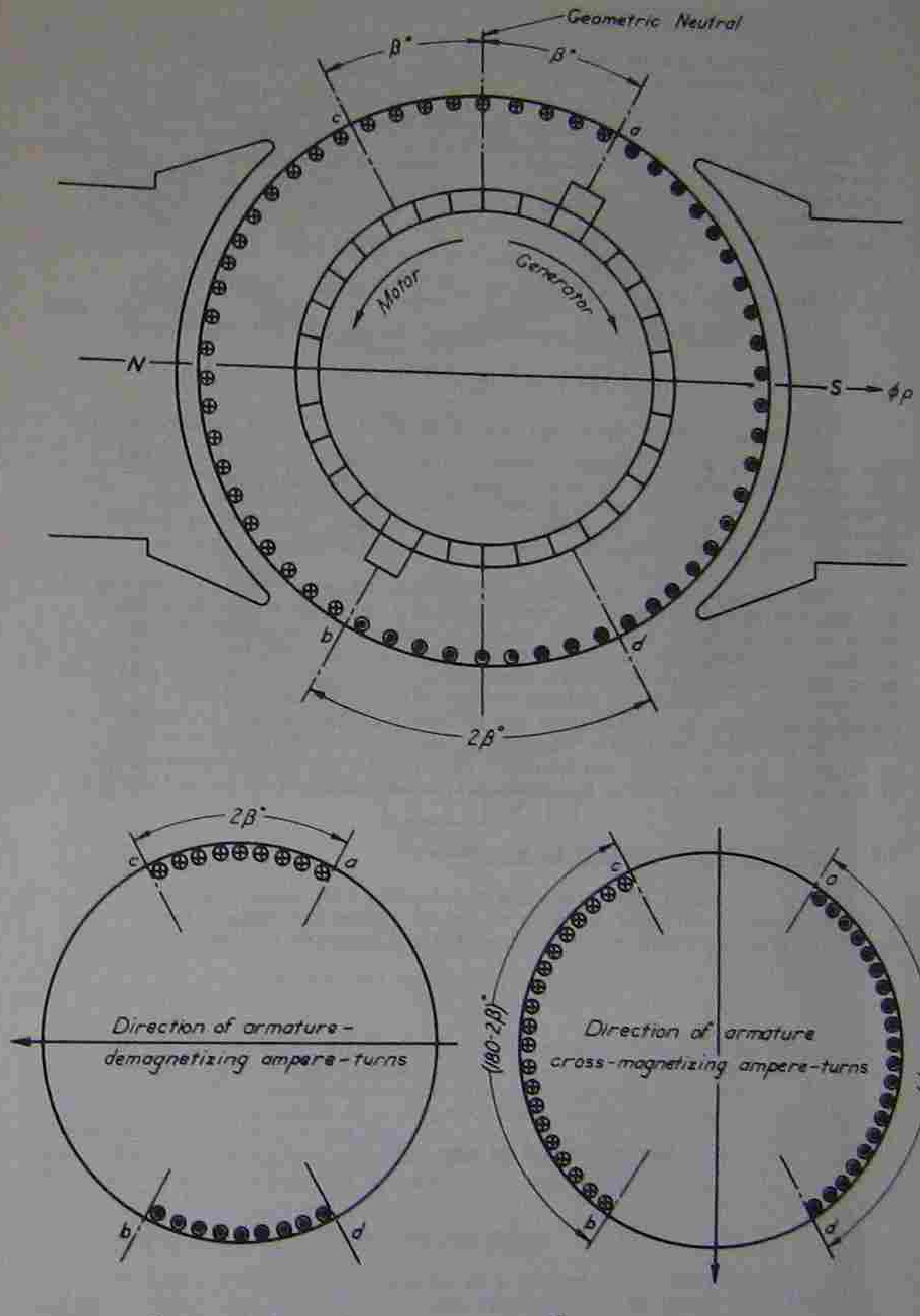
cross-magnetizing ampere turns/pole $= \dfrac{ZIa}{aP}\left(\dfrac{360 - 2P\ \beta}{720}\right)$

$$= \frac{378 \times 800}{6 \times 6}\left(\frac{360 - 12 \times 8.6}{720}\right)$$

$$= \frac{378 \times 800}{36}\left(\frac{256.8}{720}\right)$$

$$= 3000\ \text{At}/_{\text{pole}}$$

See Figure 5.5 on next page.



Demagnetizing action *Cross-magnetizing action*

Figure 5.5

Effect of Brush on Demagnetizing Ampere Turns.

5.4 VOLTAGE OF SELF-INDUCTION

During the process of commutation, the current in an armature coil reverses its direction from + 100% to - 100%. Likewise the flux Φ_c produced by this current changes its direction. Assuming ideal, that is, linear commutation when the current and flux reverse, a constant voltage of self-induction is induced in the armature coil and according to Lenz's law opposes the changes of the current. Figure 5.6 illustrates an armature coil undergoing commutation. It will be noted that the flux path around the armature conductor is in iron rather than air and that the total change of flux is twice Φ_c.

$$\text{The voltage of self-induction } E_i = \frac{N\,2\,\Phi_c}{t} \text{ volts} \quad - \quad 5.5$$

N = turns per coil short-circuited during commutation.

t = time during which current is reversing.

The local circuit around which E_i acts consists of the resistance of the turns in the short-circuited element, the carbon brush resistance and the contact resistance at the brush face. Because this resistance is comparatively low, heavy currents could develop causing arcing at the brushes which results in the commutator being damaged. However, as stated earlier, this can be minimized by using high resistance brush material.

The brush contact resistance plays a very important part in limiting the circulating current when the brush short-circuits the coil. From the above we can see that if an e.m.f. could be induced in the armature coil so that it counteracted the self-induced e.m.f. of the coil, there would be an improvement in the machine's commutating ability. In non-interpole machines this is achieved by moving brushes slightly until the coil undergoing commutation comes under the influence of the desired main pole flux. In practice, this means moving the brushes forward in the direction of rotation in a generator and backward in a motor. It is this movement of the brushes that produces the brush axis shift referred to in Section 5.3.

5.5 INTERPOLES AND COMPENSATING WINDINGS

Any d.c. machine operating on a fluctuating load would require continual movement of brush position to obtain reasonable commutation due to the armature field varying and moving the magnetic neutral.

See Figure 5.6 on next page.

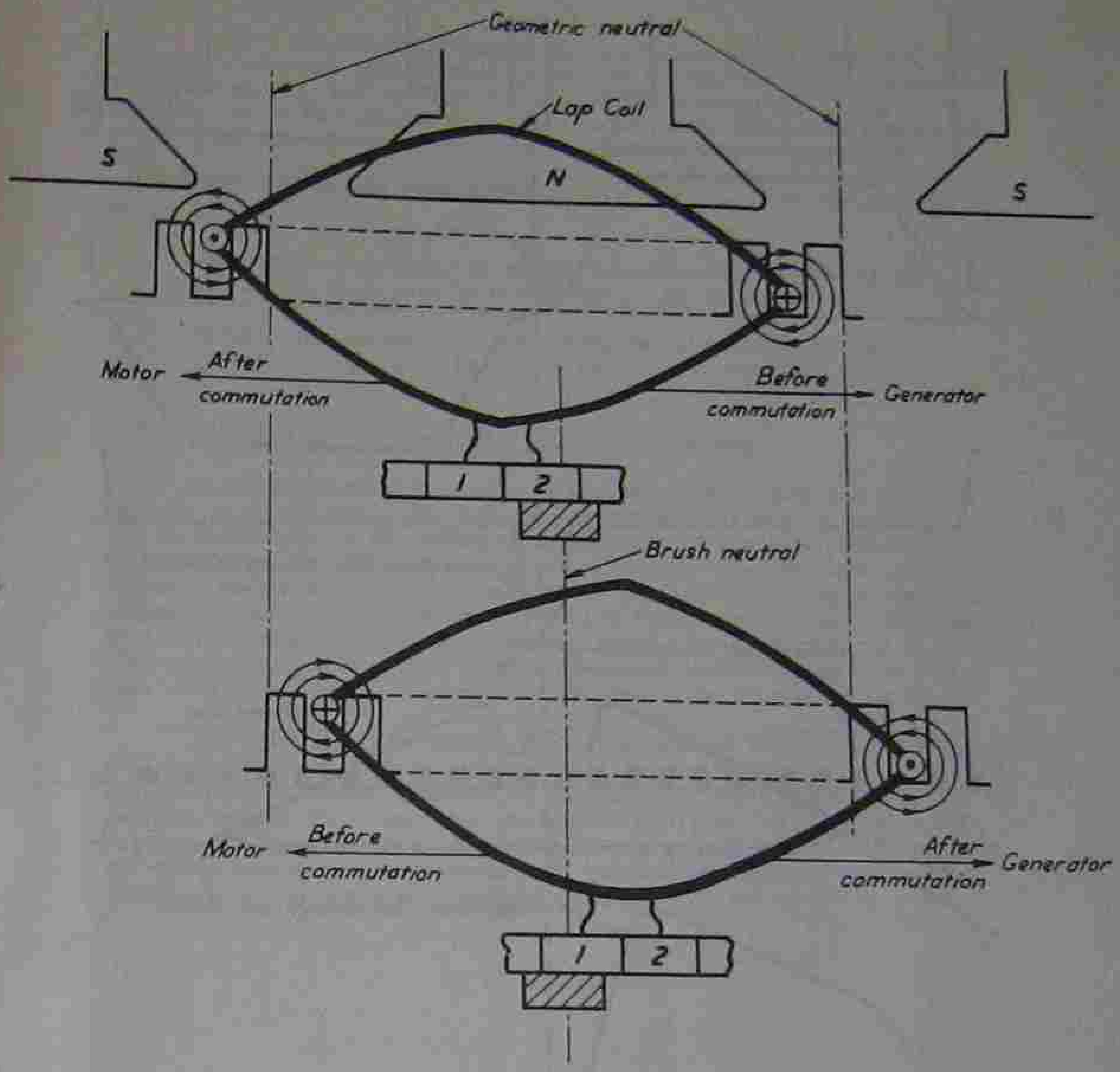


Figure 5.6

Armature Coil Undergoing Commutation

To overcome this requirement an equal and opposite field to the armature field, plus a small extra field to assist in the reversal of current in the coil undergoing commutation, is required. The former effect is obtained by means of a compensating winding, which is a winding equivalent to an armature winding, but set in the face of the main pole shoe. Its field is in the opposite sense to that of the armature. The latter effect is obtained by means of an interpole winding.

5.6 INTERPOLES OF D.C. GENERATORS AND MOTORS

As stated earlier the interpole is a narrow pole fitted in between the main poles. The winding on the pole is connected in series with the armature.

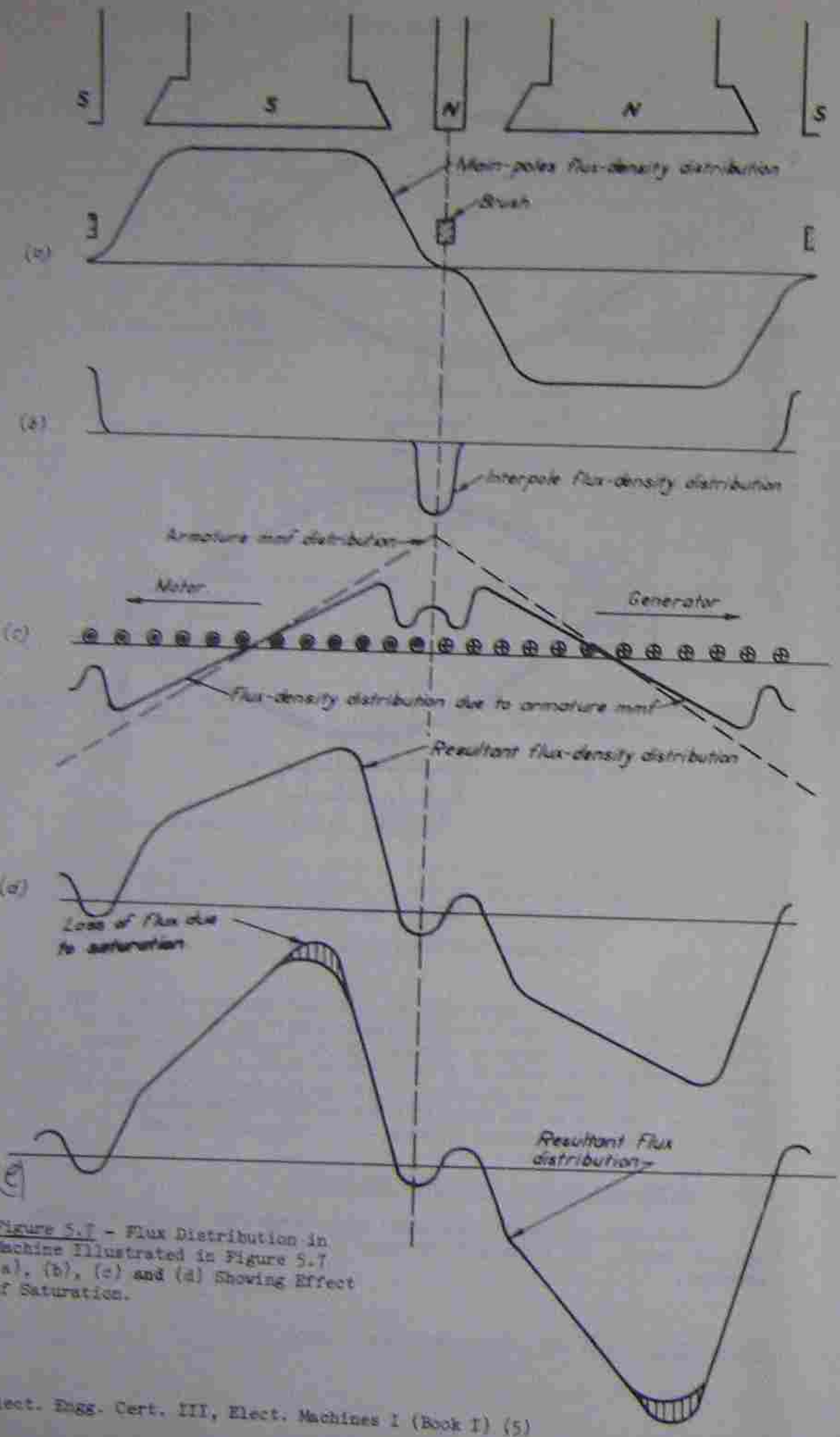


Figure 5.7 - Flux Distribution in Machine Illustrated in Figure 5.7 (a), (b), (c) and (d) Showing Effect of Saturation.

