ENERGY TRANSPORT AND CONVERSION

D.C Generators

Lecture#11

(Basic Electricity Book)

NCUK + (UET, LAHORE)
Prof. Dr. Suhail Aftab Qureshi

D.C GENERATOR

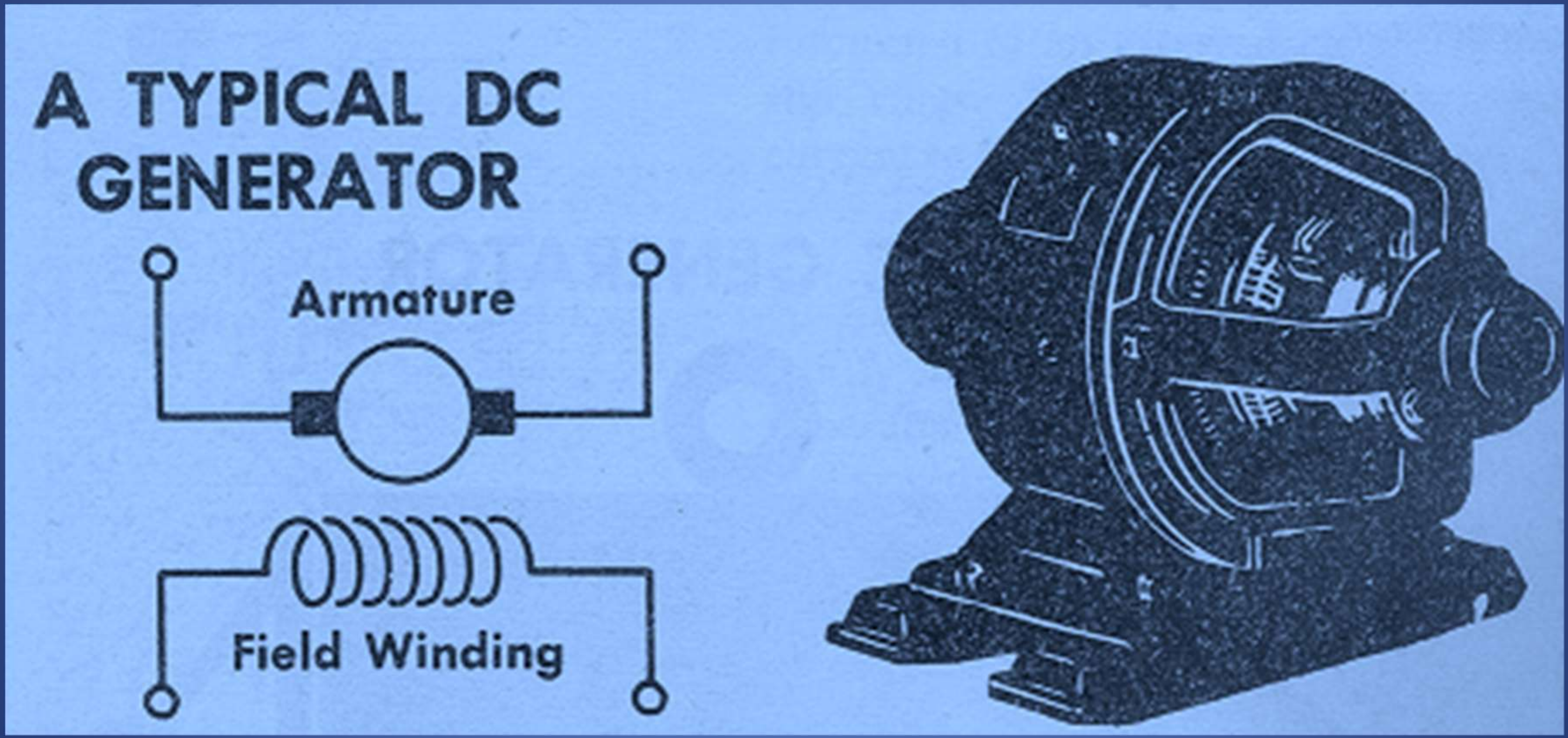
So far you have learnt the fundamentals of generator action and the theory of operation of elementary a.c. and d.c. generators. You are now ready to learn about actual generators and how they are constructed. In practice, however, d.c. generators have become relatively unimportant because of the ease with which a.c. can be converted to d.c.; but an understanding of d.c. generators provides a basis for understanding all the other types of generators and the motors you will be studying later in this Part.

Certain components are essential to the operation of a complete generator. Once you learn to recognise these components and become familiar with their function, you will find it much easier to do fault-finding and maintenance work on generators.

All generators—whether a.c. or d.c.—consist of a rotating part and a stationary part. In most d.c. generators the coil from which the output is taken is mounted on the rotating part—the *armature*. The coils which generate the magnetic field are mounted on the stationary part—the *field*.

In most a.c. generators, on the other hand, the opposite is true—the field is mounted on the rotating part—the *rotor*; and the armature is wound on the stationary part—the *stator*. Some modern generators are exceptions to the above in that a permanent magnet or a simple iron core forms the rotor, while both the field and the output coils are mounted on the stator. You will learn about these later on.

D.C GENERATOR



D.C GENERATOR

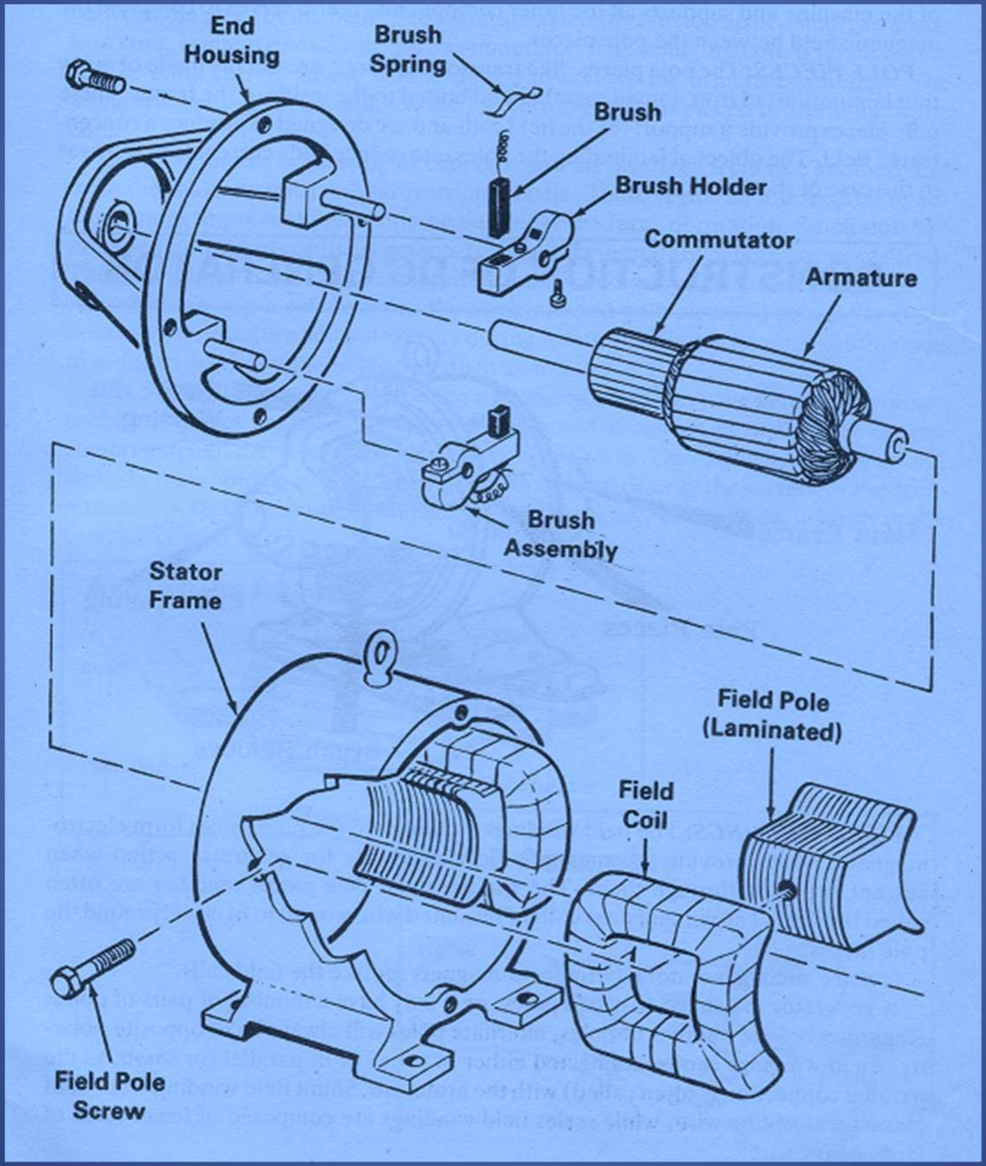
Whatever the detailed arrangements, there exists in every case *relative motion such that a coil cuts through magnetic lines of force*. An e.m.f. is induced in the coil, and a current is caused to flow through the external load.

Since the generator supplies electrical power to a load, mechanical power must be put into the generator to cause the rotor to turn and to generate electricity. The generator converts mechanical power into electrical power. Consequently, all generators must have machines associated with them that will supply the mechanical power necessary to turn their rotors. These machines are called *prime movers*, and may be steam, petrol or diesel engines; electric motors; turbines driven by water power; or steam turbines actuated by the heat given off in the combustion of coal or oil, or in nuclear fission.

D.C. Generator Construction

The relationship between the various components making up a d.c. generator is illustrated below. In the generator the field coils form the stator, and one end housing (*not illustrated*) is bolted to the stator frame.

The armature is then inserted between the field poles and the housing end, with the brush assemblies mounted last.



End Housing
Brush Spring
Brush
Brush Holder
Commutator
Armature
Brush Assembly
Stator Frame
Field Pole (Laminated)
Field Coil
Field Pole Screw

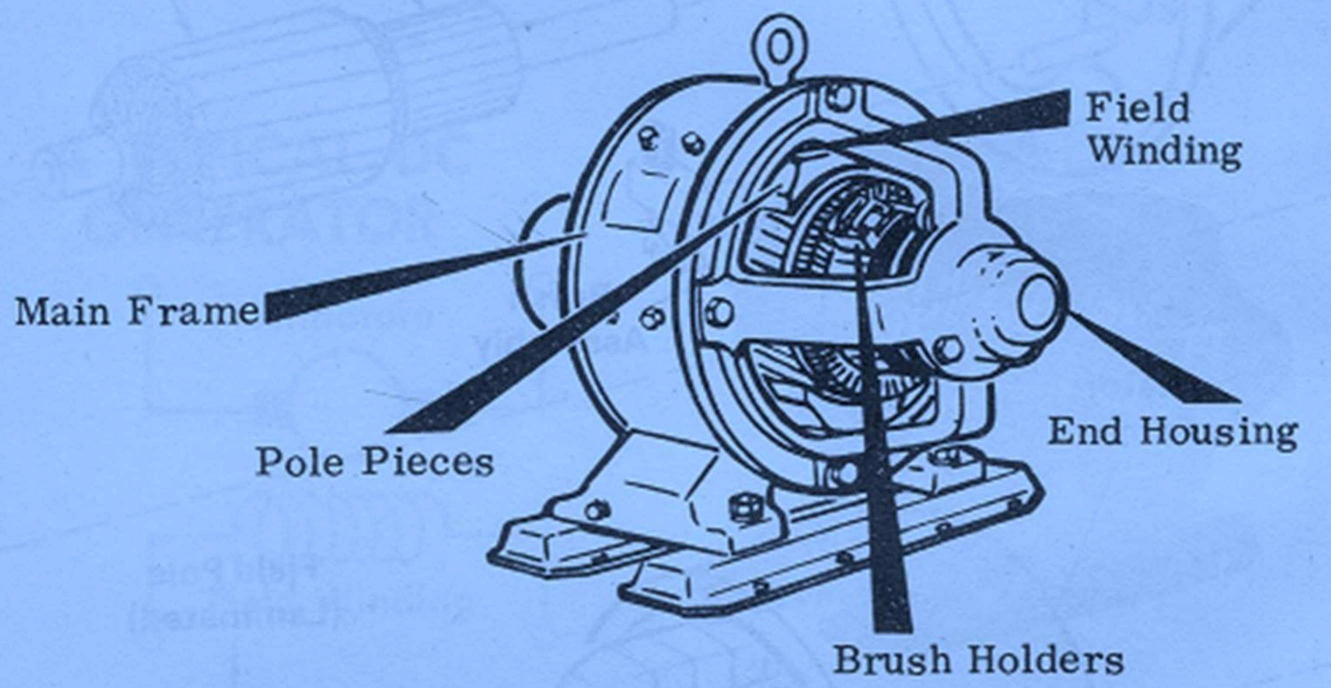
D.C. Generator Construction (*continued*)

Generator design varies depending on the size, type and manufacturer; but the general arrangement of the parts is as illustrated on the last page. The major parts of a practical d.c. generator will be described in the following pages. Compare each part and its function with those of the elementary generator which has just been described.

