ENERGY TRANSPORT AND CONVERSION

THE D.C. MOTOR

Lecture# 14

(Basic Electricity Book)

NCUK + (UET, LAHORE)

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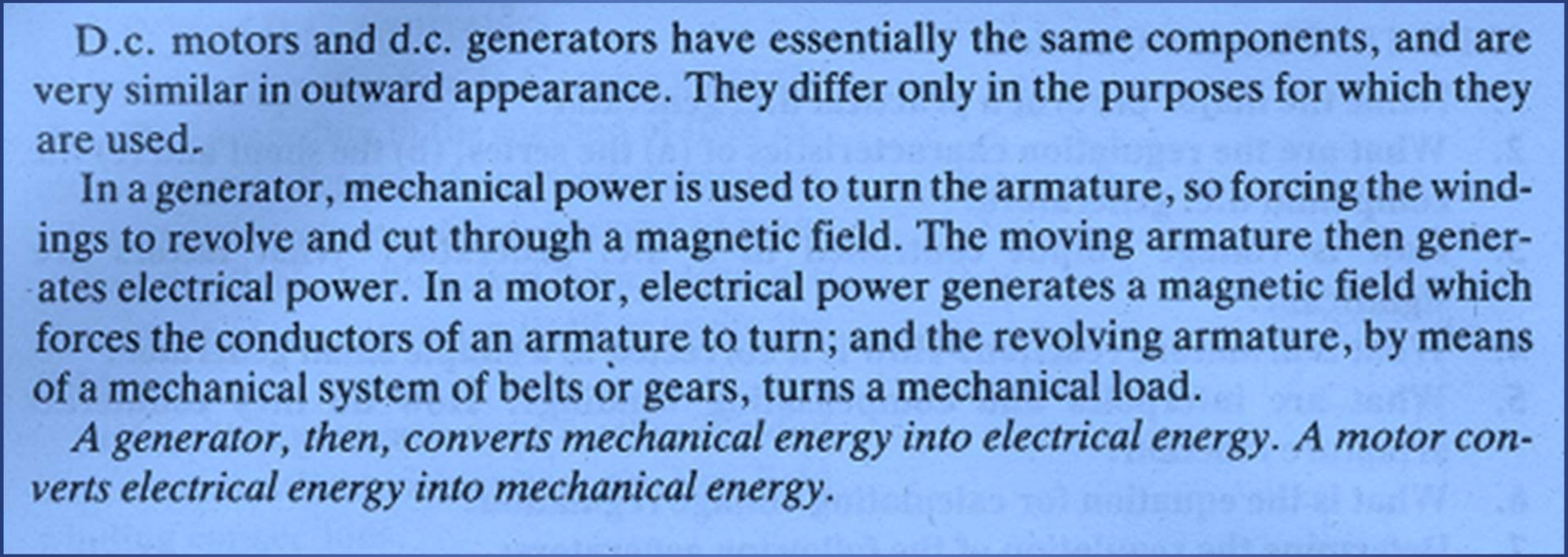
THE D.C MOTOR