Since a compensating winding is very expensive, on small and medium sized d.c. machines this winding is omitted and the interpole winding has to compensate for all the ampere turns of the armature field plus a component which is injected into the armature coil undergoing commutation to overcome the self-inductance of the armature coil. Figures 5.7 (a), (b), (c), (d) and (e) illustrate curves of m.m.f. flux and flux density against position for an interpole machine. The rules for the polarity of the interpoles are:

Generator. The polarity of the interpole is the same as the succeeding main pole in the direction of rotation.

Motor. The polarity of the interpole is the same as the preceding main pole in the direction of rotation.

5.7 SPARKING AT THE COMMUTATOR WITH S.C.R. DRIVES

On machines used in conjunction with S.C.R. drives the armature current is not constant but includes an appreciable ripple content. Due to difference in the relative inductances of the interpole and armature circuits there will be a definite time interval between the instants that the two fields reach their maximum value. As a consequence, during one part of the commutation period the effect of the interpoles will be to over-compensate for the armature field, for another portion of the commutation period the two fields will cancel each other and for the remainder of the cycle the armature field will be over-compensated.

The sparking that results from this type of fluctuating compensation will actually vary in intensity but will appear to be constant. For this reason apparent faulty commutation indicated by the sparking will not be as injurious to the commutator surface as would be the case where the machine was supplied from a steady d.c. source. The final criterion as to the harmfulness or otherwise of commutator sparking will be the condition of the commutator after a prolonged period of use.

REVIEW QUESTIONS

1. Describe how a rotating system of conductors can produce a field that is constant in magnitude and direction.

2. Explain how the action of the armature field which causes an increase in the flux over one half of the pole and a decrease in the flux over the other half of the pole results in a net decrease in the total flux.

3. Why are there two expressions (namely equations 5.1 and 5.4) for calculating the cross-magnetizing ampere turns per pole?

4. Explain the difference in the function of commutating poles and compensating winding.

5. What are two ways in which the self-induced voltage in a coil undergoing commutation can be opposed?

ASSIGNMENTS

Marks

ASSUME INTERPOLES

15 1. The power input to an 8-pole 500 volt d.c. motor is 200 kW. If the armature is lap wound and comprises 2000 effective conductors, calculate the cross-magnetizing ampere-turns.

Additional data:

field circuit resistance - 100 Ω
surface length of pole face - 400 mm
diameter of armature - 1.2 metres.

15 2. A coil of two turns when not being commutated can be considered to be in a flux of 0.002 Wb. Calculate the e.m.f. induced in the coil if the commutator is rotating at 1500 r.p.m. and contains 240 segments. Each brush can be assumed to short-circuit three segments. What would be the maximum speed if the induced e.m.f. must be limited to 12 volts?

1125 RPM

20 3. A d.c. motor armature develops a cross-magnetizing m.m.f. of 3000 ampere turns. If the main fields of the motor each are wound with 4500 turns, calculate the value for the term ΔI_f shown in Figure 5.1.

25 4. The commutator of a d.c. motor has a diameter of 600 mm and the relationship between the armature and main field is such that if the brushes are moved to coincide with the magnetic neutral axis this involves a shift of 12 commutator segments. If the armature is wound with 720 elements, each having one turn and the machine is 4-pole lap wound, calculate:

a) β,

b) cross-magnetizing ampere-turn,

c) demagnetizing ampere-turns,

if Ia is 500 amperes.

25 5. Repeat Problem 4 assuming that the movement of the brushes represents a distance of 20 mm on the commutator diameter. In addition, determine the extent of the brush movement in terms of the number of segments.

ELECTRICAL MACHINES I

WH 6

UNIT No. 6

DIRECT CURRENT MACHINES

This unit will cover the following topics:

6.1 Percent voltage regulation.

6.2 Loading a generator.

6.3 Polarity of self-excited generators.

6.4 Control of terminal voltage.

Review Questions.

Assignments.

- - - -

6.1 PERCENT VOLTAGE REGULATION

When load is applied on a self-excited shunt generator the terminal voltage will drop due to three effects. These are:

1. The drop in the resistance of the armature windings which is termed the Ia Ra drop.
2. The effects of the increased armature field on the main field which will decrease the effective flux.
3. The resultant drop in V_t due to 1. and 2. will cause a drop in the field current which is a function of V_t. This, in turn, will decrease the generated e.m.f. The ratio of the change in terminal volts due to load to the load volts expressed as a percentage is termed the percentage regulation.

In terms of the British Standard Specification:

> *The Inherent regulation of a d.c. self-excited generator is defined as the maximum change in voltage, expressed as a percentage of rated voltage, occurring at any load, when the load changes from full load (at rated voltage and speed) to any lower load, including no load, without change in speed and without adjustment of the excitation circuit.*

That is:

$$\text{Percent regulation} = \frac{E_g - V_{FL}}{V_{FL}} \times 100 \qquad - \qquad 6.1$$

V_{FL} = full load (rated volts)

E_g = no load or open circuit (generated) volts.

Or, in general:

$$\text{Regulation} = \frac{E_g - V_t}{V_t} \qquad - \qquad 6.2$$

where V_t represents the terminal voltage.

Example 6.1

V_{FL} of a shunt generator is 480 volts. What is the percent regulation if the open circuit voltage is 510?

Solution

Using equation 6.1

$$\text{Percent regulation} = \frac{510 - 480}{480} = 6.25\%$$

Example 6.2

A 75 kW 500 volt generator has a voltage regulation of 4%.

Calculate:

(a) the open circuit volts; and

(b) assuming the voltage varies uniformly between no load and full load current, calculate the kW output for a terminal voltage of 510.

Solution

From equation 6.1

$$\text{(a)} \qquad 4 = \frac{E_g - 500}{500} \times 100$$

$$\frac{500 \times 4}{100} + 500 = 520 \text{ volts.}$$

$$\text{(b)} \qquad \text{Full load current} = \frac{75000}{500} = 150 \text{ amperes}$$

$$I_{510} = I_{520} \times \frac{520 - 510}{520 - 500}$$

$$= 150 \times \frac{10}{20}$$

$$= 75 \text{ amperes.}$$

$$\therefore \quad \text{Output} = 510 \times 75 \times 10^{-3}$$

$$= 38.25 \text{ kW}$$

6.2 LOADING A GENERATOR

To completely specify the manner in which a generator behaves under load conditions particularly with regards the behaviour of the terminal voltage, the following relationships are required:

$$E_g = f(I_f, N) \quad - \quad 6.3$$

$$V_t = E_g - Ia\ Ra \quad - \quad 6.4$$

$$I_f = \frac{V_t}{R_f} \quad - \quad 6.5$$

$$I_f{}^1 = I_f - \Delta I_f \quad - \quad 6.6$$

$$\Delta I_f = f\ (Ia) = k\ Ia \quad - \quad 6.7$$

and assuming that $Ia = I_L$

$$Ia = \frac{V_t}{R_L} \quad - \quad 6.8$$

Regarding these expressions the following comments should be made:

i) For constant speed the expression 6.1 can be represented by the magnetization curve of the generator.

ii) Equation 6.6 is true for separately excited generators but the assumption introduces a small error in self-excited generators due to the field current, I_f. At full load this will be about 5% of the full load current but an error of this magnitude can be neglected in practical applications due to the fact that a graphical solution is being used.

At first glance the simultaneous solution of the set of equations listed above appears a formidable task as the list includes 12 variables. Practical purposes can be considerably simplified by the imposition of restraints which, in effect, assign constant values to a number of these variables. The more usual of these restraints are:

1) *The terminal voltage* (V_t) - This quantity may be considered constant where a machine is connected to a grid system in which the total input power is greater than ten times the power supplied by the generator concerned. For this analysis, however, where the emphasis will be on the output characteristic of the given machine V_t is the variable which will be the final criterion of machine behaviour. The purpose of the analysis will be to obtain a relationship between V_t and I_a.

2) *The field circuit resistance* (R_f) - In practice, this factor generally is varied by some control device in order to give a constant V_t. For this analysis the field resistance will be held constant to give a valid comparison of the behaviour.

---

3) *The speed* (N) - In order to simplify the analysis the speed is assumed to be constant which, in practice, would be the case with a governed prime mover.

4) *The armature* RESIST (R_a) - This factor is assumed to be constant as in practice it is unlikely that any variation would be made in the armature resistance.

A) Separately Excited Machines

a) *No demagnetizing effect.*

Special Note: The block diagram representations used in this analysis are essential either to the explanation or the end result. They are included, primarily, simply as a means of representing the relationship between the various quantities. In a lesser sense they serve as an introduction of this type of representation in applications where the output of a system can exercise some control over the input. If the block diagrams present any difficulty to the student they can be completely ignored.

The use of block diagrams will be covered more fully in control engineering subjects where the time constants of the various systems are considered.

Where the effects of demagnetization are neglected only equations 6.3, 6.4 and 6.8 apply.

Although some operational and design restraints have been imposed, equation 6.8 still has two unknown variables. To simplify the problem, which is to find V_t for a given load current, a value of Ia will be assumed as a reference quantity. With Ia as the independent variable the simultaneous relationship can now be solved to give the required value of V_t.

To solve for V_t in separately excited machines, it is customary to assume a no load value of E_g. Under these circumstances, the problem now simplifies to a solution of equation 6.4.

The relationship between these equations can be illustrated as shown in the block diagram of Figure 6.1.

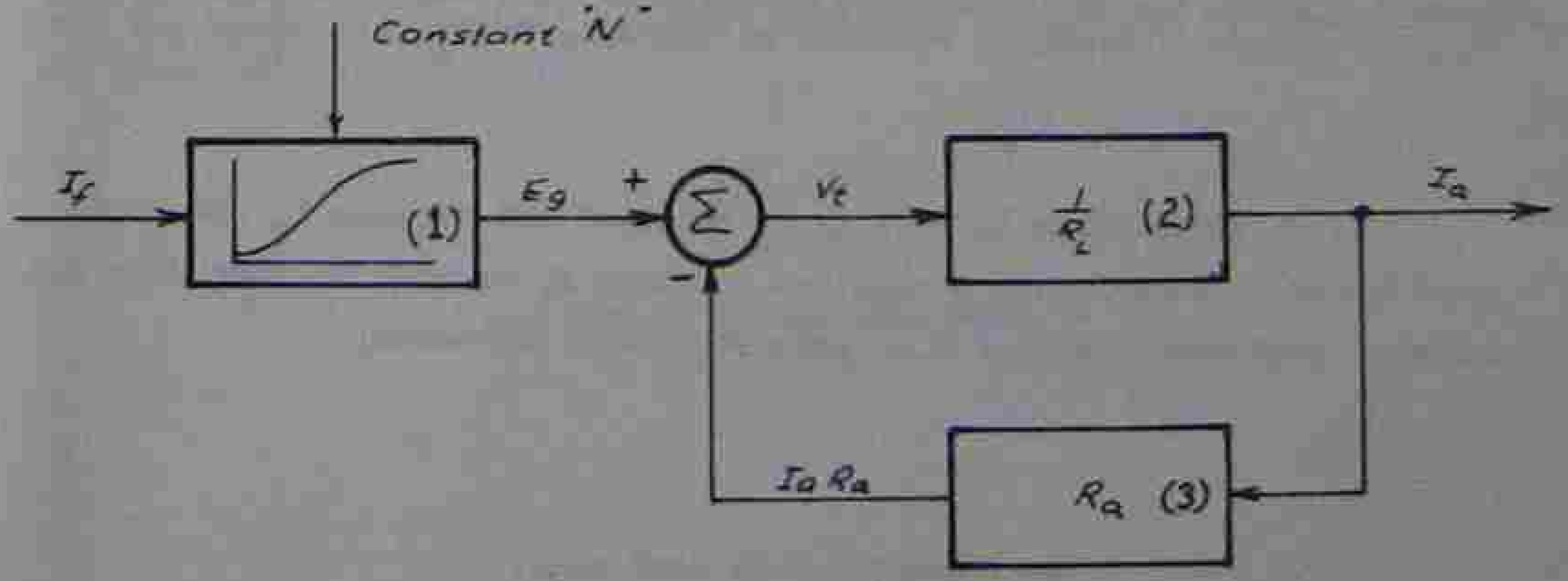


Figure 6.1 - Block Diagram for Self-Excited Machine - No Demagnetization.

The system shown in Figure 6.1 can be considered as having one output variable, the armature current denoted by I_a and two input variables, the speed (N) and the field current (I_f). It is assumed that the armature resistance (R_a) and the load resistance (R_L) are constant.

In the diagram block 1 represents the relationship between the generated e.m.f. (E_g) the field current (I_f) and the armature speed. Thus for a constant speed the input N can be neglected and the output of the block (E_g) is then a function of I_f only. This is indicated by the diagram in the block which represents the magnetization curve of the machine. Thus any variation in I_f produces a corresponding variation in E_g. The non-linearity of the relationship is indicated by the curve.

The next circle enclosing the symbol Σ is a summing point. As both E_g and $I_a R_a$ are shown as entering the summing point and V_t is shown as leaving the junction this implies that

$$V_t = E_g - I_a R_a$$

This is the relationship expressed in equation 6.4.

At block 2, the input is the output from the summing junction. As given by equation 6.4 this is the terminal voltage V_t. The output from block 2 is the input multiplied by the gain of the block. That is

$$I_a = V_t \times \frac{1}{R_L}$$

$$= \frac{V_t}{R_L}$$

A feed-back loop links the output to the input through block 3. The output of block 3, $I_a R_a$, is fed to the summing junction. The fact that this is a subtractive input is denoted by the minus sign.

In Figure 6.3, and in following figures, where the gain of the block is unknown this is undefined. For example, in the armature reaction feed-back loop since the effect of armature reaction cannot be defined without a knowledge of the machine the gain of this block is denoted by K. Thus the effect of armature reaction on the main field is:

$$\Delta I_f = KI_a$$

As an alternative to holding R_L constant and varying I_f the usual practice is to hold I_f and N constant and vary R_L as will be seen when the external characteristics of d.c. generators are discussed.