MAIN FRAME: The main frame is sometimes called the *yoke*. It is the foundation of the machine and supports all the other components. It also serves to complete the magnetic field between the pole pieces.

POLE PIECES: The pole pieces, like transformer cores, are usually made of many thin laminations of iron, joined together and bolted to the inside of the frame. These pole pieces provide a support for the field coils and are designed to produce a concentrated field. The object of laminating the poles is to reduce eddy current (just as it was in the case of the transformer).

CONSTRUCTION OF DC GENERATOR



FIELD WINDINGS: The field windings mounted on the pole pieces form electromagnets, which provide the magnetic field necessary for generator action when current is passed through them. The windings and pole pieces together are often called the *field*. The windings are coils of insulated wire wound to fit closely round the pole pieces.

In some small generators, permanent magnets replace the field coils.

A generator may have only two poles, or it may have a number of pairs of poles. Regardless of the number of poles, alternate poles will always be of opposite polarity. Field windings can be connected either in series or in parallel (or *shunt*, as the parallel connection is often called) with the armature. Shunt field windings consist of many turns of fine wire, while series field windings are composed of fewer turns of fairly heavy wire.

D.C. Generator Construction *(continued)*

END HOUSINGS: These are attached to the ends of the main frame and contain the bearings for the armature. The rear housing usually supports only the bearing, whereas the front housing also supports the brush assemblies.

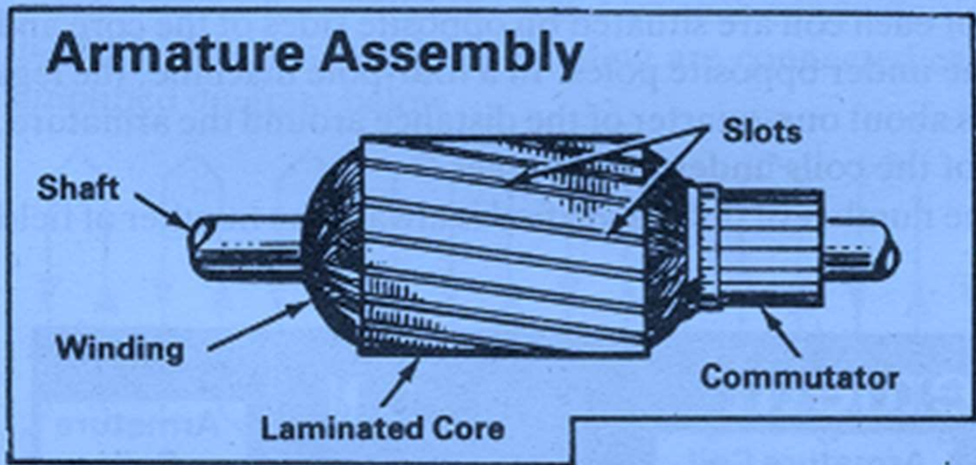
BRUSH HOLDER: This component supports the brushes and their connecting wires. The brush holders are secured to the front end housing by clamps. On some generators, the brush holders can be rotated around the shaft for adjustment.

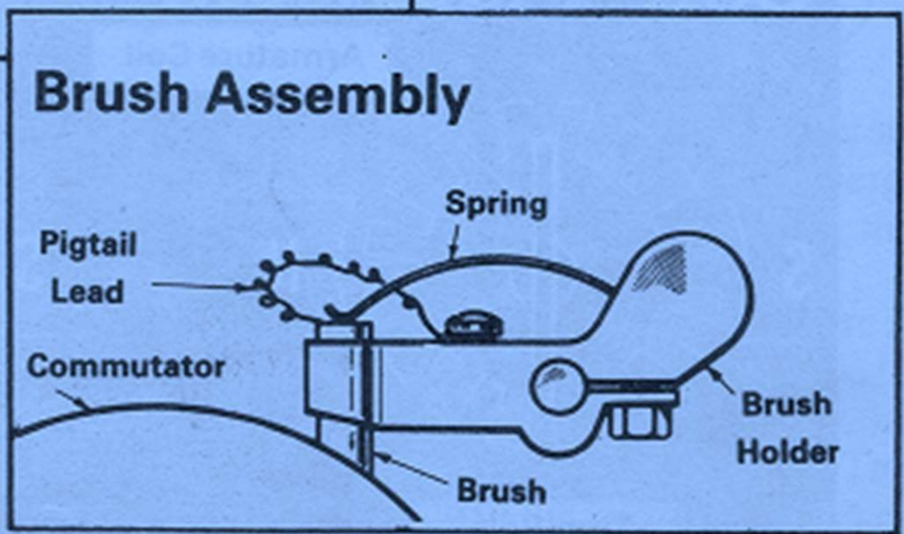
ARMATURE ASSEMBLY: In practically all d.c. generators, the armature rotates between the poles of the field. The armature assembly is made up of a shaft, an armature core, armature windings and a commutator. The armature core is laminated to reduce eddy current losses, and is slotted to receive the armature windings. The armature windings are usually wound in forms and then placed in the slots of the core.

The commutator is made up of copper segments insulated from one another, and from the shaft, by mica or heat-resistant plastic. These segments are secured by retainer rings to prevent them slipping out under the force of rotation. Small slots are provided in the ends of the segments to which the armature windings are soldered. The shaft supports the entire armature assembly and rotates in the end bearings.

A small air gap is left between the armature and pole pieces to prevent rubbing between the armature and pole pieces during rotation. This gap is kept to a minimum in order to maximize the field strength available.

BRUSHES: The brushes ride on the commutator and carry the generated voltage to the load. They are usually made of a high grade of carbon, or of a carbon-copper compound; and they are held in place by brush holders. The brushes can slide up and down in their holders so that they can follow irregularities in the surface of the commutator. A flexible braided conductor, called a *pigtail*, connects each brush to the external circuit.


Armature Assembly
Slots
Shaft
Winding
Commutator
Laminated Core


Brush Assembly
Spring
Pigtail
Lead
Commutator
Brush
Holder
Brush

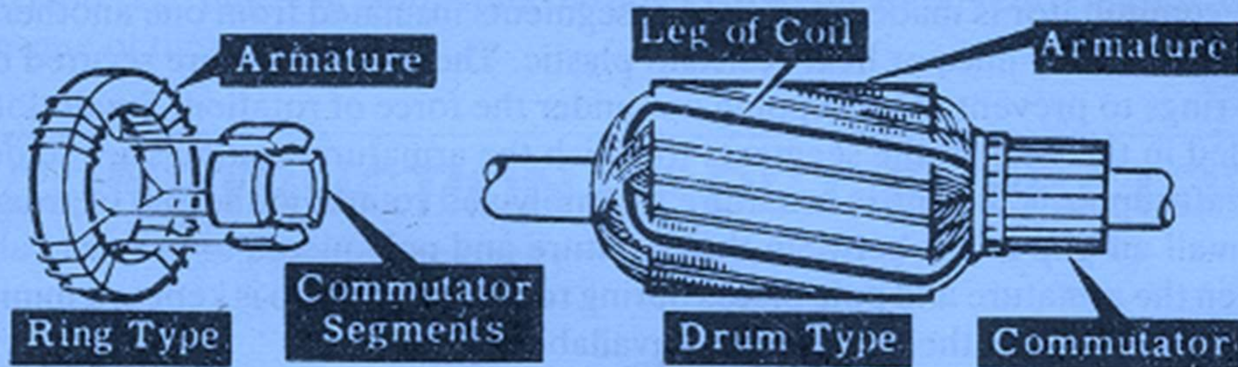
Types of Armature

The armatures used in d.c. generators can be divided into two general types. These are the *ring*-type armature and the *drum*-type armature.

In the ring-type armature, the insulated armature coils are wrapped round an iron ring, with taps taken off at regular intervals to form connection to the commutator segments. The ring-type armature was used in early designs for rotating electrical machinery, but is not used nowadays.

The drum-type armature is the standard armature construction of today. The insulated coils are inserted into slots in the cylindrical armature core. The ends of the coils are then connected.

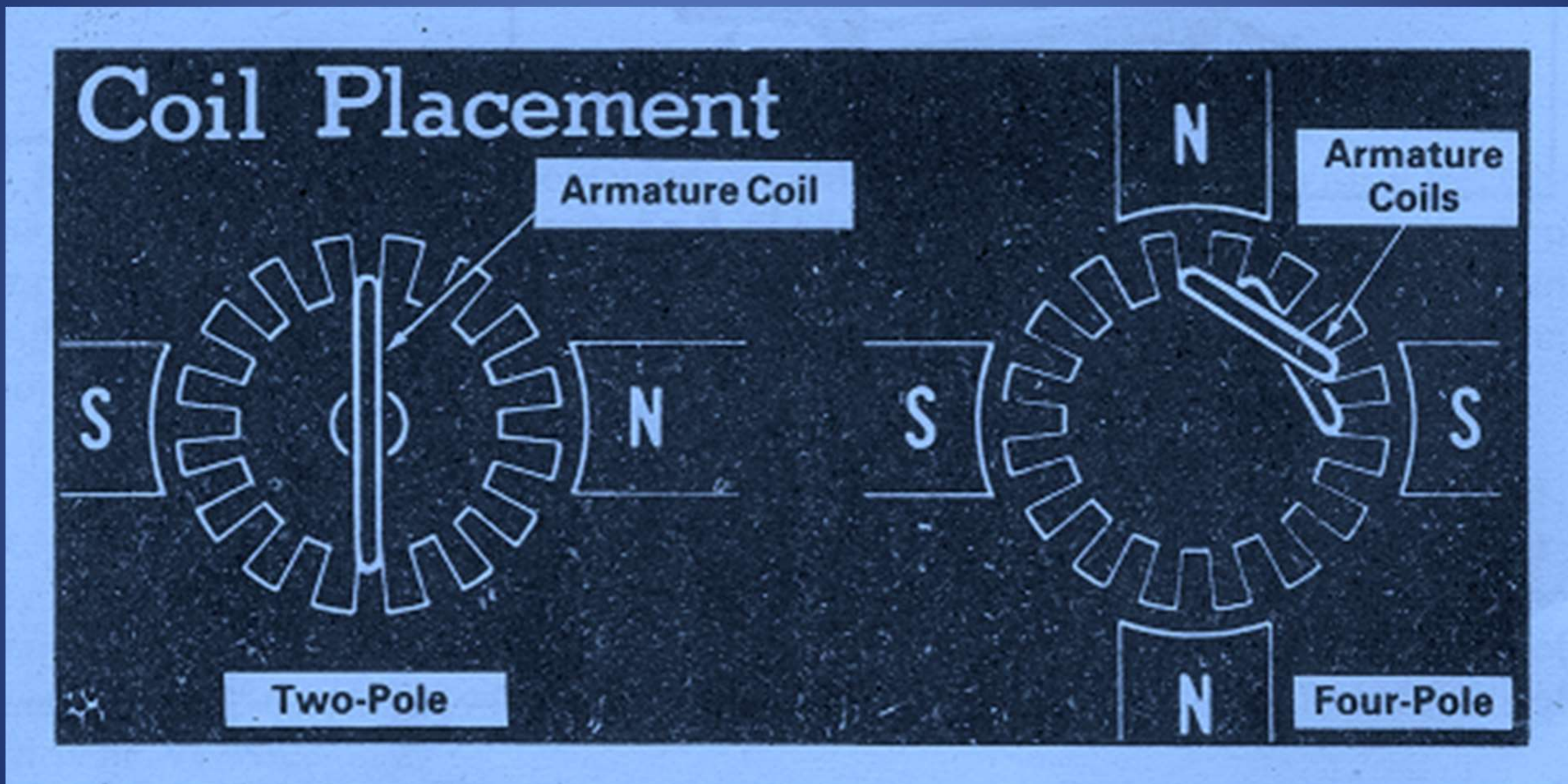
Types of Armatures



Most d.c. armatures are constructed of form-made coils. These coils are wound by machine with the proper number of turns and in the proper shape. The entire coil is then wrapped in tape or otherwise insulated, and inserted into the armature slots as one unit.