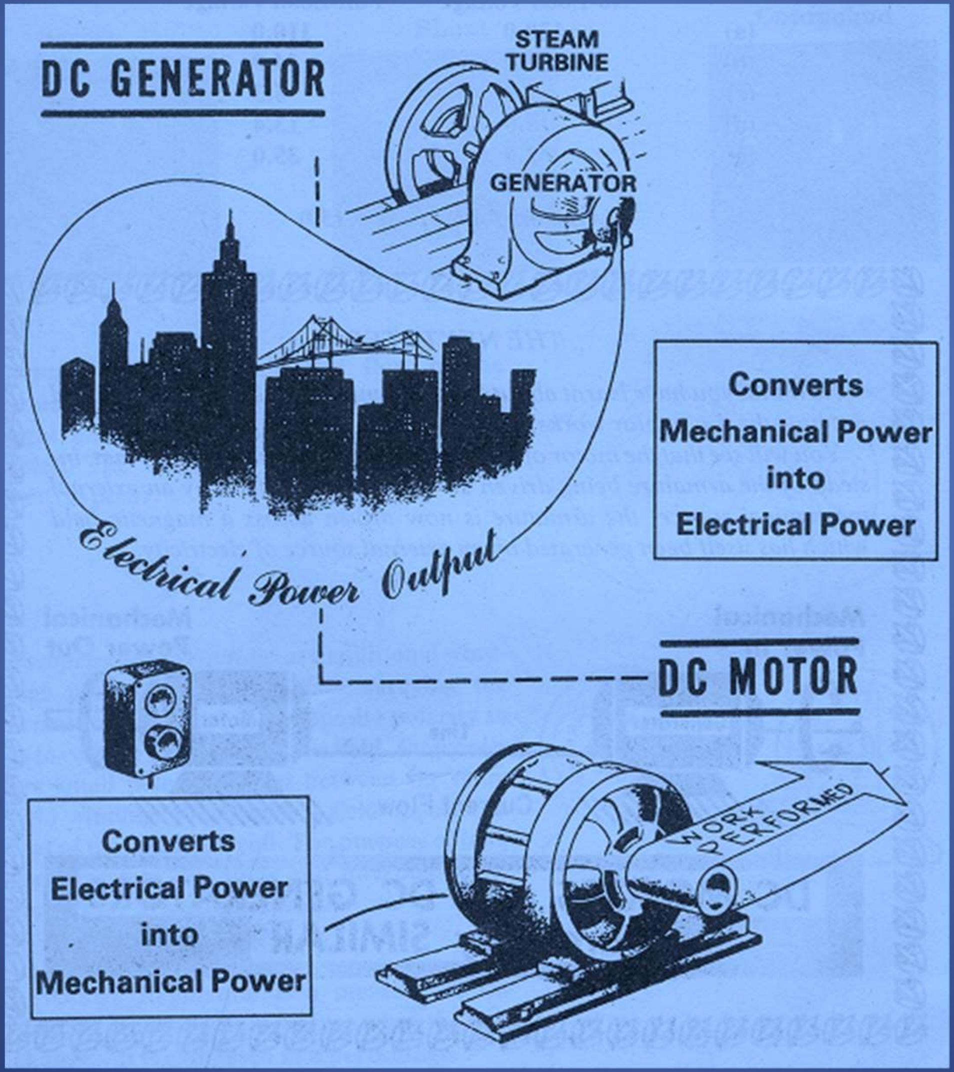


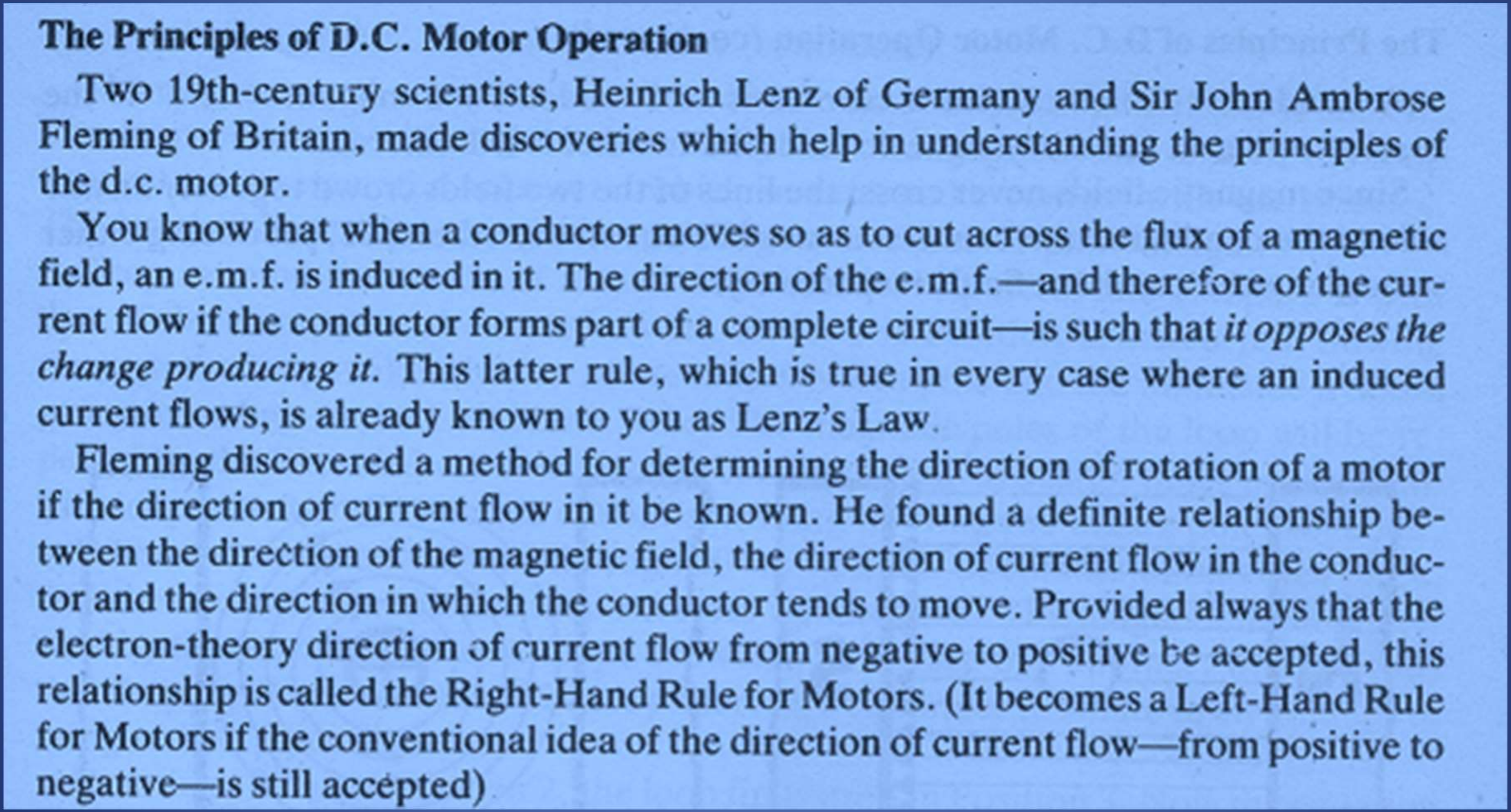
D.c. motors and d.c. generators have essentially the same components, and are very similar in outward appearance. They differ only in the purposes for which they are used.

In a generator, mechanical power is used to turn the armature, so forcing the windings to revolve and cut through a magnetic field. The moving armature then generates electrical power. In a motor, electrical power generates a magnetic field which forces the conductors of an armature to turn; and the revolving armature, by means of a mechanical system of belts or gears, turns a mechanical load.

A generator, then, converts mechanical energy into electrical energy. A motor converts electrical energy into mechanical energy.

D.C MOTOR


DC GENERATOR
STEAM TURBINE
GENERATOR
Electrical Power Output
Converts Mechanical Power into Electrical Power
DC MOTOR
WORK PERFORMED
Converts Electrical Power into Mechanical Power