See Figure 6.2 on next page.

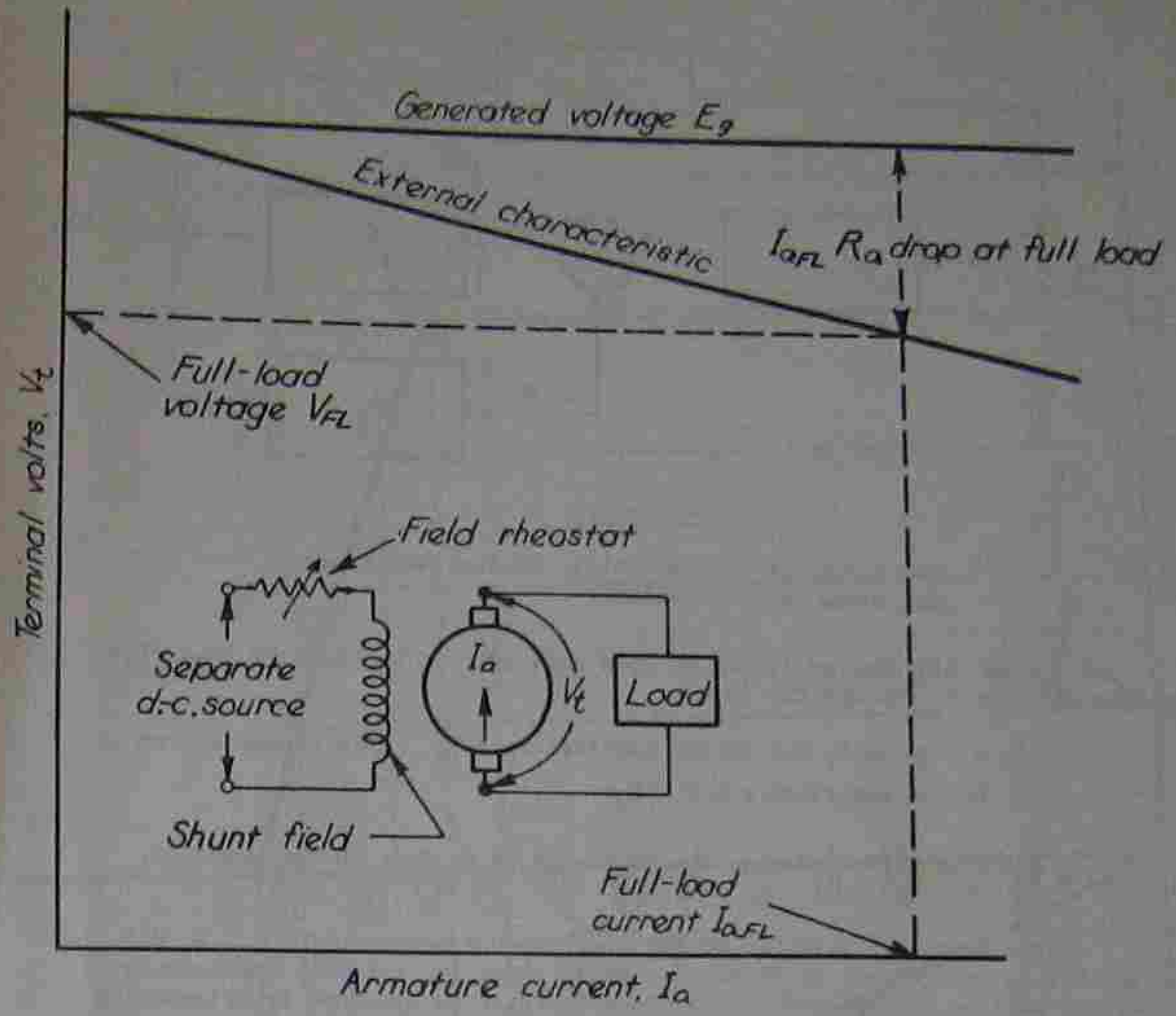


Figure 6.2

External Characteristic of Separately-Excited Machine - No Demagnetization.

B) With Demagnetization

Where the effects of demagnetization are neglected in separately excited generators, there is no real problem if the correct restraints are imposed. To introduce the effects of demagnetization involves the inclusion of equations 6.6 and 6.7 into the problem with the consequent increase in the difficulty of the analysis. The modified block diagram for the separately excited machine, including the effects of demagnetization, is shown in Figure 6.3.

See Figure 6.3 on next page.

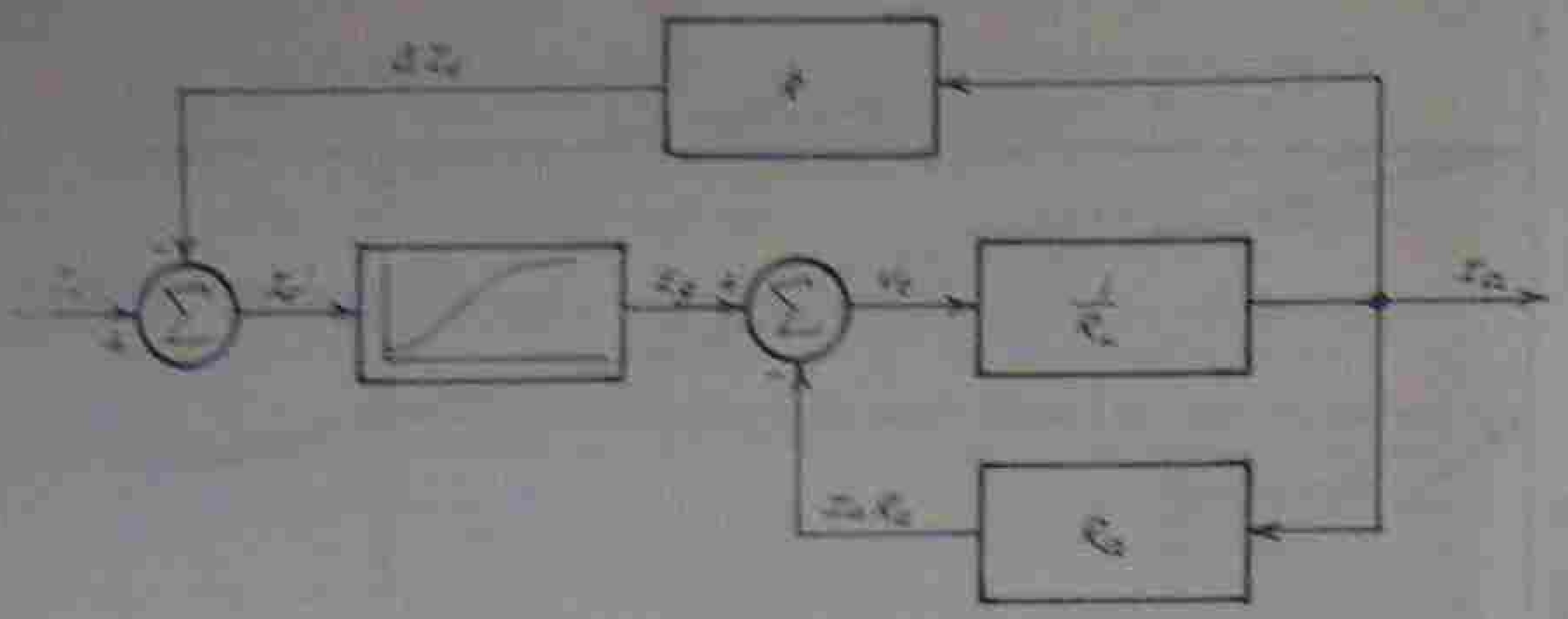


Figure 6.3

Block Diagram for Separately Excited Machines - Including Demagnetization.

From this diagram it can be seen that with an increase in load (Ia) the value of V_t changes due to

1) A drop in I_f due to the increase in ΔI_f. This causes a drop in the generated e.m.f. (E_g).

2) A drop in V_t due to the increased Ia Ra drop in the armature.

The graphical solution to the simultaneous equations 6.3, 6.4, 6.6 and 6.7 is carried out in Figure 6.4 which shows the external characteristic of the machine in question. This characteristic is obtained by determining the value of V_t at 25%, 50%, 75%, 100% and 125% of full load current.

See Figure 6.4 on next page.

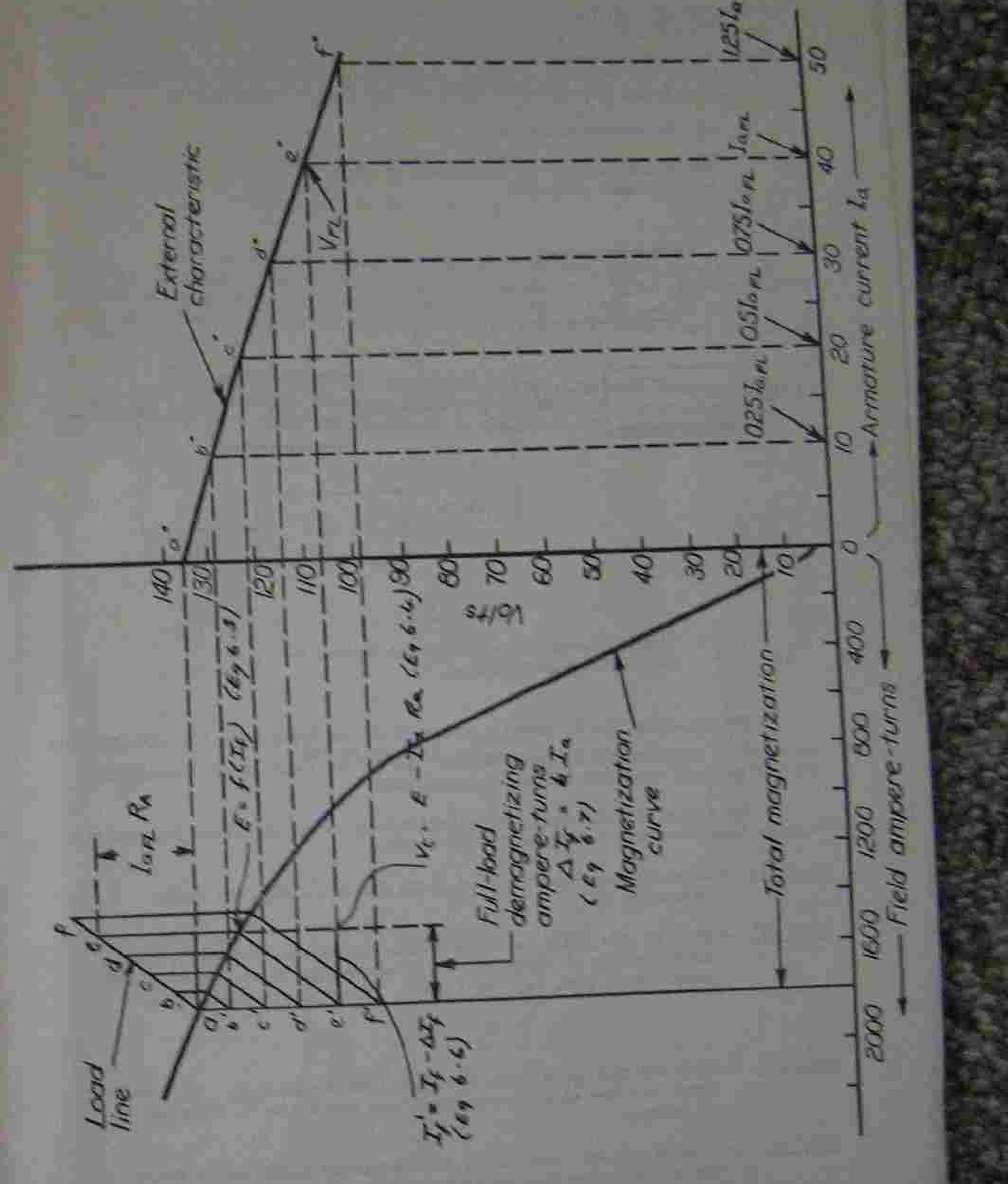


Figure 6.4

Graphical determination of external characteristic separately excited shunt generator with demagnetization.

c) Self-Excited Machines

In self-excited machines the field current, and hence the generated e.m.f., is a function of the terminal voltage. As a consequence, the block diagram for this type of machine must include a link between the field current and the terminal voltage. Mathematically, this is represented by equation 6.5 and this equation must be included in the analysis.

a) *No demagnetisation.*

The block diagram for this case is shown in Figure 6.5 where the V_t-I_f link has been included.

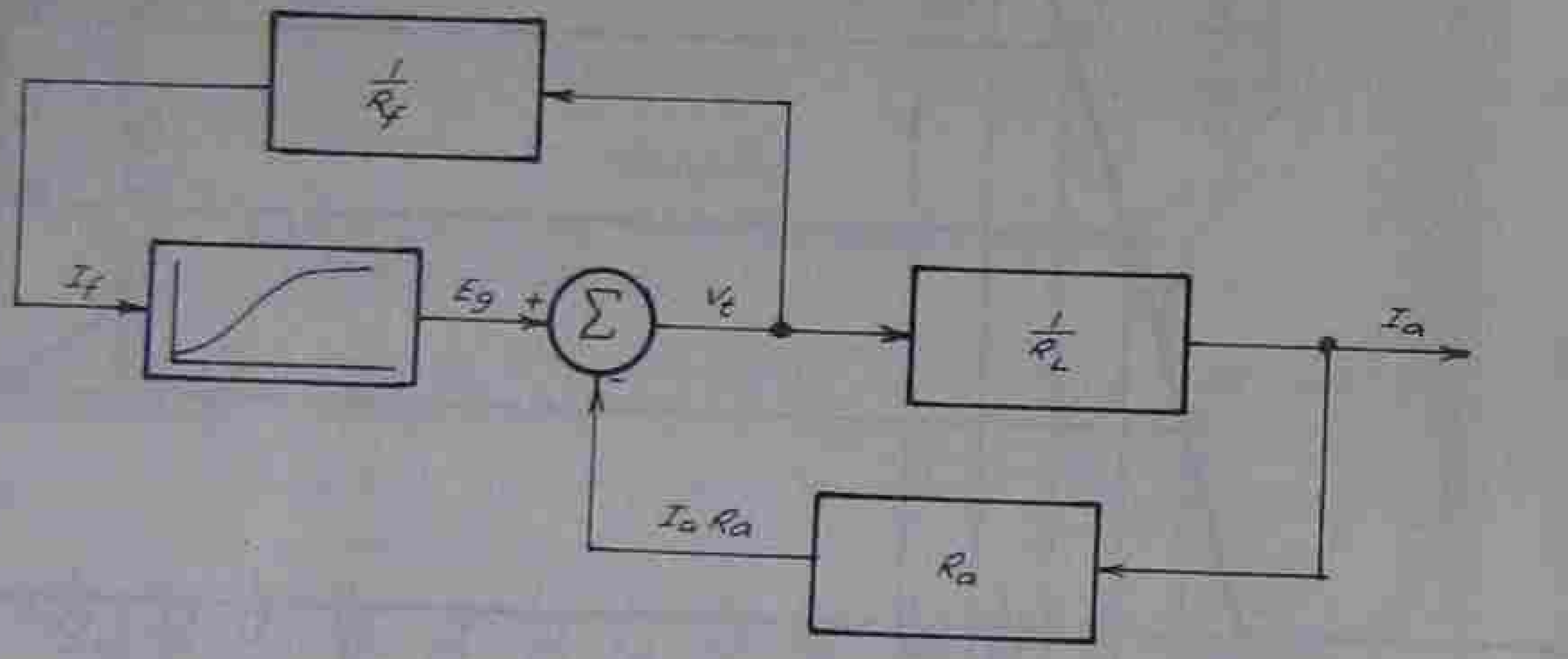


Figure 6.5

Block Diagram of Self-Excited Generator - Without Demagnetization.