The coils are so inserted that the two legs of each coil lie under *unlike* poles. In a two-pole machine, the legs of each coil are situated on opposite sides of the core and therefore automatically come under opposite poles. In a four-pole machine, the legs of the coils are placed in slots about one-quarter of the distance around the armature, thus again keeping the legs of the coils under unlike poles.

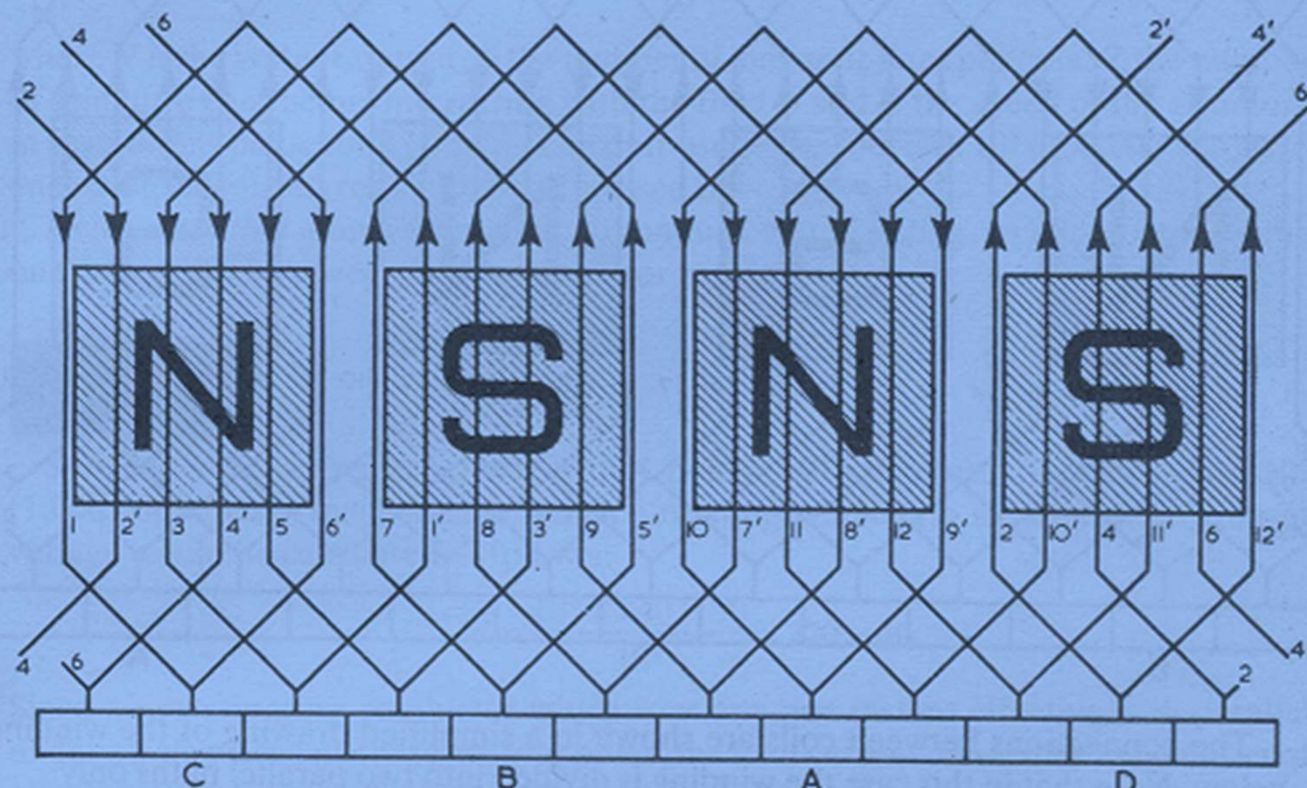
In electrical machinery, the number of poles specified is always the number of field poles.


Coil Placement
Armature Coil
S
N
Two-Pole
N
Armature Coils
S
S
N
Four-Pole

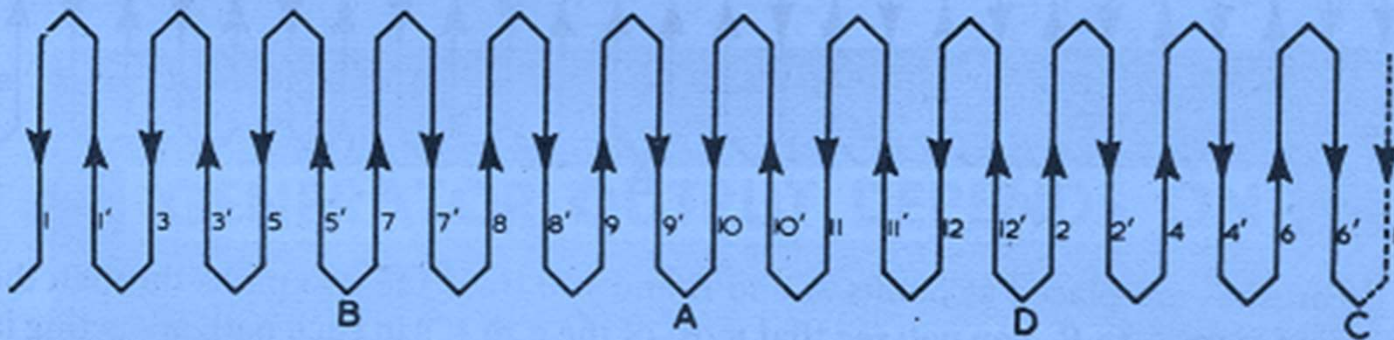
Types of Armature Winding

The windings on a drum-type armature may be either of two kinds—a *lap* winding or a *wave* winding.

In a lap winding the two ends of each coil are connected to adjacent commutator segments, and the winding forms the pattern (in a four-pole generator) illustrated below. The armature is pictured as being laid out flat. In practice, the extreme right-hand side folds round to connect to the extreme left-hand side.



The direction in which the e.m.f. in each conductor is acting is indicated. The way in which the coils in the lap-winding are connected can be seen more easily in the simplified diagram below.



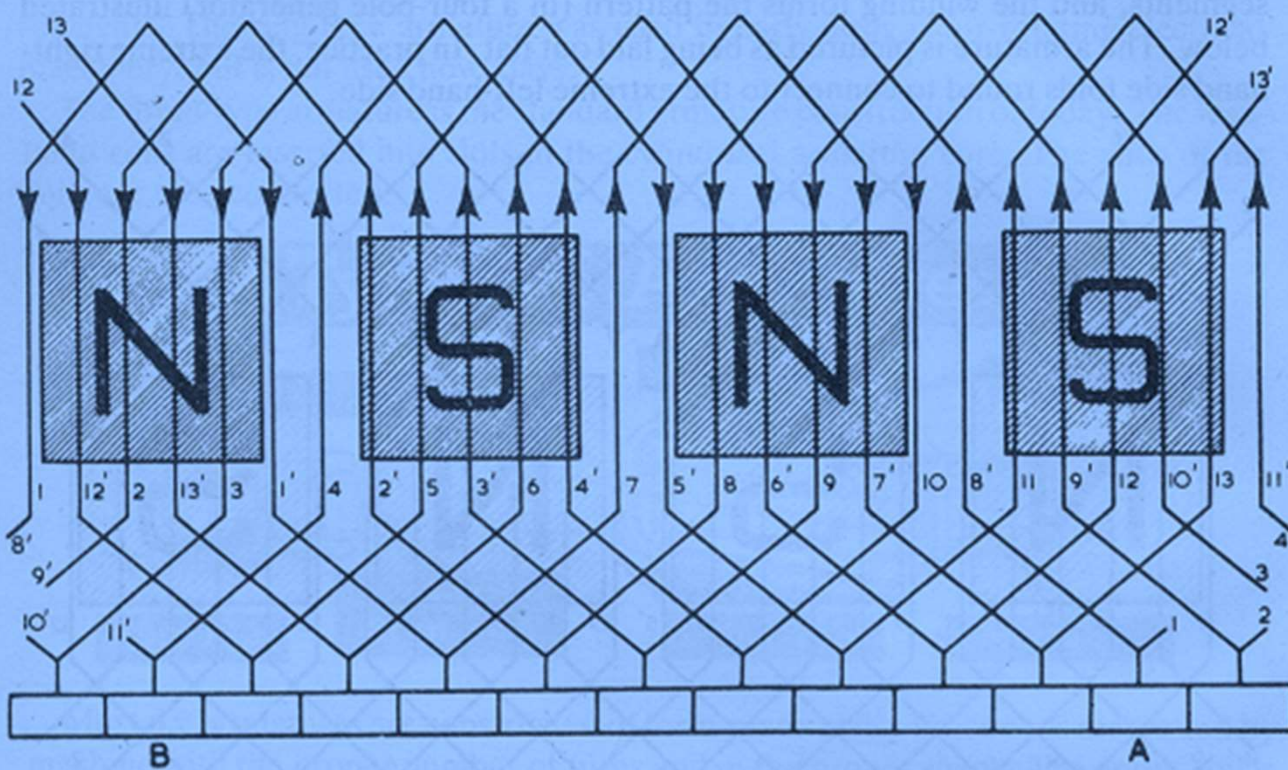
You can see that there are two points where the e.m.f.'s in adjacent conductors meet—A and C; and two points where the e.m.f.'s in adjacent conductors are diverging—B and D. If brushes are placed at these points, current will flow *from* the armature winding at A and C and *into* the winding at B and D.

Brushes having the same polarity can be connected together, and the armature is thus effectively divided into four parallel paths.

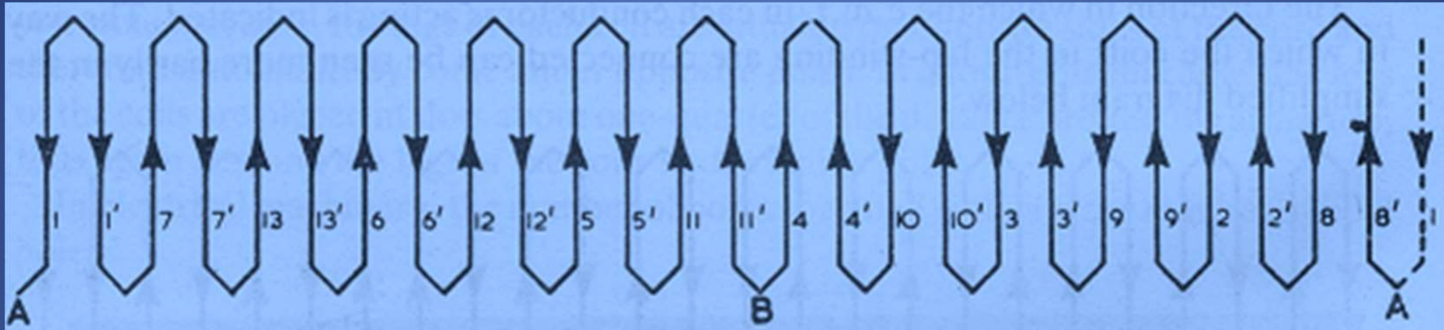
In general, the number of parallel paths through a lap winding is equal to the number of poles. The terminal e.m.f. is equal to the e.m.f. induced in one path. The current delivered to the external circuit is equal to the sum of the currents in each of the parallel paths. For this reason the lap winding is used in high-current applications.

Types of Armature Winding (*continued*)

The other type of winding used on drum-type armatures is the *wave* winding, illustrated below. In this case the connections are made so that the winding passes under every pole before it comes back to the pole from which it started.



The connections between coils are shown in a simplified drawing of the winding below. Note that in this case the winding is divided into two parallel paths only.



If brushes are placed at points A and B and you trace the two paths through the winding from A to B, you will see that most of the e.m.f.'s in each path are acting in the direction A to B. A small number of e.m.f.'s in each path are in opposition to the others, but if you check the position of these conductors carefully you will see that they are in the spaces between poles so that the e.m.f.'s induced in them are small.