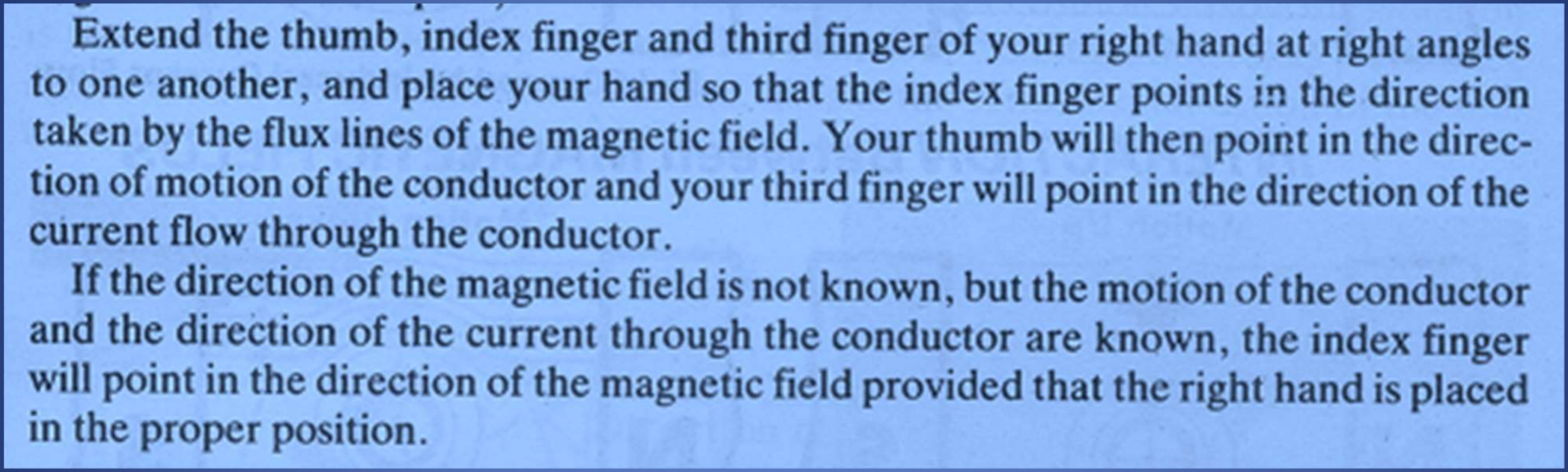


The Principles of D.C. Motor Operation

Two 19th-century scientists, Heinrich Lenz of Germany and Sir John Ambrose Fleming of Britain, made discoveries which help in understanding the principles of the d.c. motor.

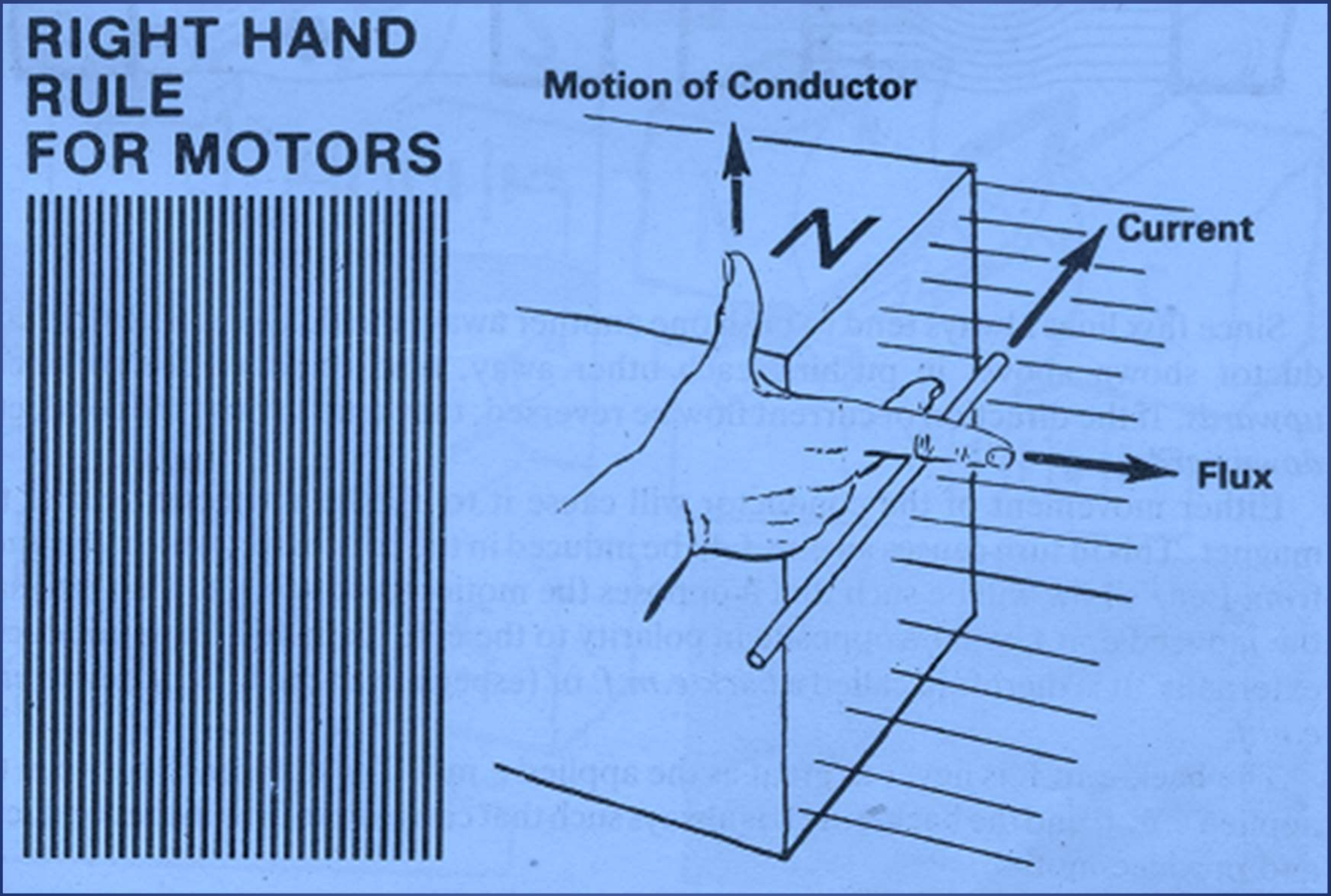
You know that when a conductor moves so as to cut across the flux of a magnetic field, an e.m.f. is induced in it. The direction of the e.m.f.—and therefore of the current flow if the conductor forms part of a complete circuit—is such that *it opposes the change producing it.* This latter rule, which is true in every case where an induced current flows, is already known to you as Lenz's Law.