The solution for V_t given a value of Ia is found from the simultaneous solution of equations 6.3, 6.4 and 6.5. As in the case of the separately excited machine equation 6.8 can be neglected.

The steps in obtaining this solution are shown in Figure 6.6 and the correct procedure may be summarized as follows:

Step (1) - draw in the magnetization curve for the specified speed (equation 6.3).

Step (2) - draw in the field resistance line (from equation 6.5); the intersection of these curves gives the solution for no load conditions, that is, for Ia = 0. Under these conditions

$$V_t = E_g$$

Step (3) - mark off the Ia Ra drop for full load conditions. Note that there are two alternative positions where the Ia Ra drop can be located.

Step (4) - from practical conditions, the operation position is found where the difference between the generated e.m.f. and the terminal voltage is equal to the Ia Ra drop (equation 6.4).

This is found by drawing a line parallel to the resistance line. The intersection of this line and the magnetization curve gives the full load value of E_g.

Step (5) - the point on the resistance line directly below the point found in Step 4 will give the full load V_t.

It will be noted that at this point

$$f\,(I_f,\ N) - \mathrm{Ia\ Ra} = I_f\,R_f \qquad - \qquad 6.9$$

From the curve it will also be observed that there is a second point that satisfies the above equation (equation 6.9) but, it will be seen when the external characteristic is plotted, this second point (5') is in the unstable operating range and, in practice, this point can be neglected.

The complete external characteristic of a machine between no load and 125% full load is shown in Figure 6.7 where, for convenience, the solution of the foregoing equations is placed in the second quadrant.

See Figure 6.6 on next page.

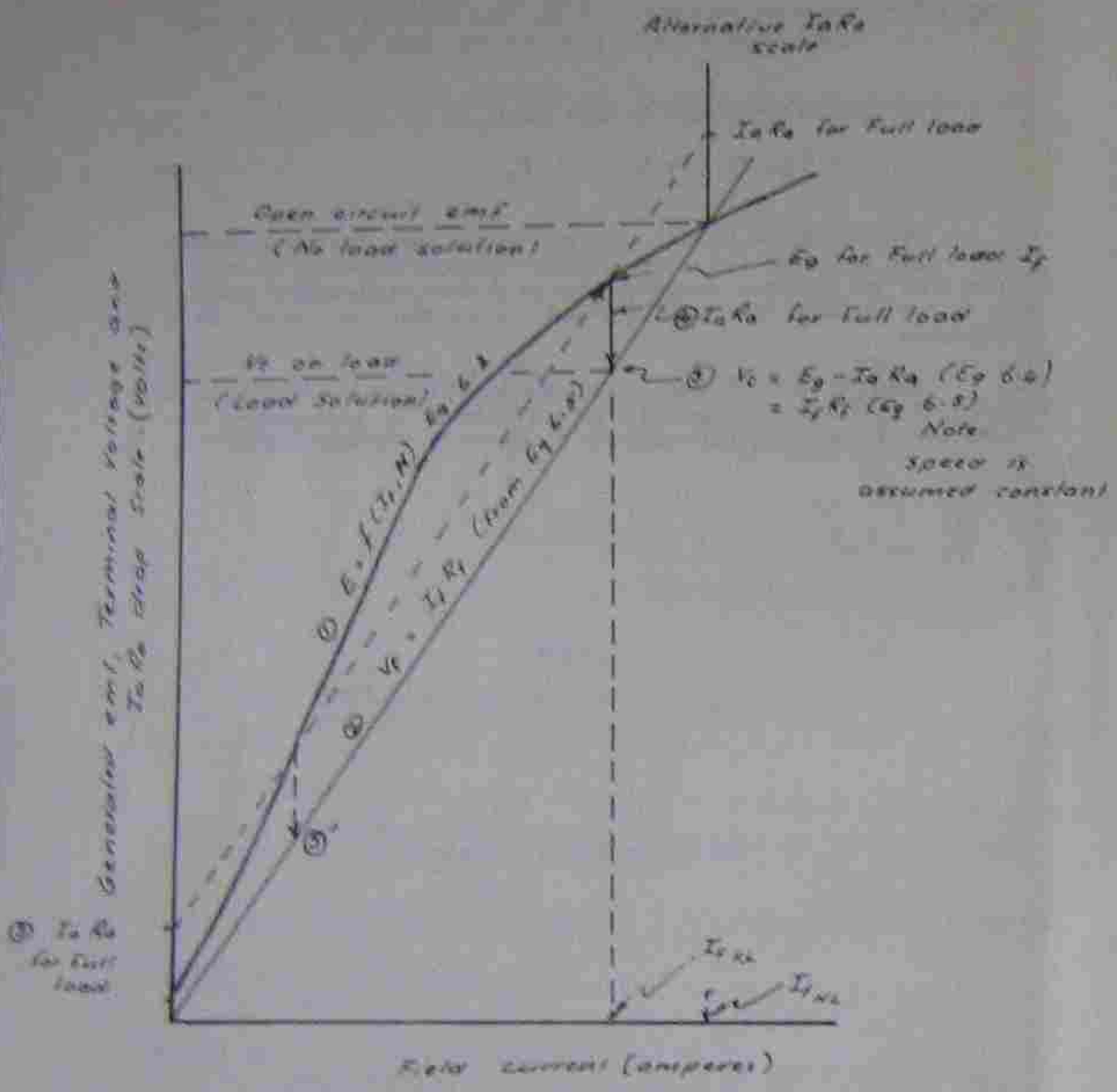


Figure 6.6

Diagram illustrating the sequence of operations to obtain V_t for a given Ia.

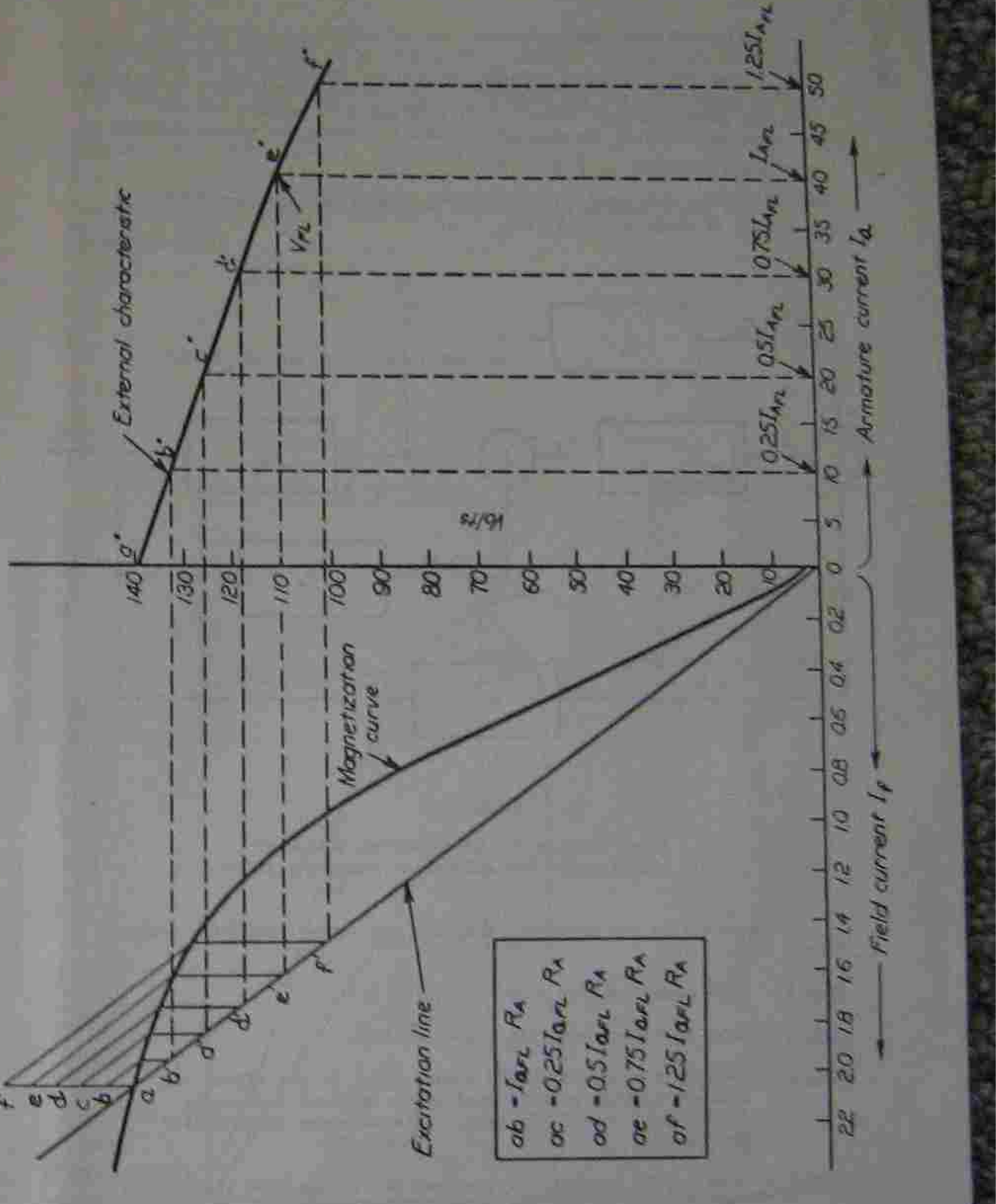


Figure 6.7

External Characteristic of Shunt Generator - No Demagnetization.

b) *With demagnetization.*

When the effects of demagnetization are considered with self-excited generators all the equations, 6.3 - 6.8 inclusive, are considered with the provision that values of Ia will again be assumed and the relevant values of V_t determined in order to obtain the representative load characteristic of this class of generator.

The block diagram representing the relationship between the equations is shown in Figure 6.8.

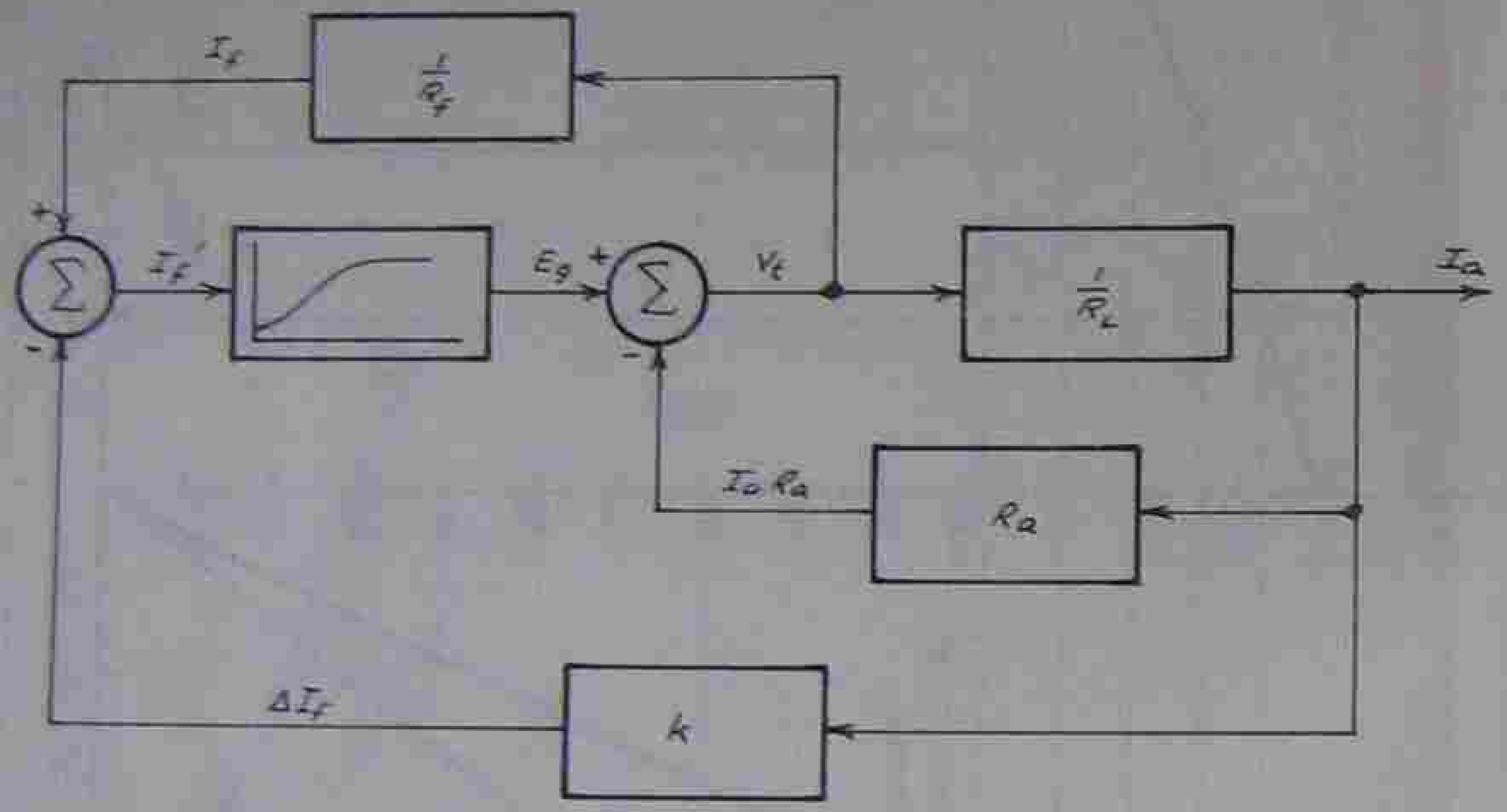


Figure 6.8

Block Diagram for Self-Excited Generator
Allowing for the Effects of Demagnetization.