In general, the wave winding has only two parallel current paths, and uses only two brushes regardless of the number of poles. The e.m.f. developed in a wave winding is equal to that induced in one-half of the total number of armature conductors. For this reason the wave winding is used in high-voltage applications.

The current delivered to the external circuit is twice the current in an individual armature conductor because the two halves of the armature winding are effectively in parallel.

The D.C. Generator—Voltage Output

You know that the output obtained from a generator depends on the conductors in the generator cutting through lines of force. You also know that the induced e.m.f. is proportional to the numbers of turns, to the flux density, and to the speed with which the flux lines are cut.

Since this is true for any generator, it can be written as a general formula:

$$V = \frac{\phi Z N}{10^8}$$

where V is the voltage output, ϕ the number of magnetic lines per pole, Z the number of armature conductors interacting with the field ϕ and N the speed of the armature in revolutions per second (r.p.s.). The purpose of the constant 10^8 (100,000,000) is to enable all calculated results to be expressed in volts.

Remember that a single turn has two conductors interacting, so Z is *not* merely the number of turns between two commutator segments.

GENERATOR OUTPUT DEPENDS ON

1. The Magnetic Field Strength
2. The Number of Conductors
3. The Speed at which it is Driven

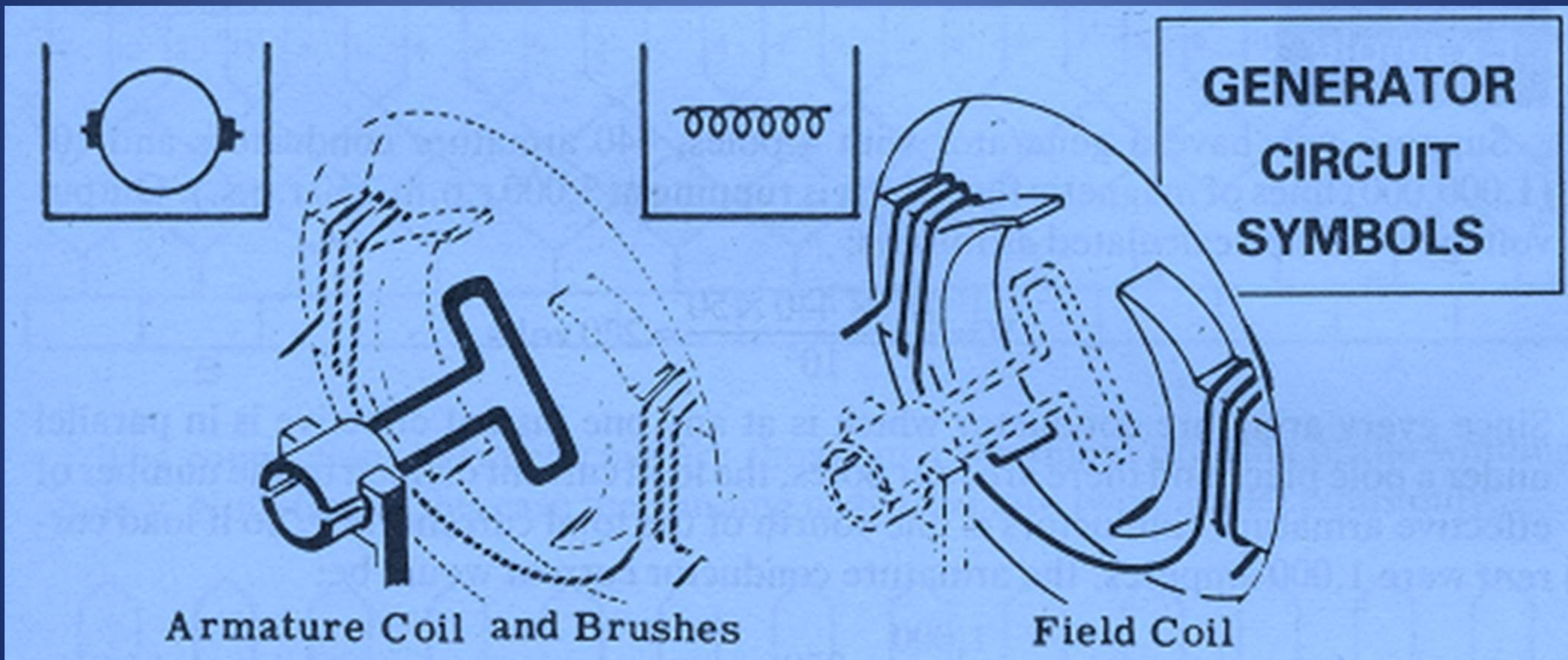
Types of D.C. Generator

Most large d.c. generators have electromagnetic fields. Permanent-magnet fields are used only in small generators called *magnetos*. To produce a constant field for use in a generator, the field coils must be connected across a d.c. voltage source, because a.c. current flow in a field coil does not produce a constant field.

The d.c. current flow in the field coils is called the *excitation*. It may be supplied either from a separate d.c. voltage source or by using the d.c. output of the generator itself.

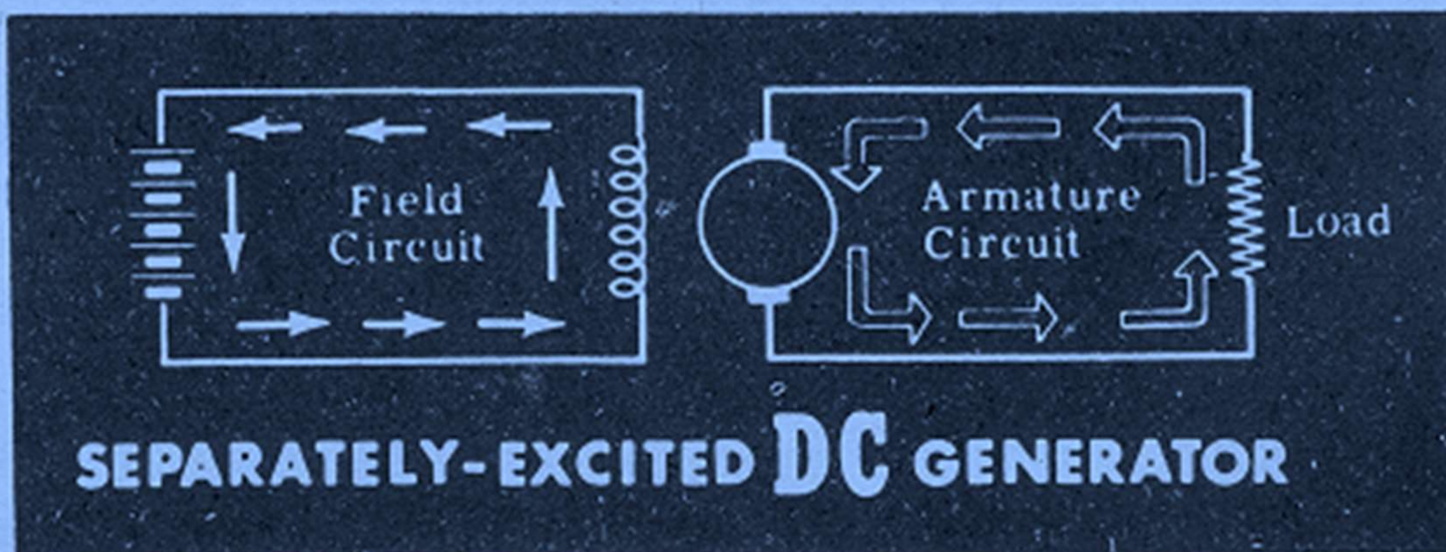
If the field is supplied with current from an external source, the generator is said to be *separately excited*. If some of the generator output is used to supply the field current, it is said to be *self-excited*. In a self-excited generator the field coils may be connected either in series with the armature coils (*series*), in parallel with the armature coils (*shunt*), or partly in series and partly in parallel with the armature coils (*compound*).

The symbols illustrated below are used to represent the armature and field coils in the various generator circuits.


GENERATOR
CIRCUIT
SYMBOLS
Armature Coil and Brushes
Field Coil

Separately excited d.c. generators have two external circuits—the field circuit, consisting of the field coils connected across a separate d.c. source, and the armature circuit, consisting of the armature coil and the load resistance. (When two or more field coils are connected in series with one another, they are represented by a single symbol.)

The two circuits of a separately excited generator are illustrated below, showing the current flow through the various parts of the circuit.

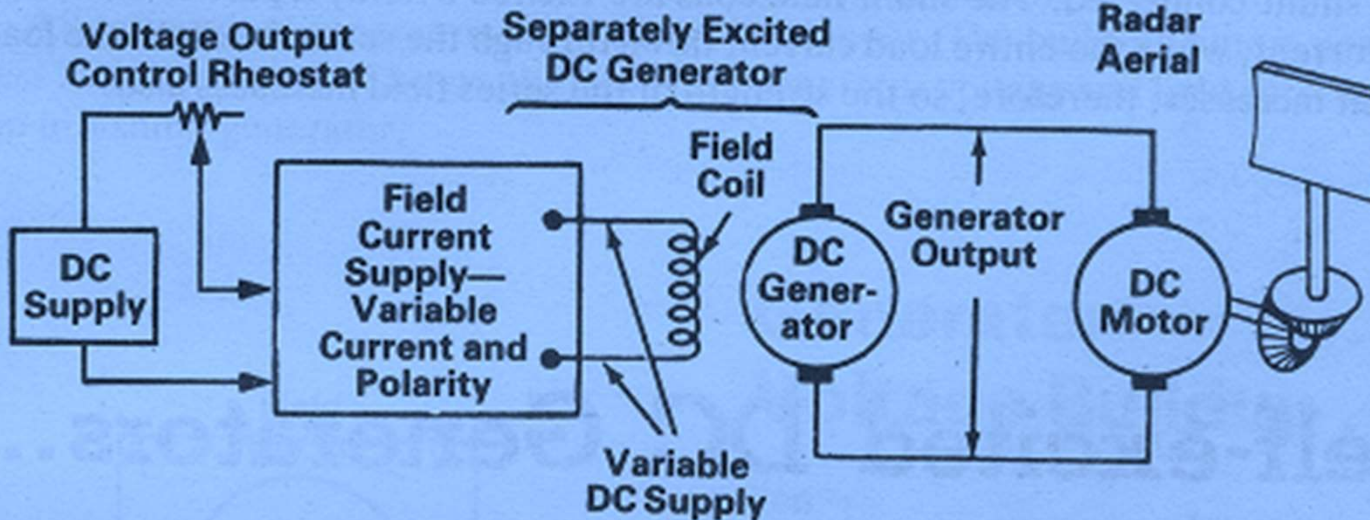


The Separately Excited D.C. Generator

In a separately excited d.c. generator, the field is independent of the armature since it is supplied with current from another generator (exciter), an amplifier or a battery. The separately excited field provides a means of controlling the voltage output of the generator, because a change in the field strength will change the magnitude of the induced voltage. Small changes in the field current can result in a large change in the load voltage (and current flow).