Fleming discovered a method for determining the direction of rotation of a motor if the direction of current flow in it be known. He found a definite relationship between the direction of the magnetic field, the direction of current flow in the conductor and the direction in which the conductor tends to move. Provided always that the electron-theory direction of current flow from negative to positive be accepted, this relationship is called the Right-Hand Rule for Motors. (It becomes a Left-Hand Rule for Motors if the conventional idea of the direction of current flow—from positive to negative—is still accepted)

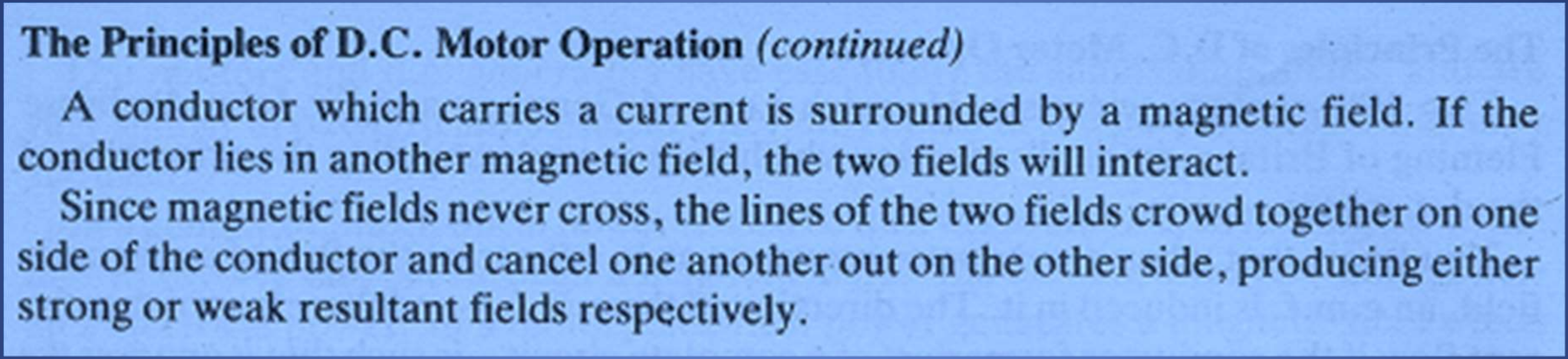


Extend the thumb, index finger and third finger of your right hand at right angles to one another, and place your hand so that the index finger points in the direction taken by the flux lines of the magnetic field. Your thumb will then point in the direction of motion of the conductor and your third finger will point in the direction of the current flow through the conductor.