③

The steps in the graphical analysis are summarized below (refer Figure 6.9).

Step 1 - Draw magnetization curve (equation 6.3).

Step 2 - Draw in resistance line (equation 6.5).

Step 3 - Construct triangle having a base equal to the effect of demagnetization at full load and a vertical side equal to the full load Ia Ra drop. This is known as a "Potier Triangle".

Step 4 - Draw a line parallel to the resistance line from the apex of the triangle to cut the magnetization curve.

Step 5 - From the point obtained in Step 4 draw a line parallel to the hypotenuse of the triangle. The intersection of this last line and the resistance line will give the load terminal voltage.

From the diagram it can be seen that the conditions in the machine associated with the particular value of V_t satisfy all the relationships given in the equations. Once more, it will be observed that there are two values of V_t that could satisfy the relationship but the lower value is obtained after the machine has passed through the stable operating region. This value is of no practical consequence.

In both of the cases where self-excited machines are considered the current on short circuit, that is $V_t = 0$, will be found from equation 6.4.

$$Ia_{sc} = \frac{E_g}{Ra}$$

Where E_g is due to residual only as $I_f = 0$.

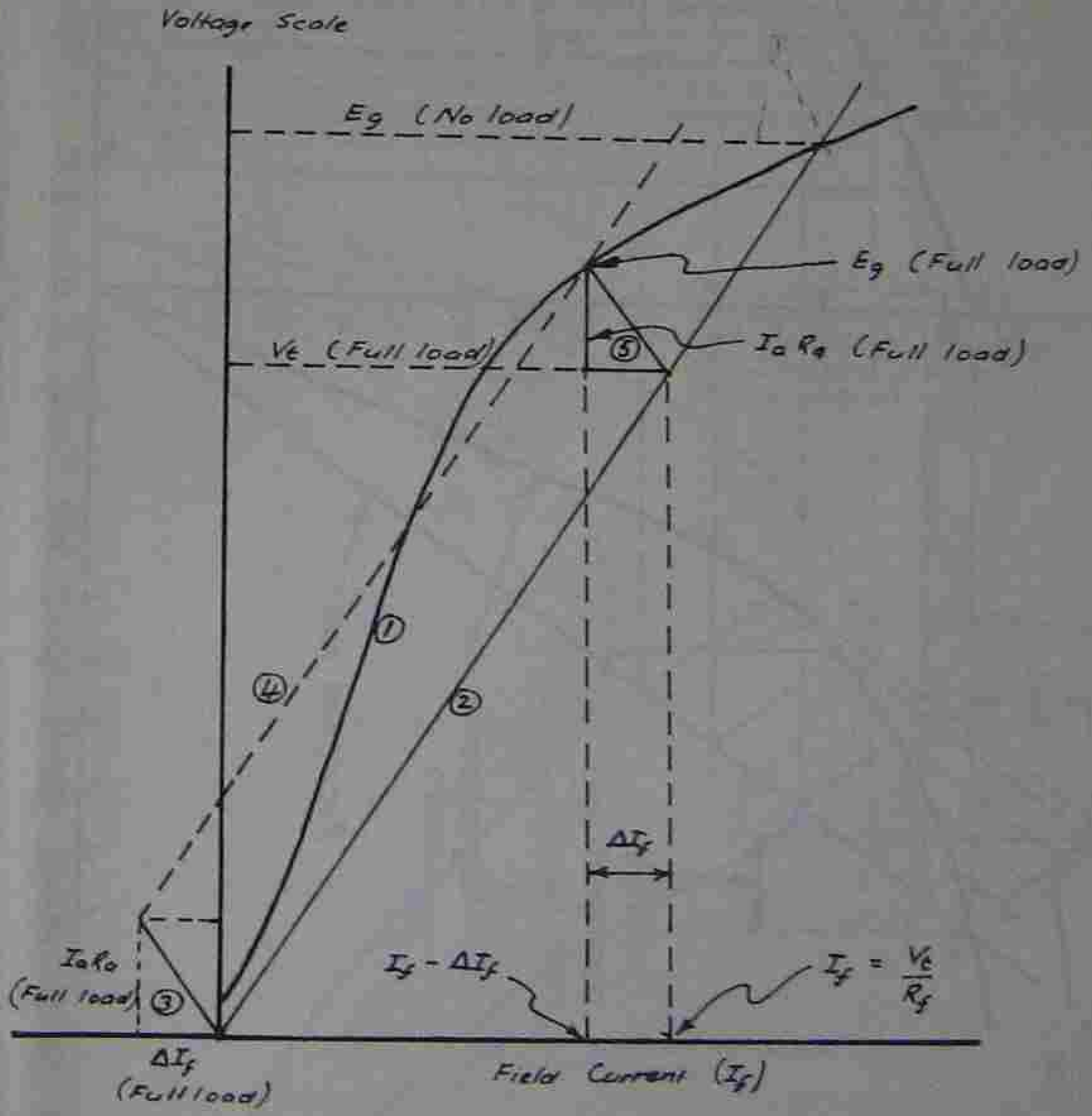


Figure 6.9

Steps in the graphical determination of V_t from a given value of Ia.

Figure 6.10 shows a complete external characteristic of a self-excited machine where the effects of demagnetization have been included. In this diagram, for convenience, the magnetization curve has been placed in the second quadrant.

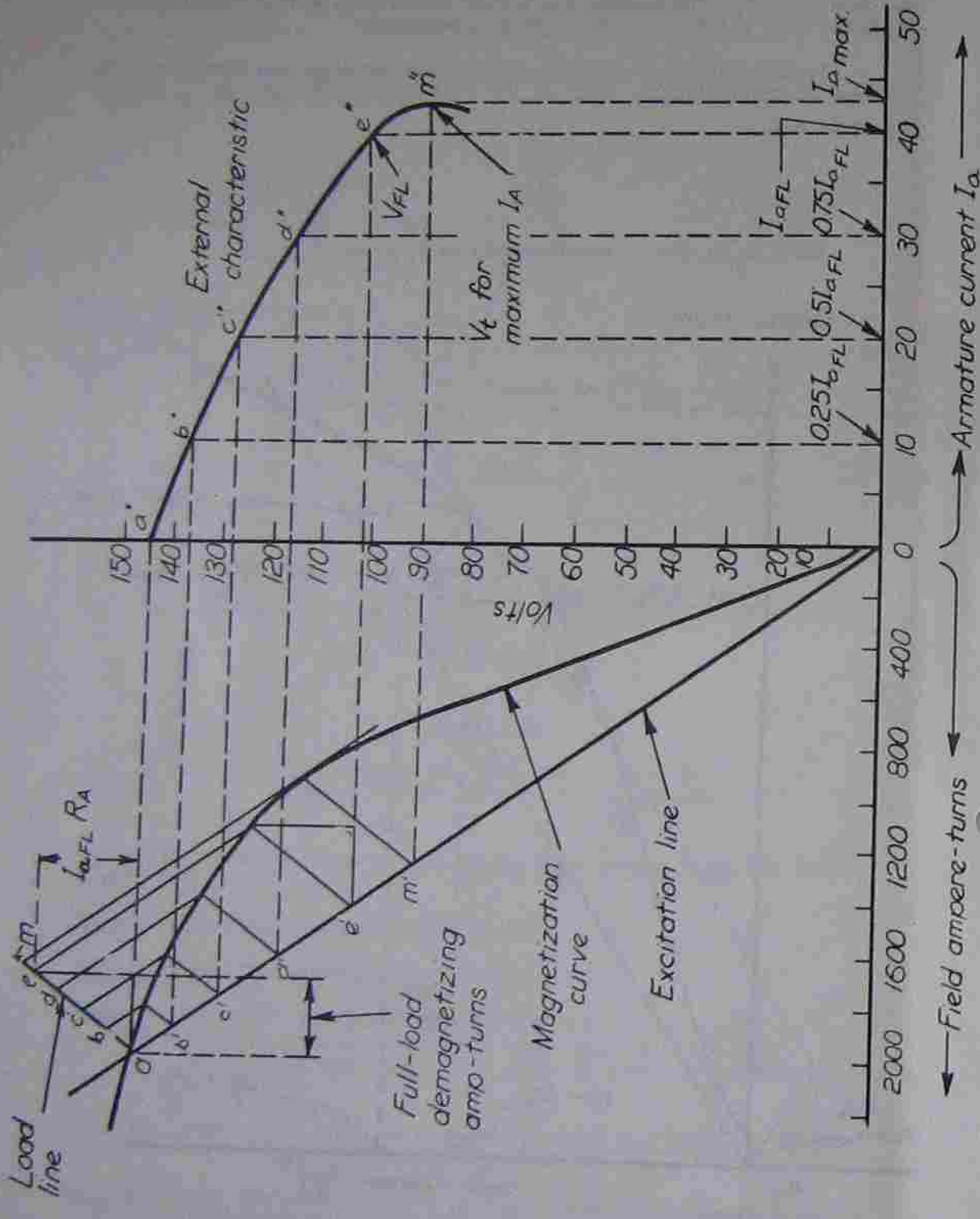


Figure 6.10

External Characteristic of Self-Excited Machine. Demagnetization included.

Where, in addition to the shunt field winding, a self-excited generator has a series winding this is termed a compound connection. The analysis of compound machines is possible but difficult due to:

1) The variation of the effect of the series field with variations in load current, although this can be treated in the same manner as the armature reaction but as a positive ΔI_f where ΔI_f is a function of Ia.

2) The fact that the series field m.m.f. can either assist or oppose the shunt field m.m.f.

Figure 6.11 shows the comparison between a shunt connected generator and a machine in which the series m.m.f. opposes the shunt m.m.f. This is termed a differential compound machine.

As a final summary on the external characteristics of d.c. generators, Figure 6.12 shows a comparison of the characteristics of a number of different methods of connection where it is required that the machines each have the same terminal voltage at full load. The three cumulative compound characteristics represent different ratios of shunt to series full load ampere turns.

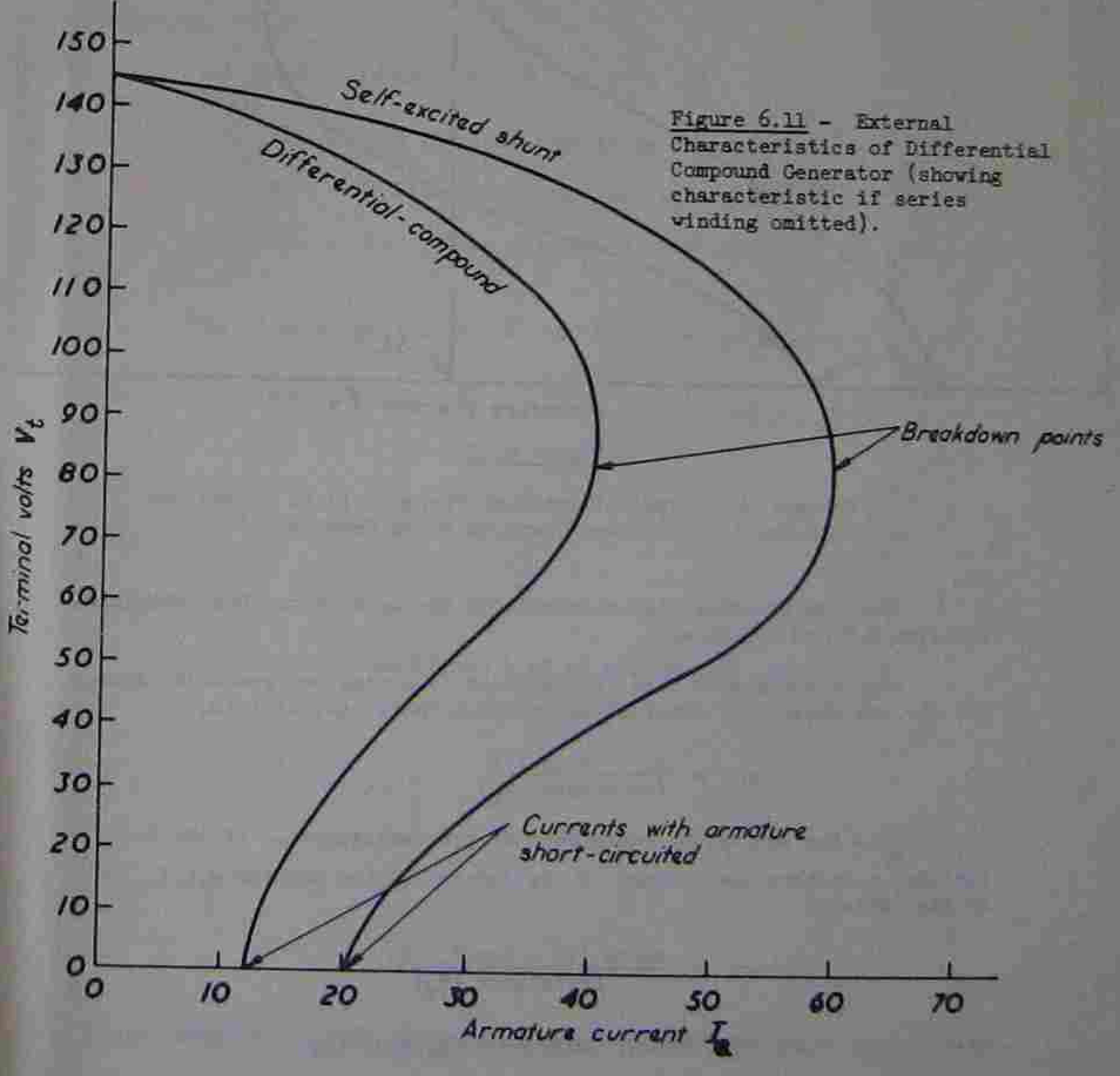


Figure 6.11 - External Characteristics of Differential Compound Generator (showing characteristic if series winding omitted).