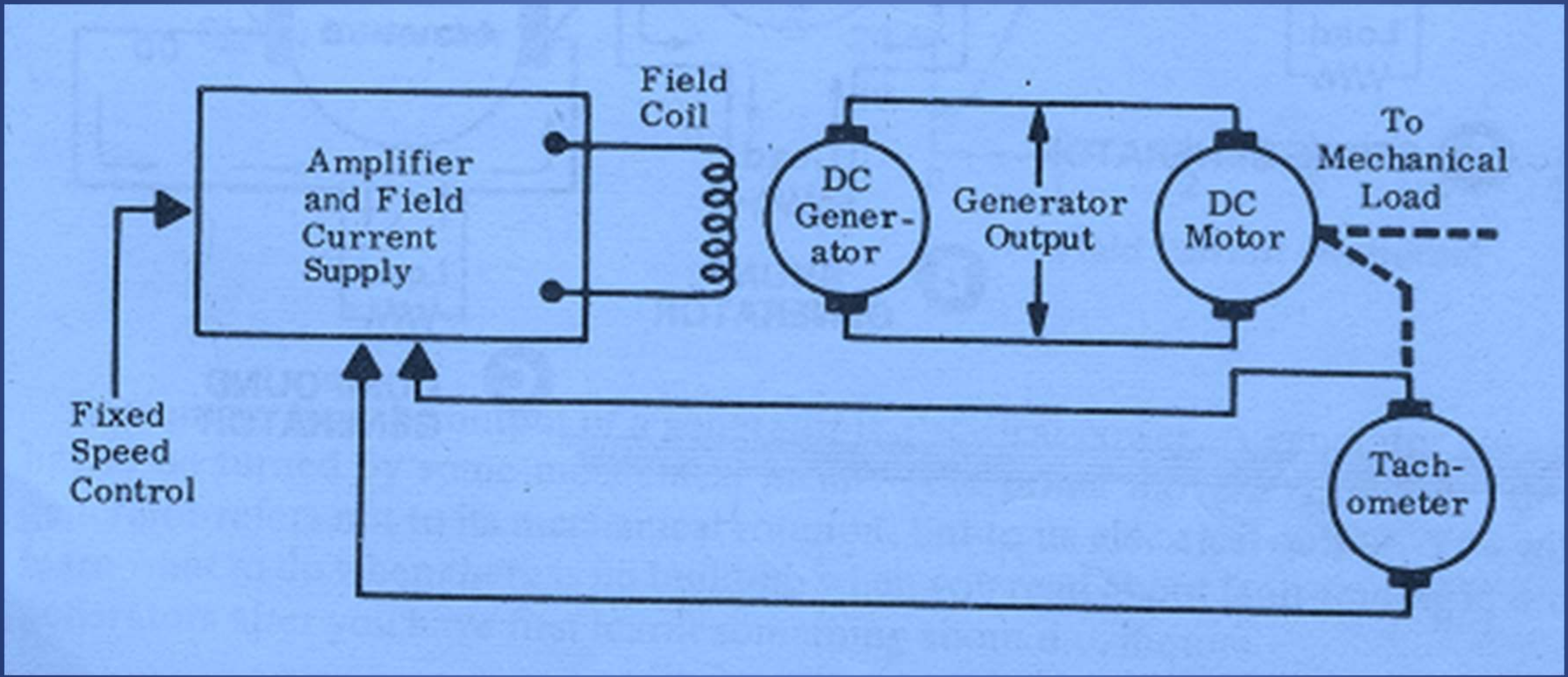
The separately excited generator is much used in automatic motor control systems. In these systems the field current is controlled by an amplifier, and the output of the generator supplies the current which drives a d.c. motor. The motor is typically used to drive a machine at constant speed, to rotate a radar aerial or to power any other heavy load.

Separately Excited DC Generators



Information about motor speed is sometimes fed back by means of a small generator called a *tachometer*. Connected to the motor shaft, the tachometer generates a voltage proportional to the speed of the motor.

The output from the tachometer is then so arranged that if motor speed increases, field current flow decreases—thus reducing the generator output and lowering motor speed once more. In this way, motor speed is held to a constant value.


Field
Coil
Amplifier
and Field
Current
Supply
DC
Gener-
ator
Generator
Output
DC
Motor
To
Mechanical
Load
Fixed
Speed
Control
Tach-
ometer

The Self-Excited D.C. Generator

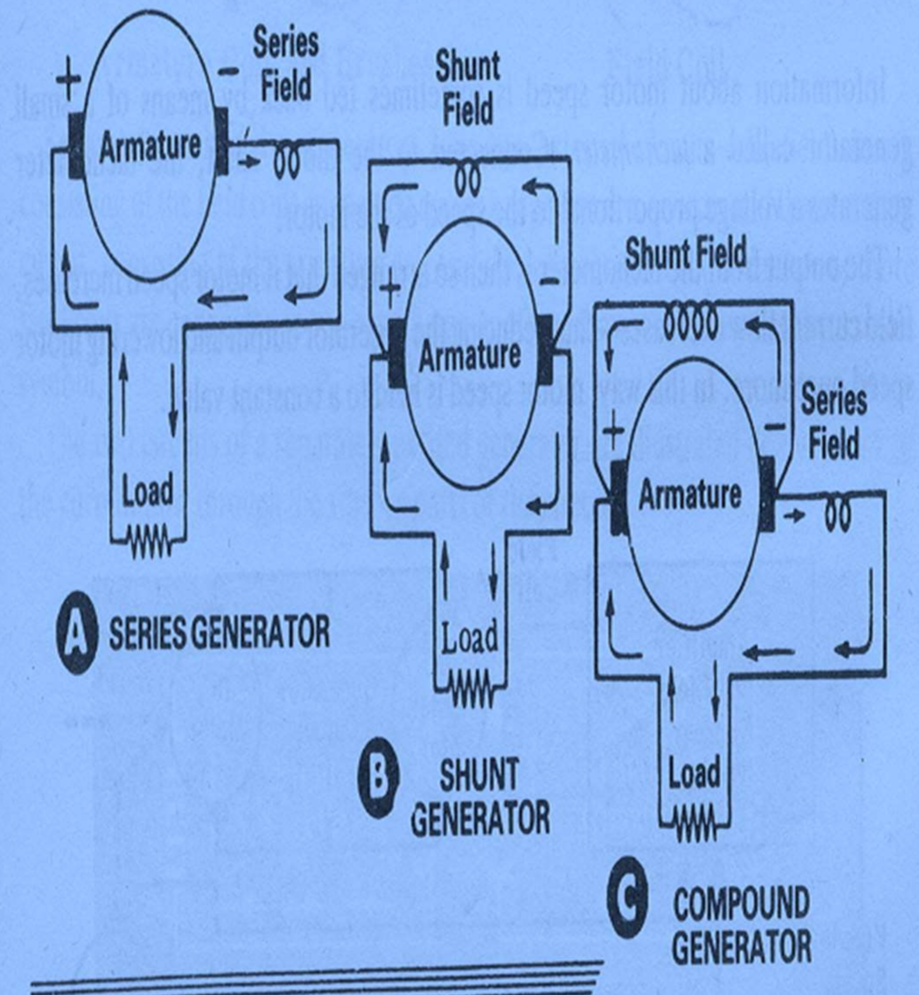
Self-excited generators use part of the generator's output to supply excitation current to the field. These generators are classified according to the type of field connection used.

In a *series* generator, the field coils are connected in series with the armature, so that the whole armature current flows through both the field and the load. If the generator is not connected across a load, the circuit is incomplete and no current will flow to excite the field. The series field contains relatively few turns of heavy wire.

Shunt generator field coils are connected across the armature circuit, forming a parallel or "shunt" circuit. Only a small part of the armature current flows through the field coils; the rest flows through the load. Since the shunt field and the armature form a closed circuit independent of the load, the generator is excited even with no load connected across the armature. The shunt field contains many turns of finer wire.

A *compound* generator has both a series and a shunt field, forming a series-parallel circuit. Two coils are mounted on each pole piece, one coil series-connected and the other shunt-connected. The shunt field coils are excited by only a part of the armature current, while the entire load current flows through the series field. As the load current increases, therefore, so the strength of the series field increases also.

Self-excited DC Generators..



The Self-Excited D.C. Generator (*continued*)

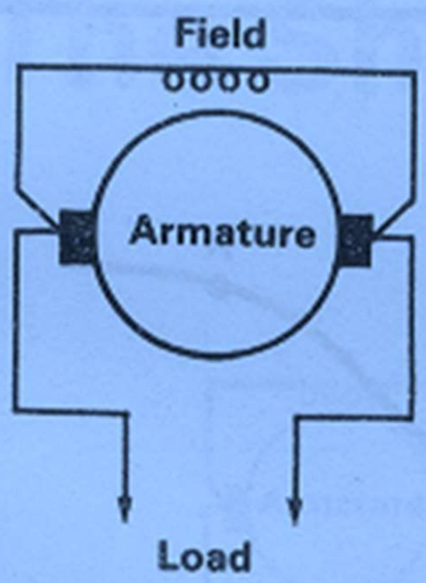
Almost all the d.c. generators in use today are either separately excited, controlled by feedback or of the self-excited type. But there is a problem with self-excitation. If the original field excitation depends on the armature output, and if no voltage is induced in the armature coil unless it moves through a magnetic field, you may wonder how the generator output can build up at all. In other words, if there is no field to start with (since no current is flowing through the field), how can the generator produce an e.m.f.?

What happens is that the field poles, because of the magnetic characteristics of their metallic structure, retain a certain amount of magnetism (called *residual magnetism*) from a previous generator run. When the generator starts turning, a field does exist which, although very weak, is enough to induce an e.m.f. in the armature.

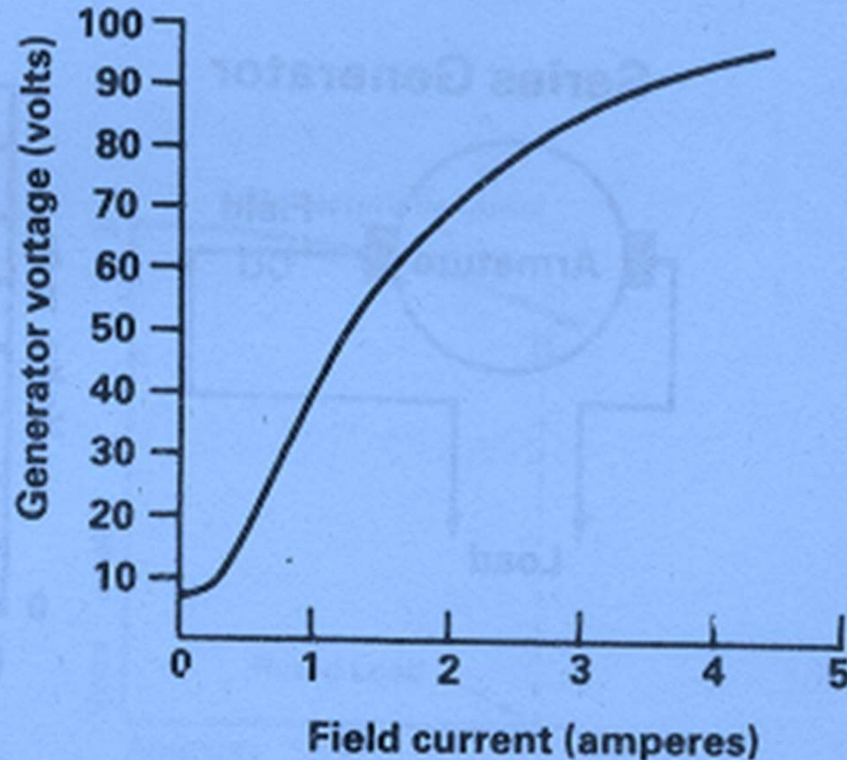
This induced e.m.f. forces current through the field coils, reinforcing the original magnetic field and strengthening the total magnetism. This increased flux, in turn, generates a greater e.m.f., which again increases the current through the field coils—and so on until the machine attains its normal field strength.

All self-excited generators build up in this manner. The build-up time is normally less than 30 seconds. The graph shows how generator voltage and field current build up in a shunt generator.

Generator Voltage Buildup . . .



Shunt Generator



Remember that the output of a generator is electrical power. A generator always has to be turned by some mechanical means—the prime mover. "Build-up" in a generator refers not to its mechanical rotation, but to its electrical output. You will learn what to do when there is no build-up when you read about fault-finding in d.c. generators after you have first learnt something about d.c. motors.

The Self-Excited Series D.C. Generator

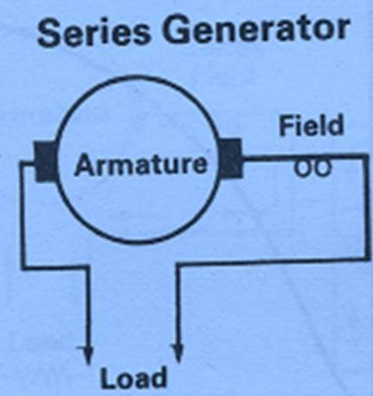
In a self-excited series d.c. generator, the armature, the field coils and the external circuit are all in series. This means that the same current which flows through the armature and external circuit also flows through the field coils. Since the field current, which is also the load current, is large, the required strength of magnetic flux is obtained with a relatively small number of turns in the field windings.