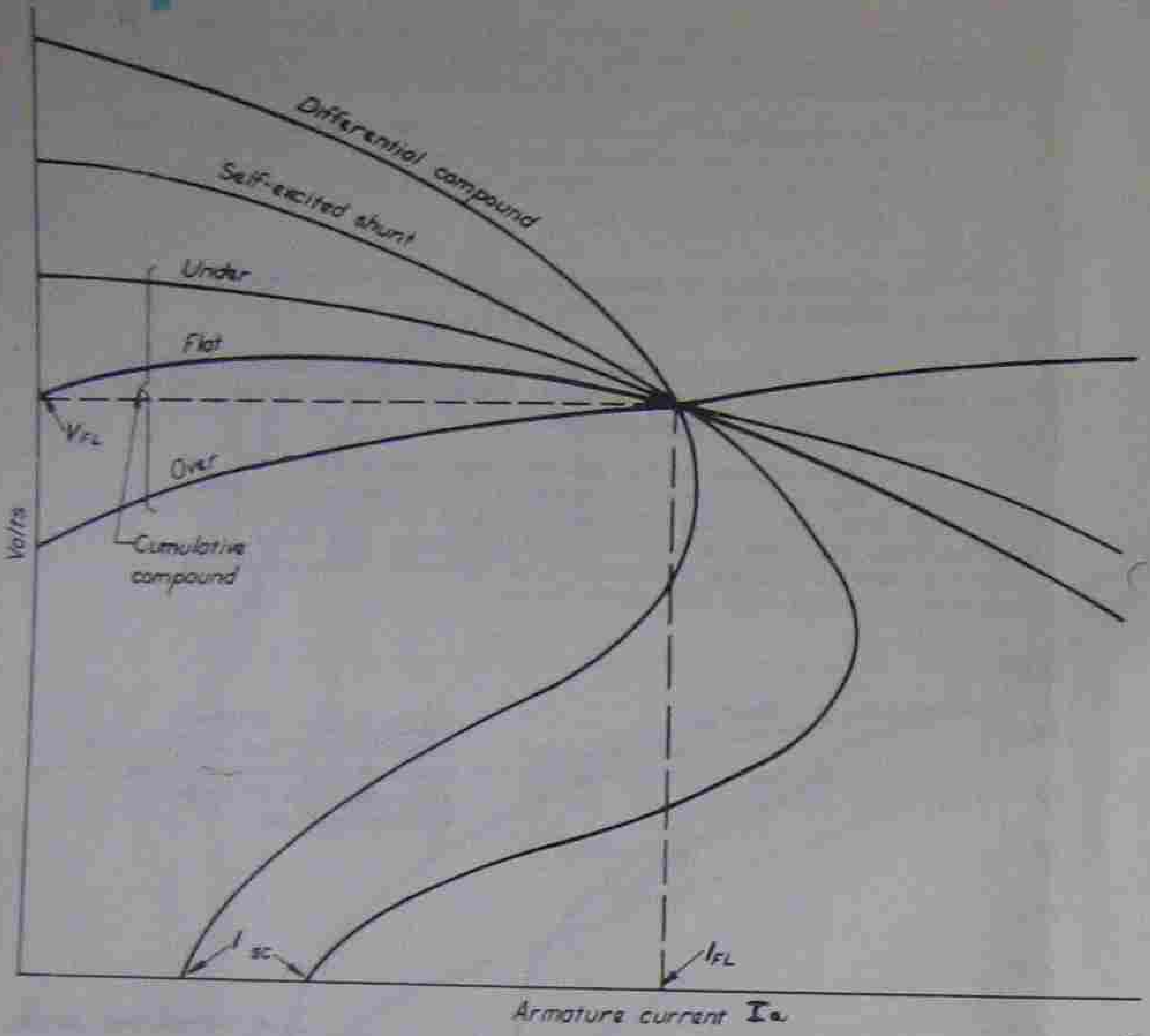


Figure 6.12

Comparison of Typical External Characteristic Curves for Self-Excited Shunt and Compound Wound Generators.

Once the external characteristic of the machine has been obtained equation 6.8 can be solved.

When a resistance load is connected to a constant potential supply the current flowing is obtained by applying Ohm's law, that is,

$$\text{current} = \frac{\text{volts } (V)}{\text{resistance } (R_E)}$$

where R_E is the equivalent resistance of the resistances. If the load includes a battery the voltage V is reduced by the counter e.m.f. (E) of the battery.

$$\text{current} = \frac{\text{volts } (V) - \text{e.m.f. } (E)}{\text{resistance } (R_E)}$$

In dealing with generators where the voltage varies with load, it is only with great difficulty that mathematical equations can be used to calculate current flowing. It is far easier to again apply a graphical method. As the resistance of the load can be expressed as the ratio $\frac{\text{volts}}{\text{amperes}}$, the resistance line or load line can be drawn as a straight line on the graph and where this line crosses the external characteristic of the generator, the voltage and current for that equivalent load resistance can be obtained. This is shown in the following examples:

Example 6.1

The external characteristic of a self-excited shunt generator is as follows:

Terminal volts	144	142	136	133	127	120	108	100
Line amperes	0	10	20	30	40	50	60	65

Determine (a) the load voltage and current for a load resistance of two ohms;

(b) the load resistance and current for a generator terminal voltage of 120 V. Figure 6.13 shows the graphic solution.

Solution

(a) load resistance $= \frac{V_t}{I_L} = 2 = \frac{80}{40}$

this enables the load line to be drawn.

Where this line intersects the characteristic,

$V_t = 113$ volts and $I_L = 56.5$ amperes

(b) from graph; for $V_t = 120$ V, $I_L = 50$ amperes

hence $R_E = \frac{120}{50}$

$= 2.4$ ohms.

See Figure 6.13 on next page.

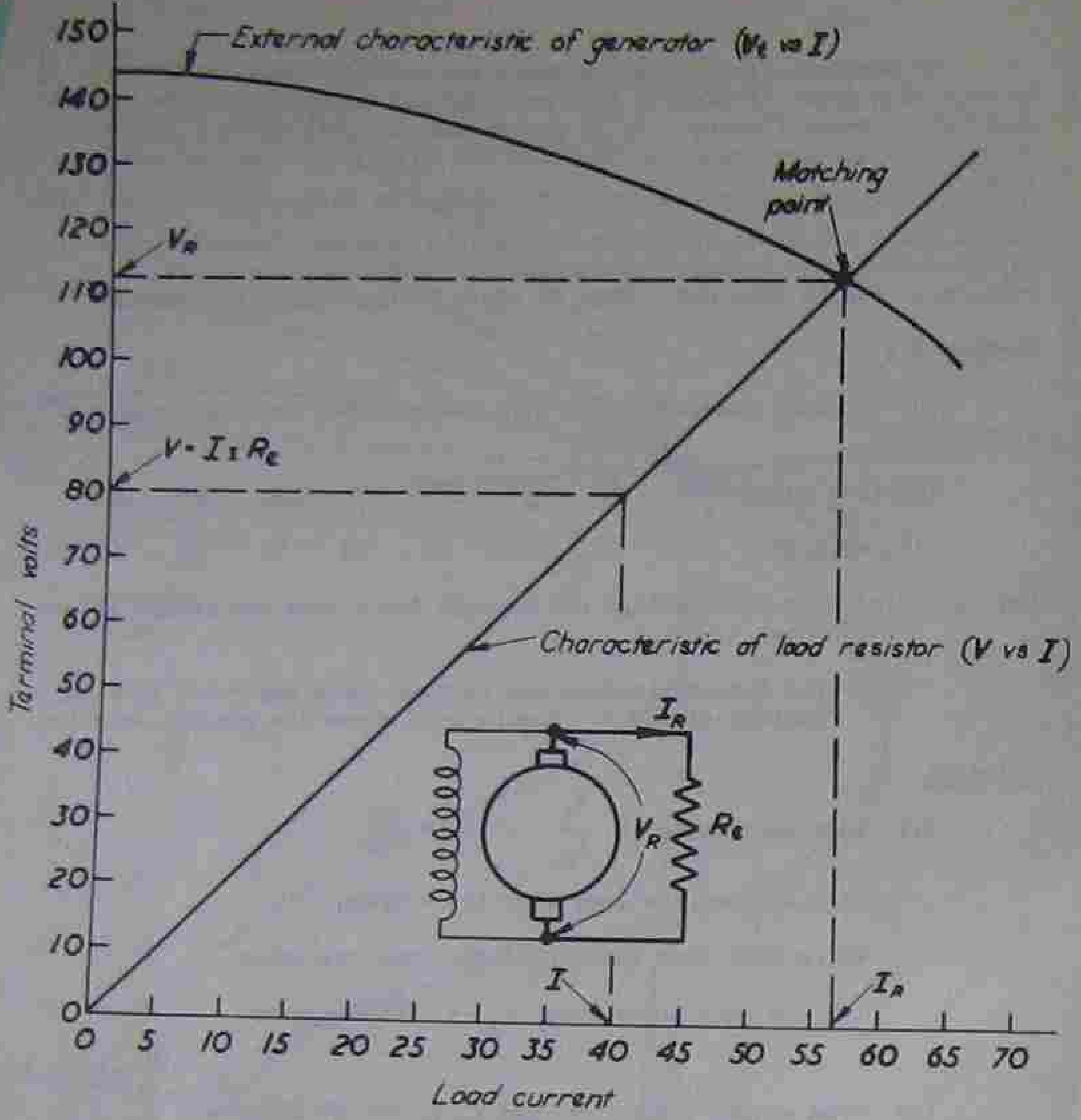


Figure 6.13

Graphical Solution of Generator with Resistance Load.

When dealing with the charging current delivered by a generator to a battery, a similar procedure is used. The battery characteristic is obtained in terms of volts and line amperes so that its characteristic can be drawn on the same graph as the external characteristic of the generator and, where the two characteristics cross, gives the load point. The battery has an internal resistance R_B and, therefore, a volts drop of $I_L R_B$ and a characteristic can be drawn of $I_L R_B$ against I_L. The battery is considered to consist of voltage supply source E_B connected in series with a resistance R_B. The $I_L R_B$ line therefore crosses the voltage ordinate at E_B.

Example 6.2

Using the same external characteristic as in Figure 6.13, the previous example, determine the charging current to a battery with an internal resistance R_B of 0.4 ohms and an open circuit voltage of 100 volts. At $I_L = 25$ amperes, $I_L R_B = 25 \times 0.4 = 10$ volts. Figure 6.14 gives the load point as 50 amperes 120 volts.

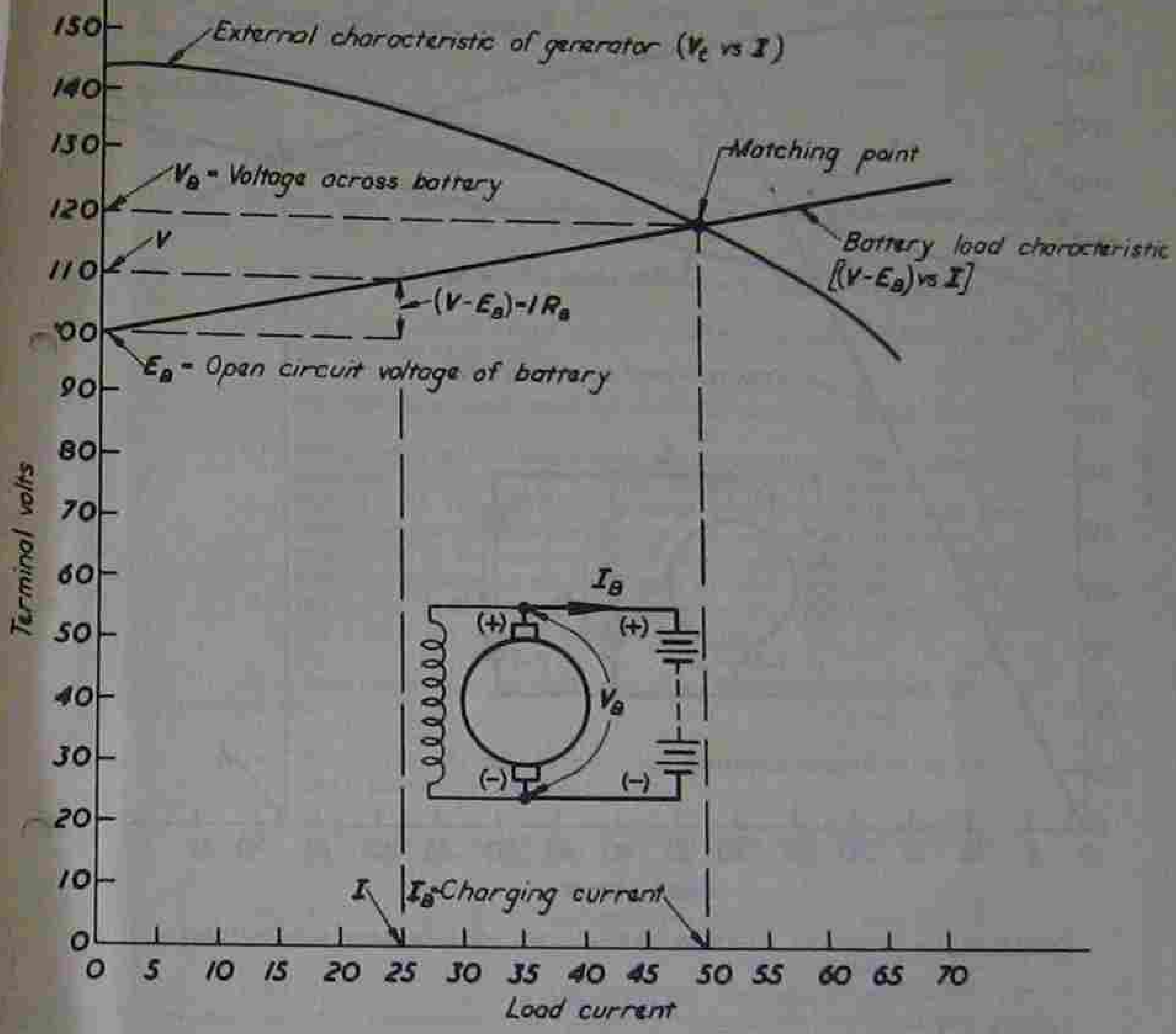


Figure 6.14 - Graphical Solution of Generator with Battery Load.

If a generator has to supply current to two types of load in parallel, batteries on charge and resistors, the two systems just described have to be combined.

The e.m.f. across both battery and resistor is the same and the current must divide properly between them according to their respective values. The open circuit battery voltage point is noted on the load resistance line as point "a" (Figure 6.15) and the total characteristic is taken from this point and through point "b". The intersection of the battery characteristic and the resistor load line will give point "c". The distance from the voltage ordinate is "db", making "bc" equal "cd".

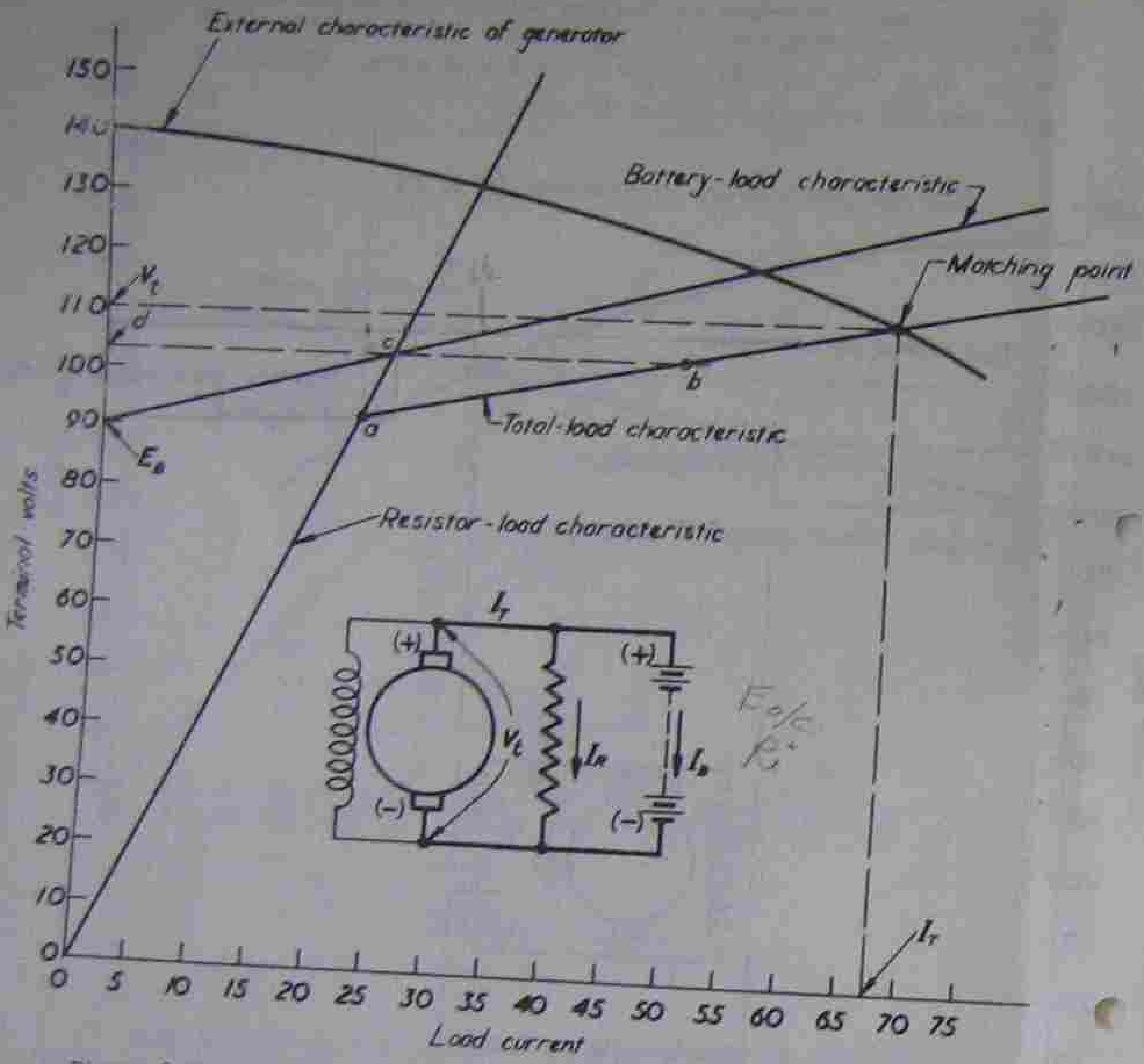


Figure 6.15 - Graphical Solution of Generator with Battery and Resistor Load.

Example 6.3

Using the same external characteristic as in Figure 6.13, a self-excited shunt generator delivers current to two loads, one a resistor of 4.0 ohms, the other a battery, internal resistance R_B of 0.5 ohm and an open circuit e.m.f. of 90 volts. Calculate:

(a) the terminal voltage of the generator V_t and the total current delivered to both loads;

(b) the current and power delivered to the resistor;

(c) the battery charging current.

Solution Figure 6.15

(a) V_t = 110 volts $\qquad I_{total}$ = 67.5 amperes

(b) $I_{resistor} = \frac{110}{4}$ = 27.5 amperes $\qquad$ Power = 110 x 27.5 = 3025 watts

(c) $I_{battery}$ = 67.5 - 27.5 = 40 amperes or

$I_B = \frac{110 - 90}{0.5}$ = 40 amperes

6.3 POLARITY OF SELF-EXCITED GENERATORS

As has been shown previously, whether or not a self-excited generator builds up depends upon the following factors:

1) The main poles must retain sufficient residual magnetism.

2) The total shunt field circuit resistance must be below a certain initial value.

3) The armature speed must be above a certain critical value.

4) The shunt field winding must be connected to the correct armature terminal for a given direction of rotation. Figure 6.16 (a) and (b). Points (1), (2) and (3) have been discussed in detail previously. A simple way to check point (4) is to observe a voltmeter connected across the armature terminals as the field circuit is opened. If the voltmeter deflection rises slightly the field terminals are not connected to the correct brushes.

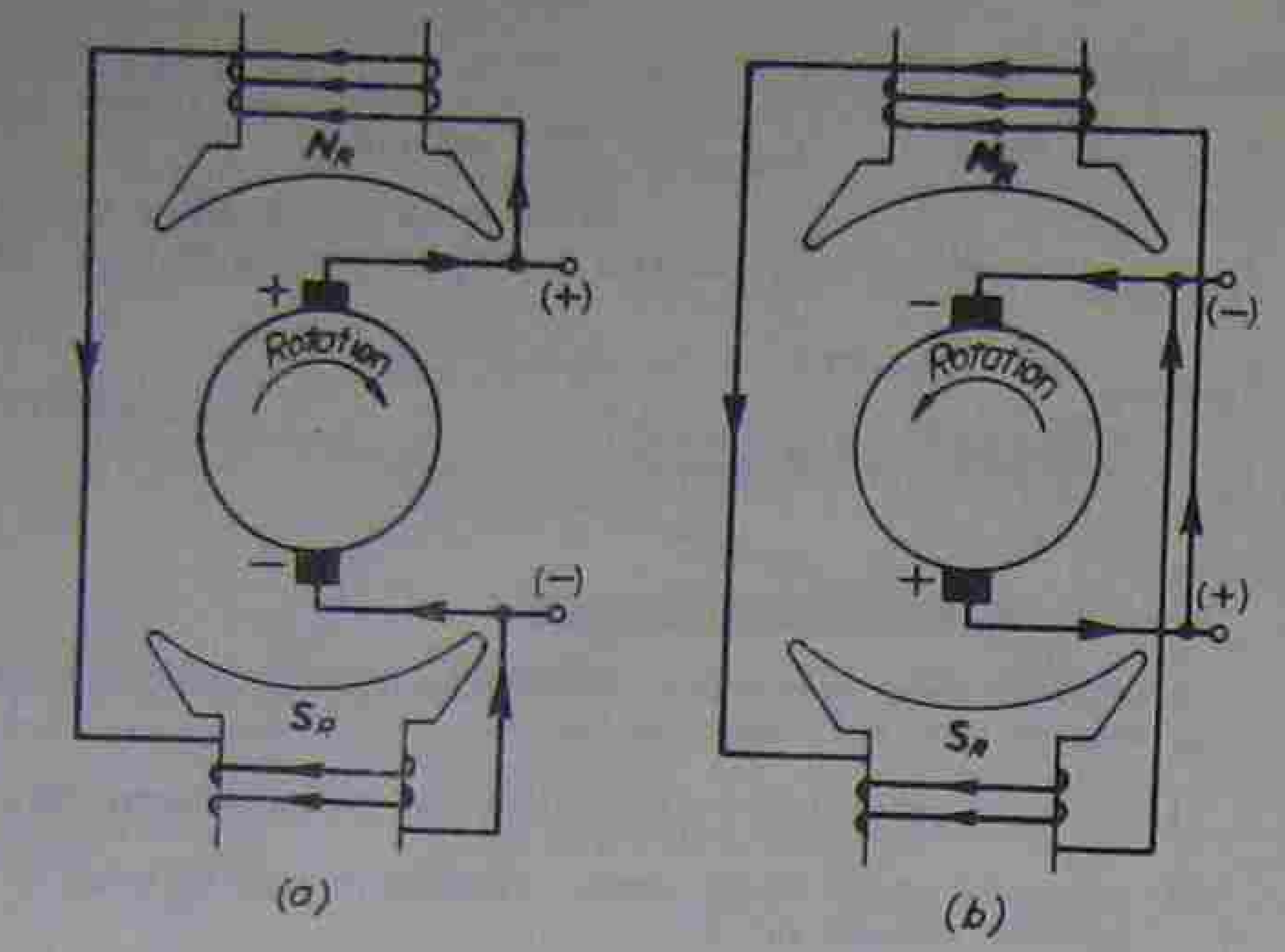
If a machine builds up with the wrong polarity this may be corrected by:

(a) Reversing the polarity of the residual magnetism in the main poles. Figure 6.16 (b).

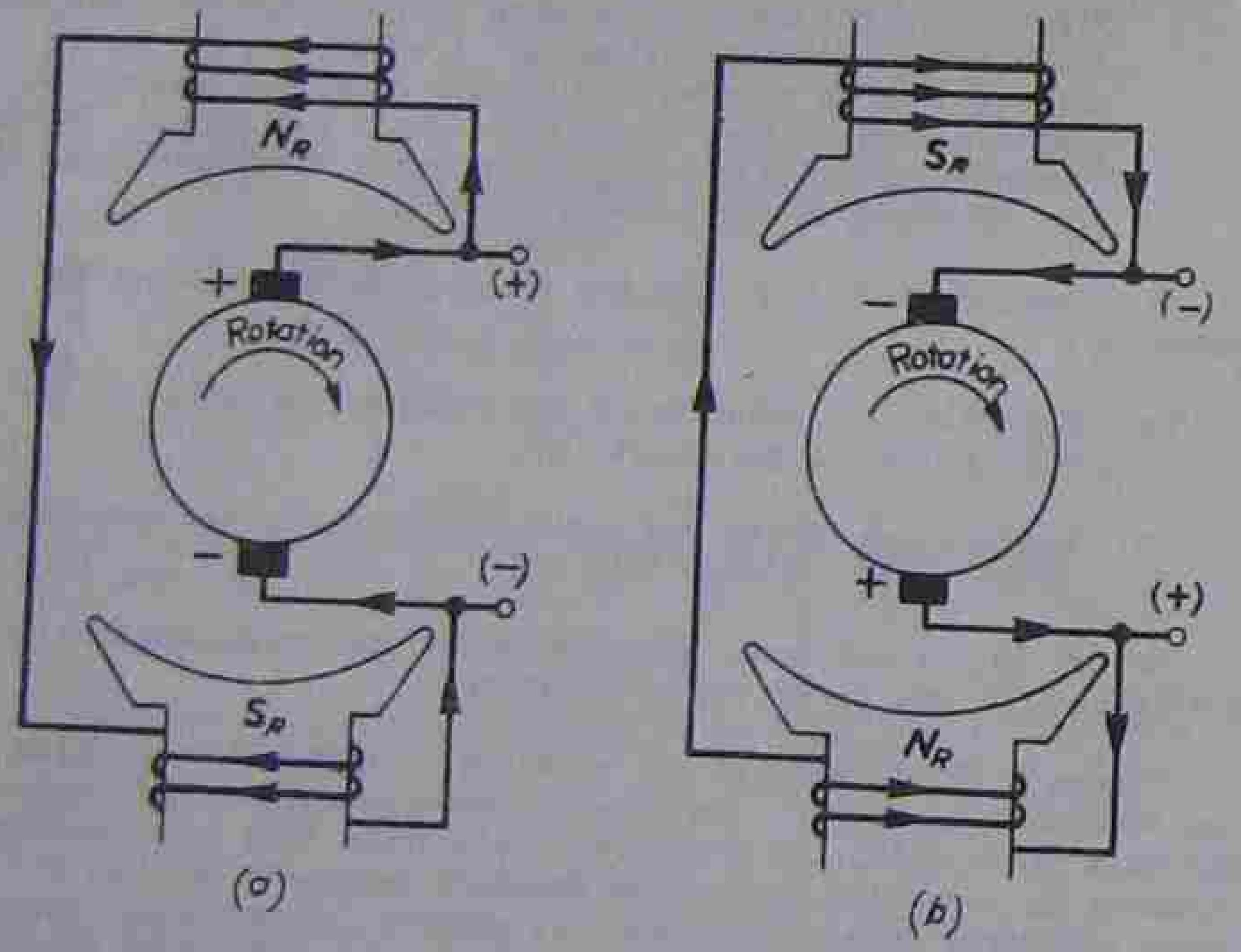
(b) Reversing rotation and interchanging field and armature connections. Figure 6.16 (a).