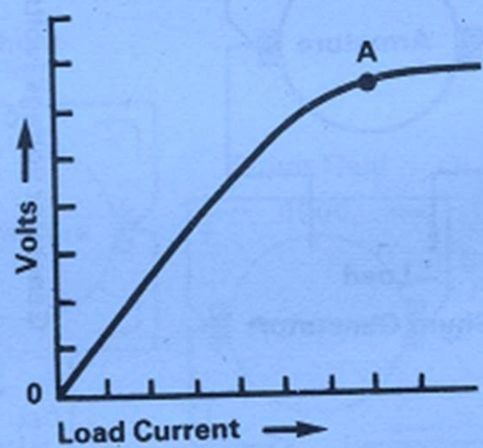
The illustration shows the schematic of a typical d.c. series generator. With no load, no current can flow and very little e.m.f. will be induced in the armature—the amount actually produced depending on the strength of the residual magnetism.

When a load is connected, however, current will start to flow, field strength will build up and the terminal voltage will increase. As the load draws more current from he generator, this additional current increases the field strength, generating more voltage in the armature winding and further increasing current flow through the load.

A point, A, is soon reached where a further increase in load current results in no greater voltage because the magnetic field has reached saturation and can increase no more.

The Series Generator





CHARACTERISTIC CURVE

The series generator is not used as a general-purpose generator; but the fact that its output voltage is proportional to its armature current makes it useful in some special applications.

The Self-Excited Shunt D.C. Generator

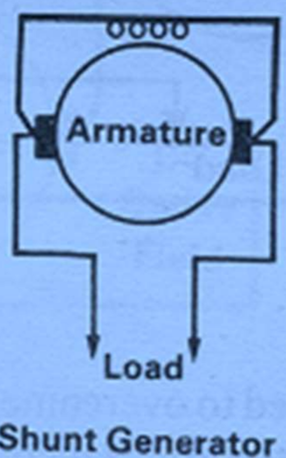
A self-excited shunt d.c. generator has its field winding connected in shunt (or parallel) with the armature. Current flow through the field coils is therefore determined by the terminal voltage and by the resistance of the field. The shunt field windings, having a large number of turns, require only a relatively small current to produce the necessary field flux.

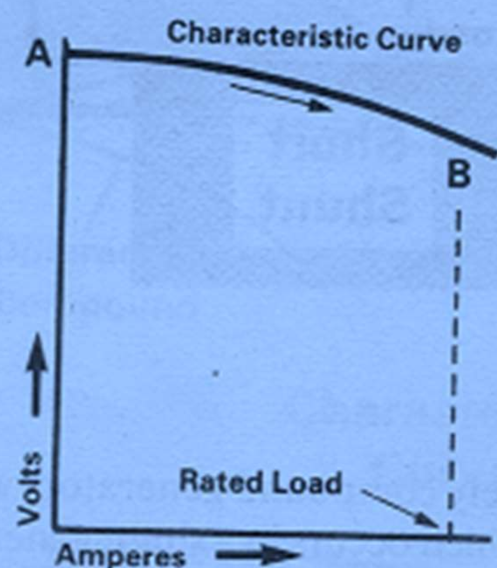
When a shunt generator is started, the build-up time for rated terminal voltage at the brushes is rapid, since field current flows even though the external circuit is open. As the load draws more current from the armature, the terminal voltage decreases because there is an increased voltage drop across the armature resistance which subtracts from the generated voltage. This, in turn, reduces field strength.

The illustration shows the schematic diagram and characteristic curve for the shunt generator. Observe that over the normal operating regions of no-load to full-load (A-B), the drop in terminal voltage as the load current increases is relatively small (typically, between 5% and 10%). The shunt generator is therefore used where a practically constant voltage is desired, regardless of load changes. If the load current drawn from the generator increases beyond point B, the full-load point, the output may start to drop off sharply—principally because of magnetic saturation.

The terminal voltage of a self-excited shunt generator can be controlled by varying the resistance of a rheostat connected in series with the field coils.

The Shunt Generator





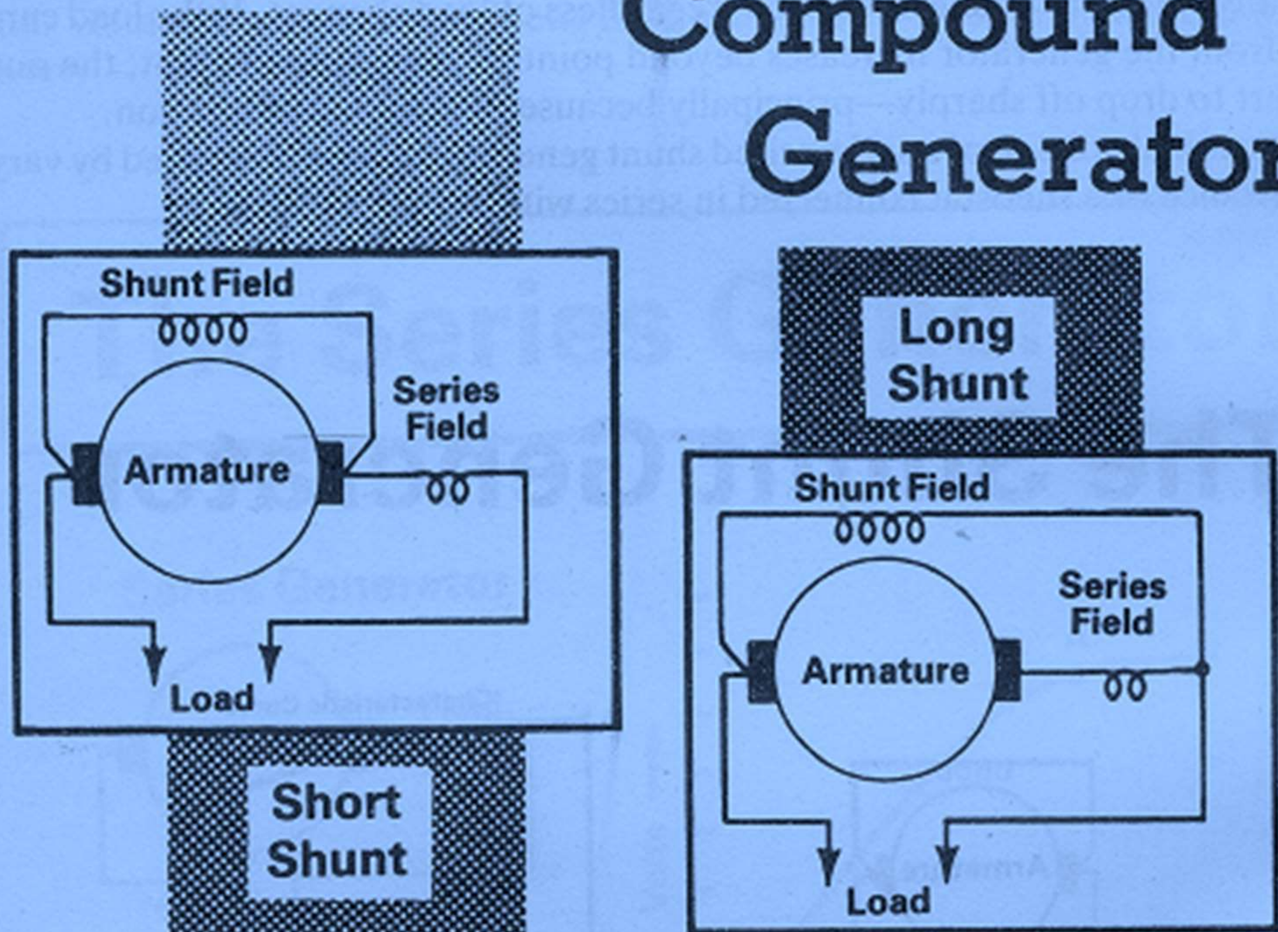
The Self-Excited Compound Generator

A self-excited compound generator is a combined series and shunt generator. There are two sets of field coils—one in series with the armature and one in parallel with it. One shunt coil and one series coil are always mounted on a common pole piece, and are sometimes enclosed in a common covering.

If the series field is connected so that it aids the shunt field, the generator is said to be *cumulatively compound*. If the series field opposes the shunt field, the generator is called *differentially compound*.

The field may also be connected either *short shunt* or *long shunt*, depending on whether the shunt field is in parallel with both the series field and the armature, or only with the armature. The operating characteristics of both types of shunt connection are practically the same.

Compound Generators



Cumulatively compound generators were designed to overcome the drop in terminal voltage which occurs in a shunt generator when the load is increased. This voltage drop is undesirable when constant voltage is required by the load. By adding the series field, which increases the strength of the total magnetic field when the load current is increased, the voltage drop caused by the extra current flowing through the armature resistance is overcome, nd a practically constant-voltage output is achieved.

The voltage characteristics of the cumulative compound generator depend on the ratio of the numbers of turns in the shunt and series field windings.

The Self-Excited Compound Generator (*continued*)

When the series windings of a compound generator are such that the terminal voltage is practically constant at all loads within its range, the generator is said to be *flat-compounded*. Usually in these machines the full-load voltage is the same as the no-load voltage, and the voltage at intermediate points is somewhat higher. Flat-compounded generators are used to provide a constant voltage to loads situated a short distance away from the generator, where voltage drops in the lines feeding the load will be small.

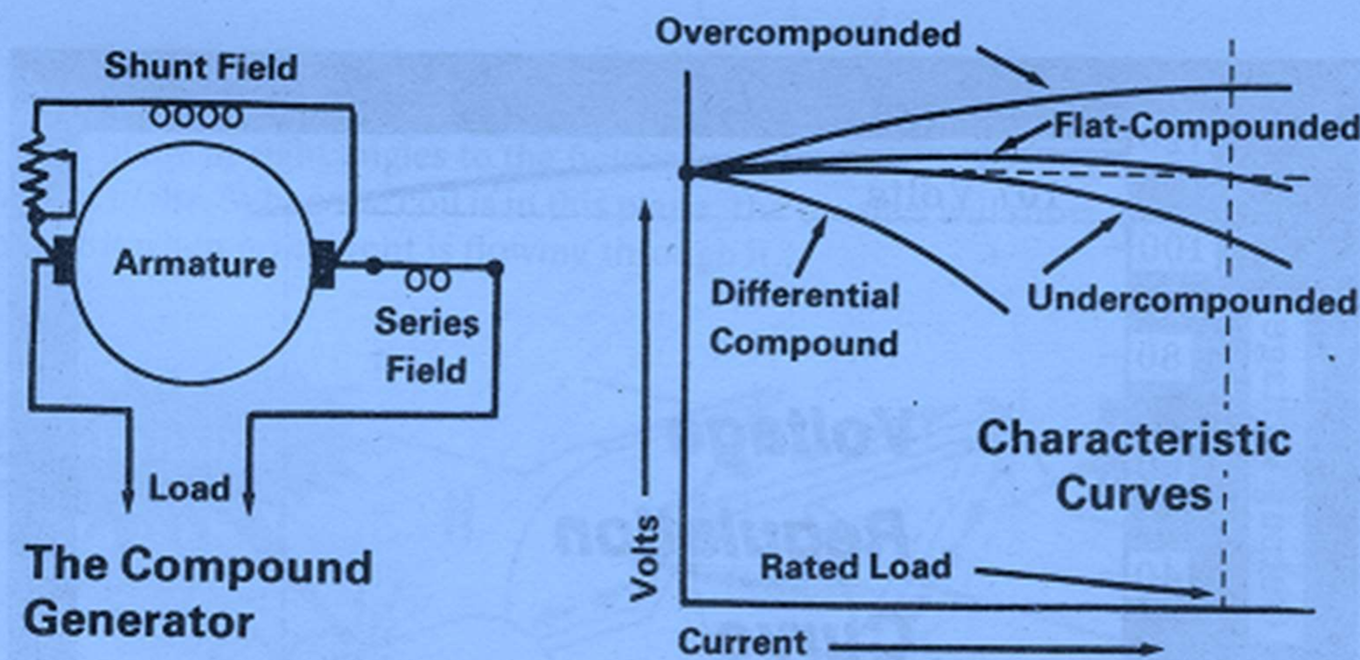
An *over-compounded* generator has a series coil so designed that the full-load voltage is greater than the no-load voltage. These generators are used where the load is situated some distance away. The increase in terminal voltage compensates for the drop in the long feeder lines, thus maintaining a constant voltage at the load.

When the rated voltage is less than the no-load voltage, the machine is said to be *under-compounded*. These generators are seldom used. Most cumulative compound generators used are either flat- or over-compounded.

The terminal voltage can always be controlled by varying a field rheostat connected in series with the shunt field. In a differentially compounded generator, the shunt and series fields are in opposition. The difference, or resultant, field is therefore weaker, and the terminal voltage drops very rapidly with an increase in load current.

The characteristic curves for the four types of compound generator are illustrated below.

The Compound Generator



Voltage Regulation in the D.C. Generator

As you have learnt, the output voltage from a generator is not usually constant. The curve which shows the value of the terminal voltage output of a generator as the load current varies is called a *regulation curve*.

Voltage regulation is the difference between the no-load and full-load terminal voltages of a generator, divided by the full-load voltage where the latter is the rated output voltage.

Voltage regulation is usually expressed as "so-much per cent regulation". The formula is as follows:

$$\text{Per Cent Regulation} = \frac{\text{No-Load Voltage} - \text{Full-Load Voltage}}{\text{Full-Load Voltage}} \times 100$$

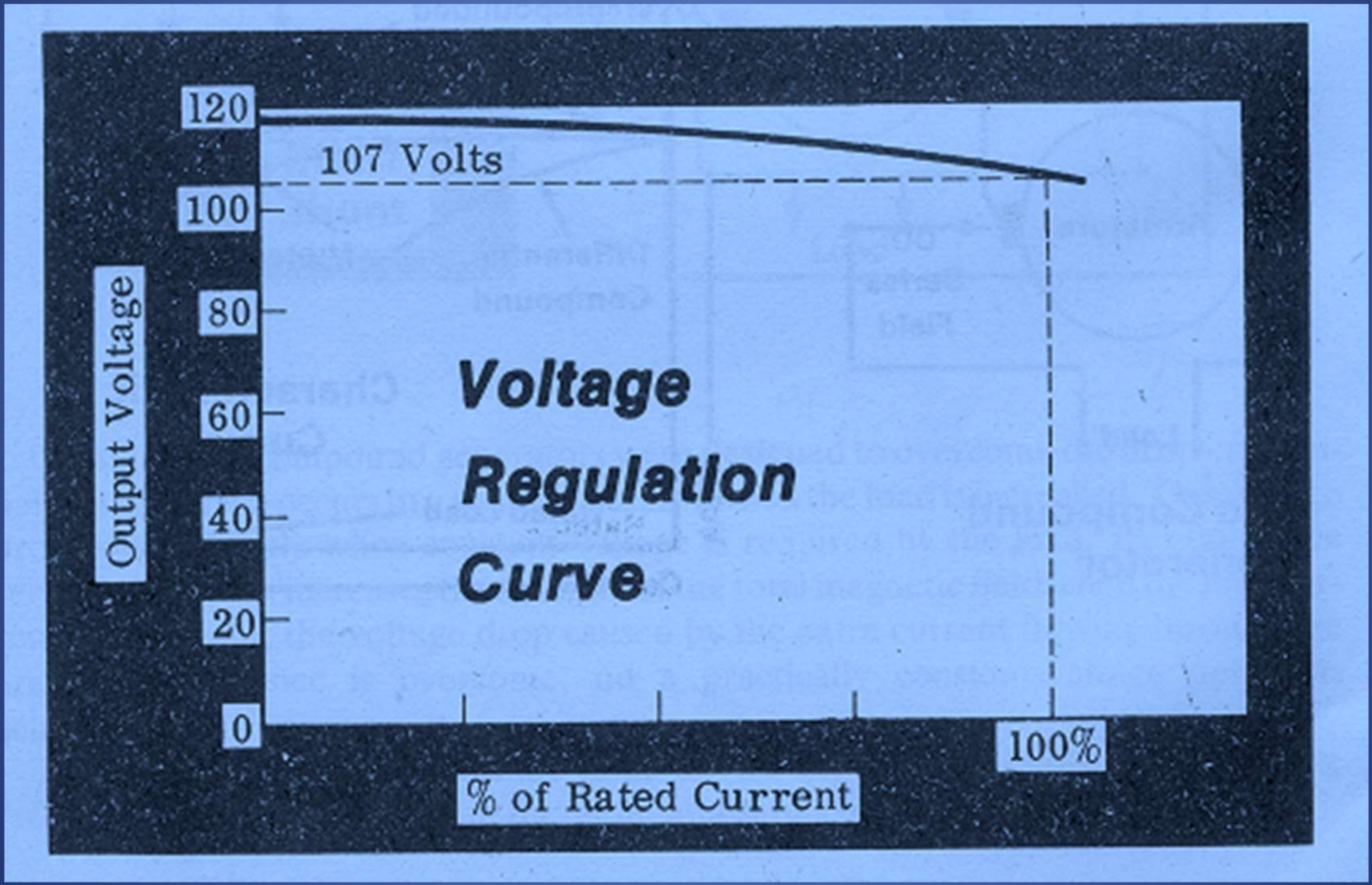
Example

Suppose you had a compound-wound generator delivering a terminal voltage of 120 volts at zero current, and of 107 volts at full load. The per cent regulation would be:

$$\frac{120-107}{107} \times 100 = \mathbf{12\%\ regulation}$$

The voltage-regulation characteristics of generators are important, for they often determine whether a given generator can be used for a specific application.

You will quite often need to calculate voltage regulation in your future work oı electrical machines, so the formula is worth remembering.


120
107 Volts
100
80
60
40
20
0
Output Voltage
Voltage
Regulation
Curve
100%
% of Rated Current

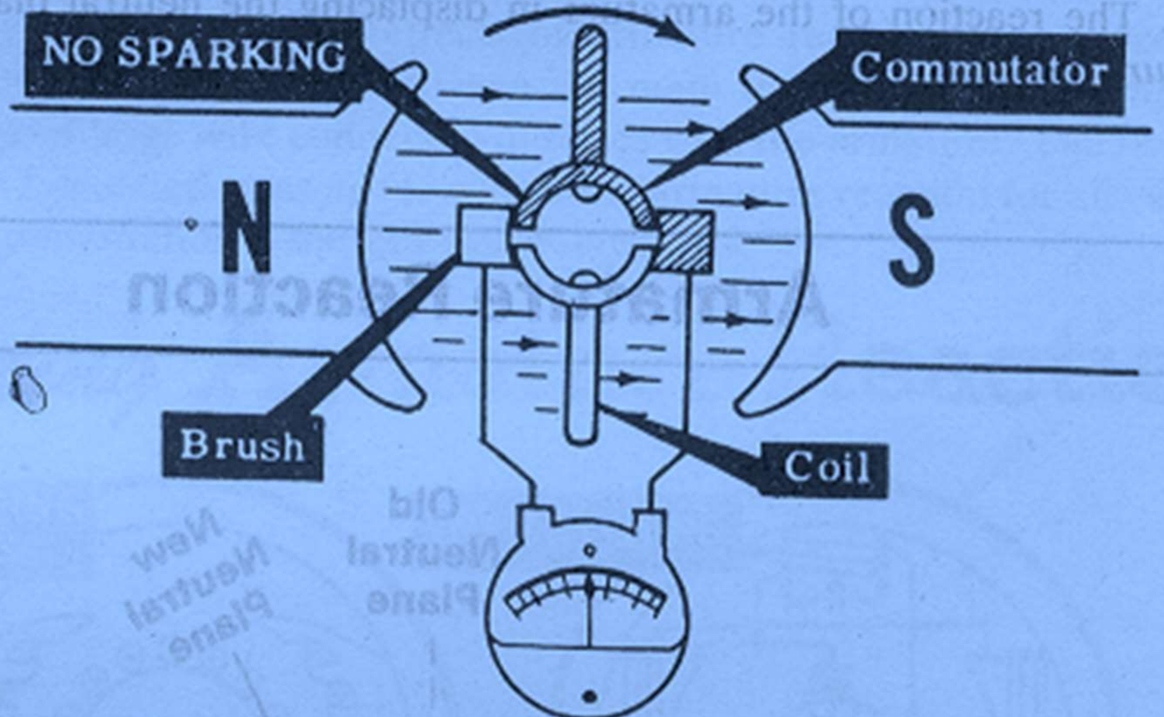
Commutation in D.C. Generators

When you were learning about the elementary d.c. generator, you found that the brushes are so positioned that they short-circuit the armature coil when it is not cutting through the magnetic field. At this instant no current flows, and there is therefore no sparking at the brushes (which are in the process of slipping from one segment of the commutator to the next).

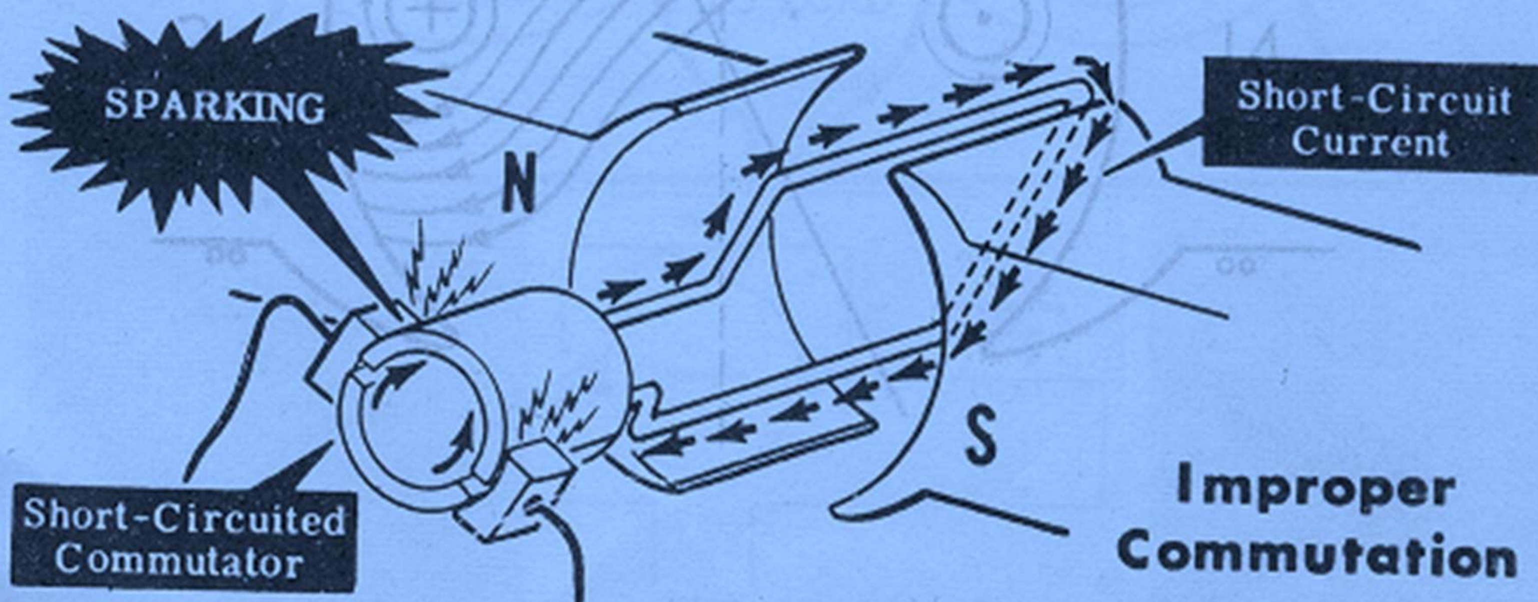
Should the brushes be moved a few degrees from their correct position, however, they will short-circuit the coil when it *is* cutting through the field. A voltage will consequently be induced in the short-circuited coil. A short-circuit current will flow and will cause sparking at the brushes. Such a short-circuit current can seriously damage the coils and burn the commutator.

This situation can be remedied by rotating both brushes in such a way that commutation takes place only when the coil is moving at right angles to the field.

Proper Commutation



The plane at right angles to the field is known as the *plane of commutation*, or the *neutral plane*. When the coil is in this plane, the brushes will short-circuit the coil at a moment when no current is flowing through it.



Armature Reaction in D.C. Generators

Consider now the operation of a simple two-pole d.c. generator. The armature is shown in a simplified view below, with the cross-section of one of its conductors represented as little circles.