Method (b) is not to be recommended as the brush position is generally set for one direction of rotation.

Figure 6.16 illustrates the possible systems of connection for the self-excited generator. In order to reverse the residual magnetism in the main field pole, the field is disconnected from the armature and a voltmeter is connected across the armature terminals so that it deflects backwards when the armature is rotated in the normal direction. The shunt field is connected to a low voltage d.c. supply so that the voltmeter deflects upwards when the armature is rotated in its normal direction. The residual magnetism is now reversed.



(a) Changing polarity of self-excited shunt generator by reversing direction of rotation and interchanging armature and field connections.



(b) Changing polarity of self-excited shunt generator by reversing residual magnetism.

Figure 6.16

Connections for Self-Excited Shunt Generators.

6.4 CONTROL OF TERMINAL VOLTAGE

Where a machine runs in isolation to supply a load the terminal voltage would normally be a function of the load current as has just been shown. If a constant terminal voltage is required some means must be introduced to exercise control over the machine parameters to ensure that the generated e.m.f. is varied to compensate for any drops in the terminal voltage.

The control method will depend on the type of machine. For separately excited machines several types of control are possible; for self-excited machines the simplest and most direct method of control is field control. The principle of field control may be summarized as follows:

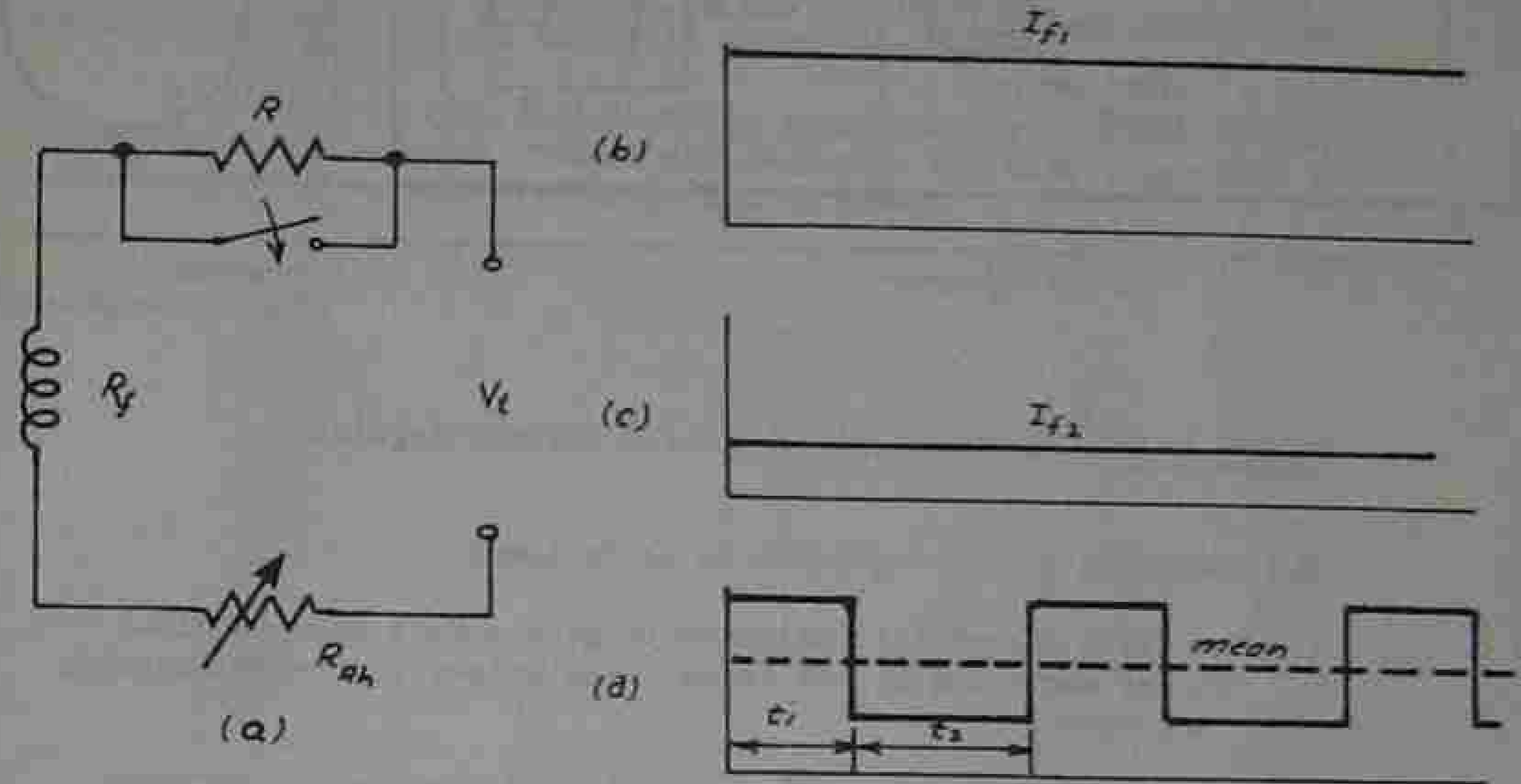


Figure 6.17 - Basic Field Control Circuit.

Consider the circuit shown in Figure 6.17 (a). With S_1 closed the circuit resistance would be $R_f + R_{Rh}$ and a certain current I_{f_1} would exist in the circuit as shown in Figure 6.17 (b). When S_1 was opened the resistance would increase to $R + R_f + R_{Rh}$ and as a result the field current would fall to a lower value as shown in Figure 6.17 (c). If the switch could now be arranged to operate in a cyclic manner being alternatively opened and closed the field current, neglecting transients, would appear as shown in Figure 6.17 (d). This introduces a method of controlling the average field current by varying the ratio of t_2 to t_1. The range of variation in the field current is from I_{f_1} to I_{f_2}.

The obvious result of this is that if the terminal voltage of the machine can be sensed in some manner and this signal used to control the ratio of t_2 to t_1 the device can be used as a voltage regulator. One device that performs this function is shown in Figure 6.18.

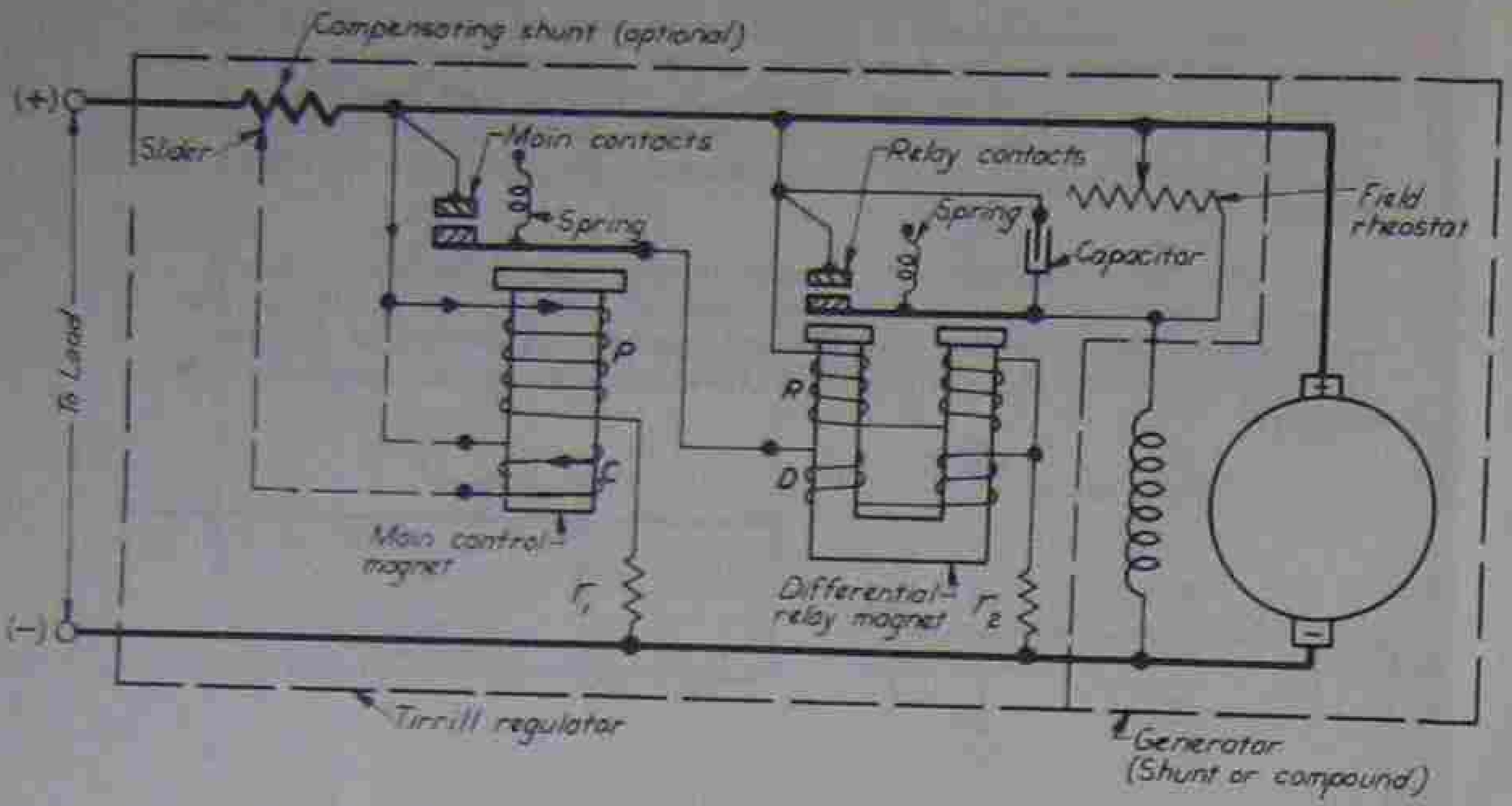


Figure 6.18 - Arrangement of Tirrill Voltage Regulator.

The operation of the regulator is as follows:

1) The field rheostat is adjusted to give a full load terminal voltage about 30% to 40% below rated value, the relay contacts being open.

2) With conditions as in (1) the voltage being low the strength of coil P on the main control magnet is reduced and the main contacts close.

3) Coil D is then excited, as this coil is in the opposite sense magnetically to coil R, and the relay contacts close.

4) The field rheostat is shorted and the shunt field current rises, causing an increase in terminal voltage V_t.

5) When V_t increases above a certain value coil P is again excited to such a strength that it causes the main contacts to open.

6) Coil D is then open-circuited and the relay contacts open, once more putting the rheostat in circuit.

7) Return to condition (1).

It should be noted that in this case the field rheostat is short circuited and no further resistance (R) is used.

The small capacitor reduces the sparking at the relay contacts. A delaying action can be imposed on the main contacts by the compensating shunt resistance and differential coil C on the main control magnet.

When the slider is adjusted for the desired degree of compounding, the differential of coil C makes it necessary for the terminal voltage to rise to a higher value than previously before the main contacts are permitted to open.

In practice, the rheostat is brought in and shorted so quickly the terminal voltage is unable to follow the field current-resistance changes. What happens is that relatively speaking the contacts remain closed longer when the e.m.f. is low and remain open longer when the e.m.f. is high.

Another method of control is where the terminal voltage is compared with a reference voltage derived from some source. The output from this comparitor is amplified, either electronically or by a magnetic amplifier and the resultant signal used to increase or decrease the field current either by altering the resistance of the field circuit or by directly controlling the output of the field excitation device.

Although it is assumed that the speed remains constant in practice speed fluctuations occur. The field regulator can also compensate for variations in E_g caused by fluctuation in speed.

REVIEW QUESTIONS

1) What is meant by the regulation of a generator?

2) What factors cause the terminal voltage of a generator to fall with increasing load in

   a) self-excited generators;

   b) separately excited generators?

3) How can the polarity of a self-excited generator be reversed?

4) What are the problems associated with the analytical solution of equations 6.2 to 6.8?

5) Under what conditions or assumptions can the operating point of a generator be established by analytical methods?

6) When obtaining the external characteristics of a self-excited shunt generator there are, in most cases, two values of V_t for a given Ia. Why is this so?

7) What is a compound generator?

8) In what way does a cumulatively compounded generator differ from a differentially compounded generator? Which of the two would be preferred where a fairly flat external characteristic was required?

ASSIGNMENTS

Marks

10 1) The no load terminal voltage of a shunt generator is 275 volts and the regulation percent 15%. Calculate the full load voltage.

25 2) The external characteristic of a d.c. generator can be described by the following table:

V_t	140	137	134	131	127	~~114~~ 122	~~106~~ 115	101
I_L	0	10	20	30	40	50	60	70

Determine the operating point of the generator when:

a) a load of total resistance of 4 ohms;

b) a 100 volt battery having an effective internal resistance of 1 ohm;

c) both of the above loads in parallel.

25 3) The relationship between the terminal voltage of a d.c. generator and the load current can be considered to be linear between no load and full load. If the no load terminal voltage is 270 volts and the full load terminal voltage is 250 volts and the rated output is 100 kW:

a) Draw a curve showing the relationship between power and terminal voltage between no load and full load.

Hint: Use the linear relationship between V_t and I to find V_t for a given I and calculate the associated power from the expression: $P = V_t I$.

b) From the graph of part (a) determine:

i) V_t when $P = 50$ kW.

ii) Power when $V_t = 260$ V.

25 4) The magnetization curve for a 4-pole d.c. generator is given by the following table:

I_f =	0	0.1	0.4	0.6	0.8	1.0	1.14	1.32	1.56	1.92	2.4	3.04
E_g =	6	20	80	120	160	200	220	240	260	280	300	320

Draw the curve and use it to determine:

a) Field resistance for an open circuit e.m.f. of 300 volts.

b) The terminal voltage when the Ia Ra drop is 30 volts, neglecting demagnetization.

c) The magnitude of the demagnetization effect in terms of I_f, if the full load V_t is 225 volts when demagnetization is considered. $I_a R_a = 30V$

PLEASE SEE OVER...

Marks

15 5) From the curve drawn for Problem 4 determine:

a) the terminal voltage at

i) 75% full load,

ii) 125% full,

neglecting demagnetization; $R_a = 0.5\Omega$

b) the current under short-circuit conditions.

V. C. N. Blight, Government Printer, New South Wales – 1974