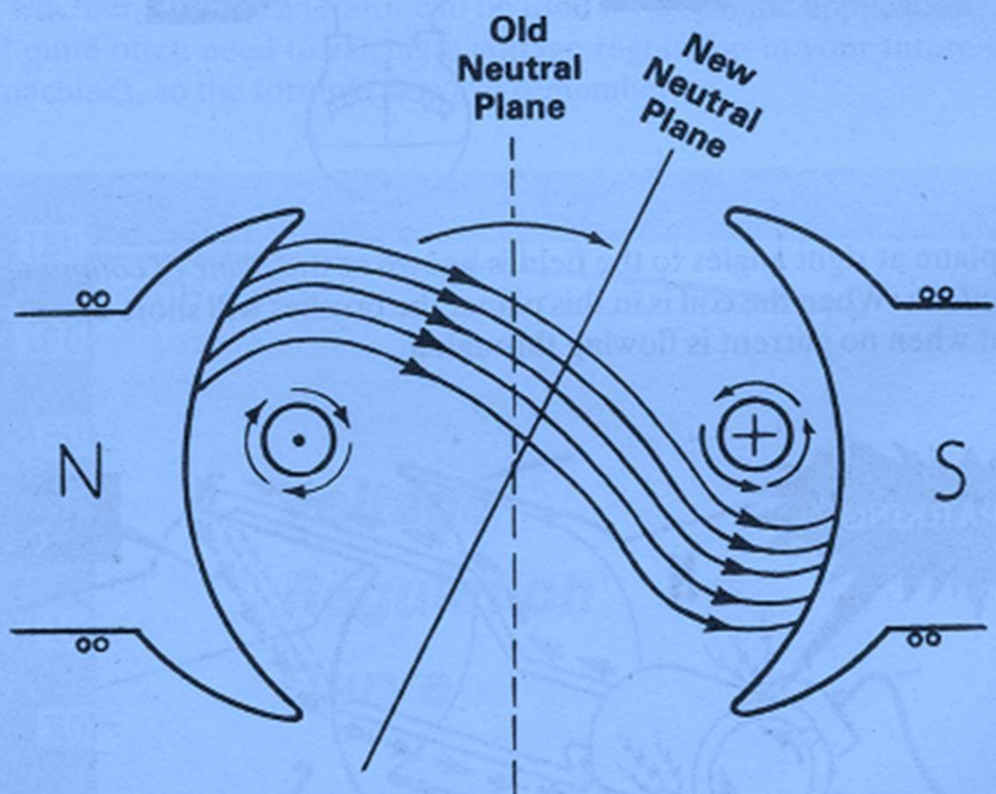
When the armature rotates clockwise, the sides of the conductor to the left will have current flowing out of the page, and the sides of the conductor to the right will have current flowing into the page. The field generated around each leg of the conductor is also shown.

You now have two fields in existence—the main field, and the field around each leg of the conductor. The diagram shows how the armature field distorts the main field, and how the neutral plane is shifted in the direction of rotation.

But you learnt on the previous page that the brushes must short-out the coil *when it lies in the neutral plane*. If the brushes are allowed to remain in the old neutral plane, they will be short-circuiting coils which have voltage induced in them. There will consequently be arcing between the brushes and commutator.

To prevent this situation arising, the brushes must be shifted to the new neutral plane. The reaction of the armature in displacing the neutral plane is known as *armature reaction*.

Armature Reaction



Compensating Windings and Interpoles

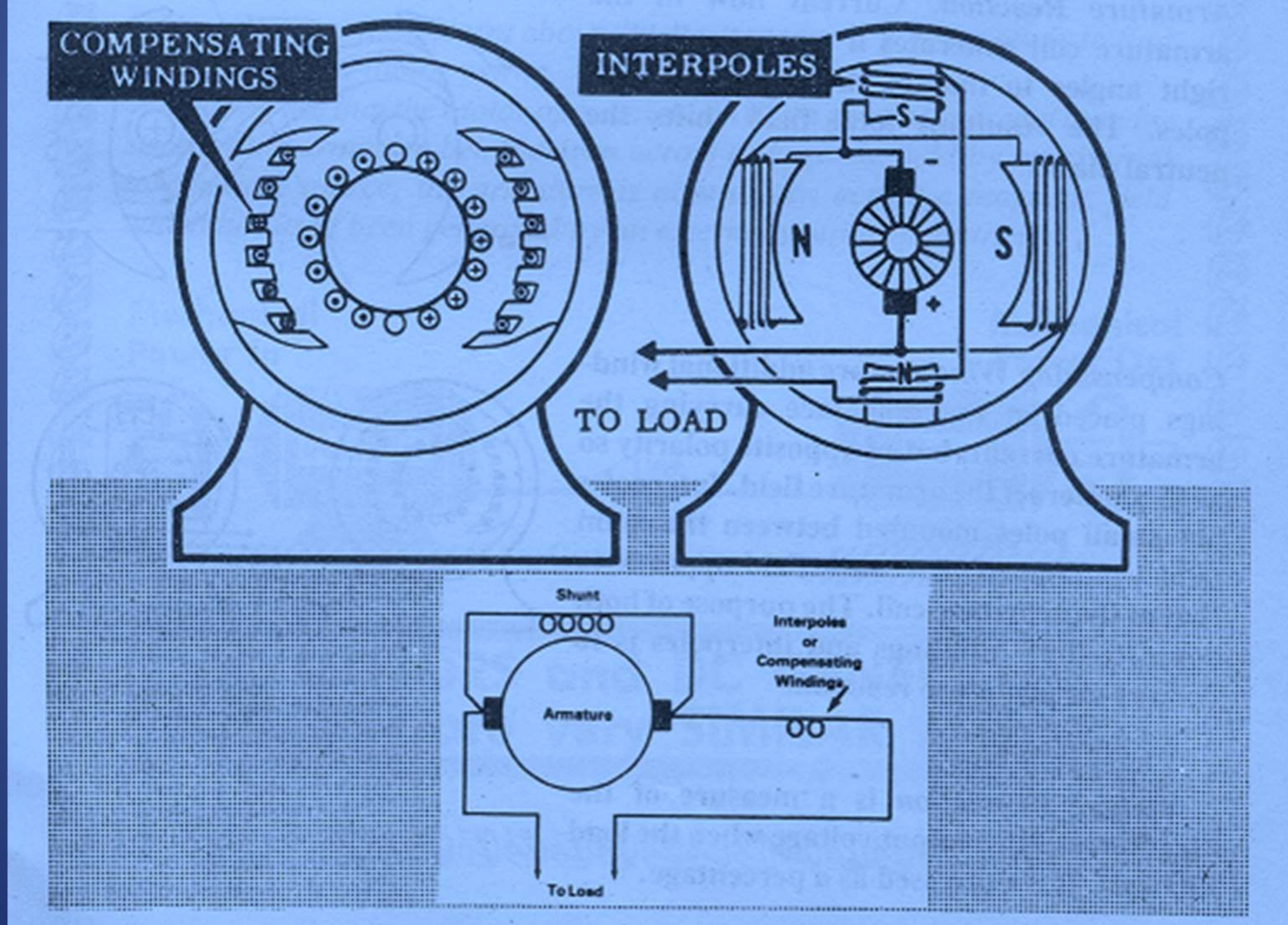
A mere shifting of the brushes to the advanced position of the neutral plane, however, does not completely solve the problems of armature reaction. For the effect of armature reaction varies with the load current; and every time the load current varies, the neutral plane shifts—which means that the brush position needs to be changed also.

In small machines, the effects of armature reaction are minimized by mechanically shifting the position of the brushes to a compromise position, in which the small amount of arc-ing which will take place is acceptable. In larger machines, more elaborate means are required to eliminate armature reaction, such as using compensating windings or interpoles.

Compensating windings consist of a series of coils embedded in slots in the pole faces. The coils are connected in series with the armature in such a way that the field they generate just cancels the effects of armature reaction. The neutral plane thus remains stationary for all values of current flow; and once the brushes have been set correctly, they do not have to be moved again.

Another way to minimize the effects of armature reaction is to place small auxiliary poles, called *interpoles*, between the main field poles. These interpoles have a few turns of large wire connected in series with the armature. The field they generate is also calculated so as *just* to cancel the armature reaction for all values of load current. Commutation is thereby much improved.

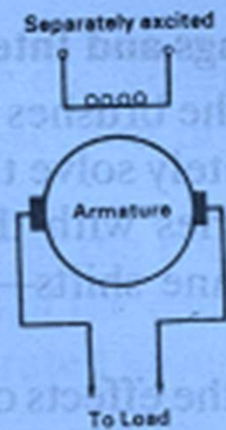
Correcting Armature Reaction

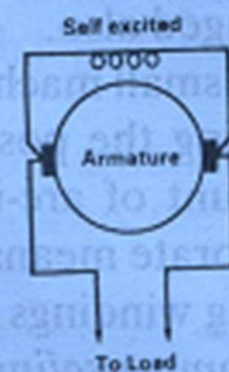


REVIEW of D.C. Generators

Generator Classification. D.C. generators are classified according to the method of field excitation used. Separately-excited generators use an outside source of d.c. current to magnetize the field. Self-excited generators use the output of the generator itself to excite the field.

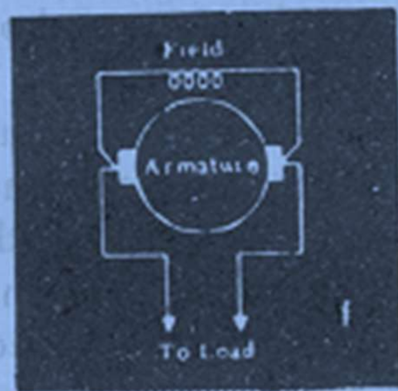
Self-excited generators are further divided into classifications depending on the field winding connections.



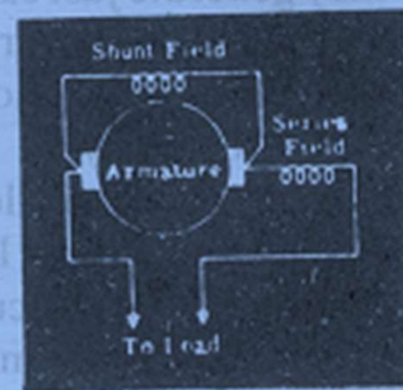


Series

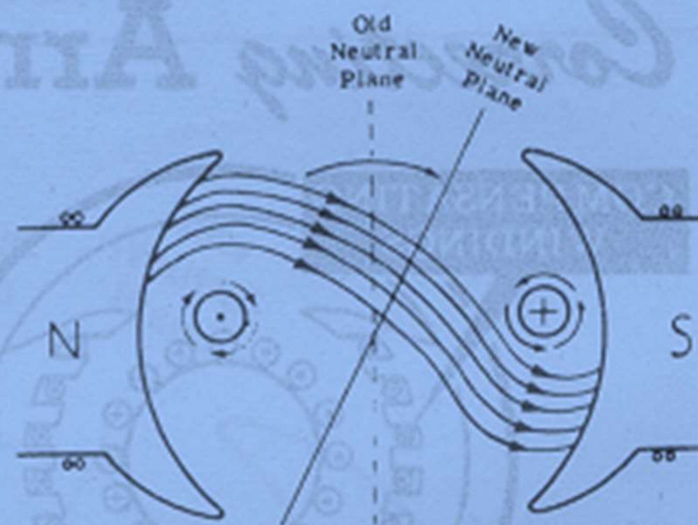
Shunt



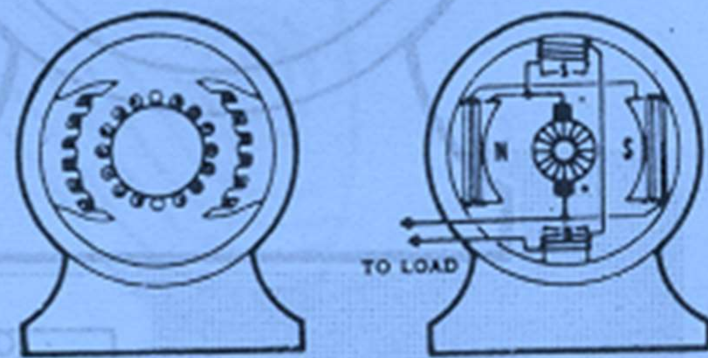
Compound



Armature Reaction. **Current flow in the armature coil generates a magnetic field at right angles to that of the generator field poles. The resultant total field shifts the neutral plane.**



Compensating Windings are additional windings placed in the pole face carrying the armature current, but of opposite polarity so as to counteract the armature field. *Interpoles* are small poles mounted between the main field windings to generate a field opposite to that of the armature coil. The purpose of both compensatory windings and interpoles is to correct for armature reaction.



Voltage Regulation is a measure of the steadiness of the output voltage when the load changes. It is expressed as a percentage.