If the direction of the magnetic field is not known, but the motion of the conductor and the direction of the current through the conductor are known, the index finger will point in the direction of the magnetic field provided that the right hand is placed in the proper position.



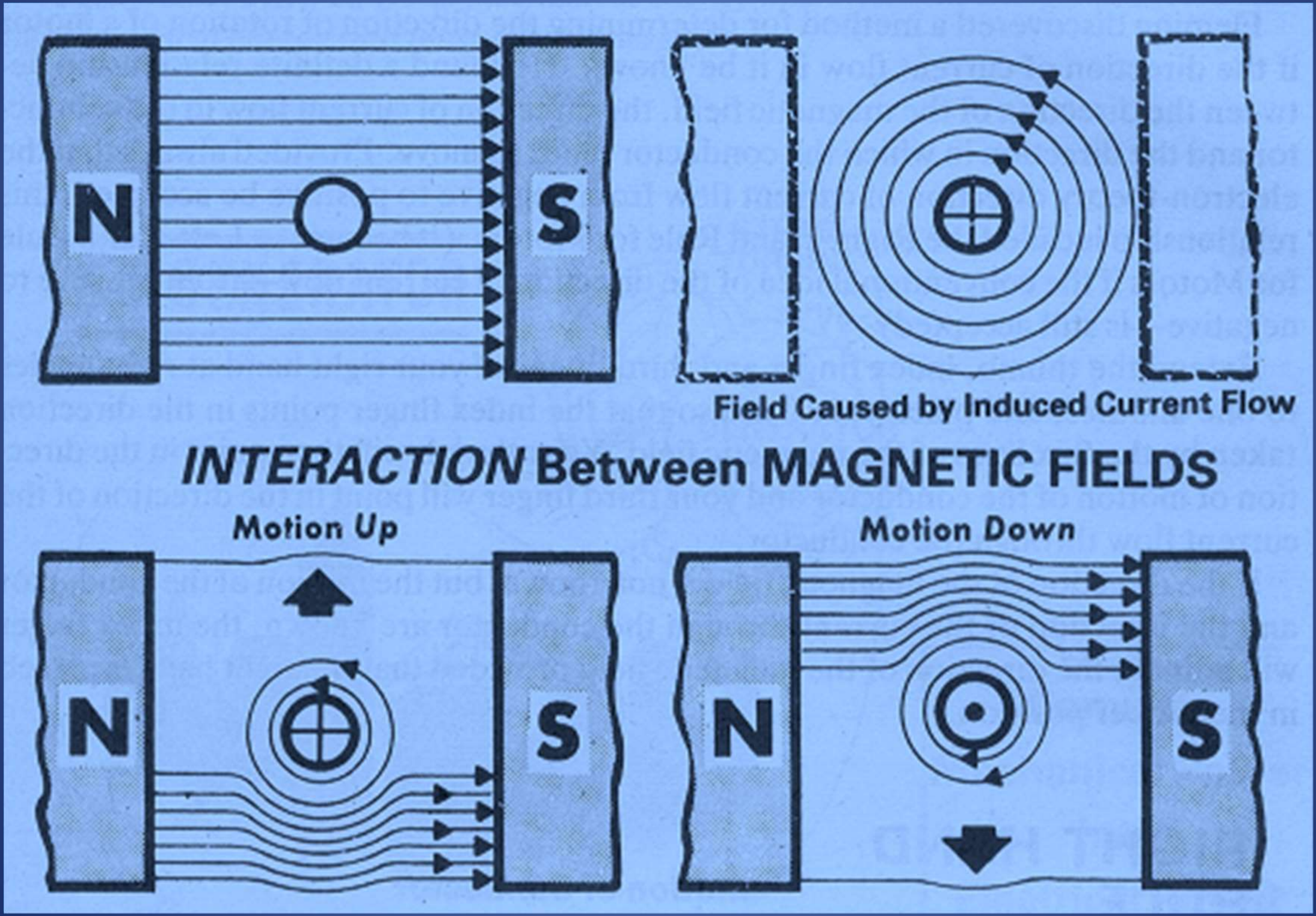
RIGHT HAND RULE FOR MOTORS

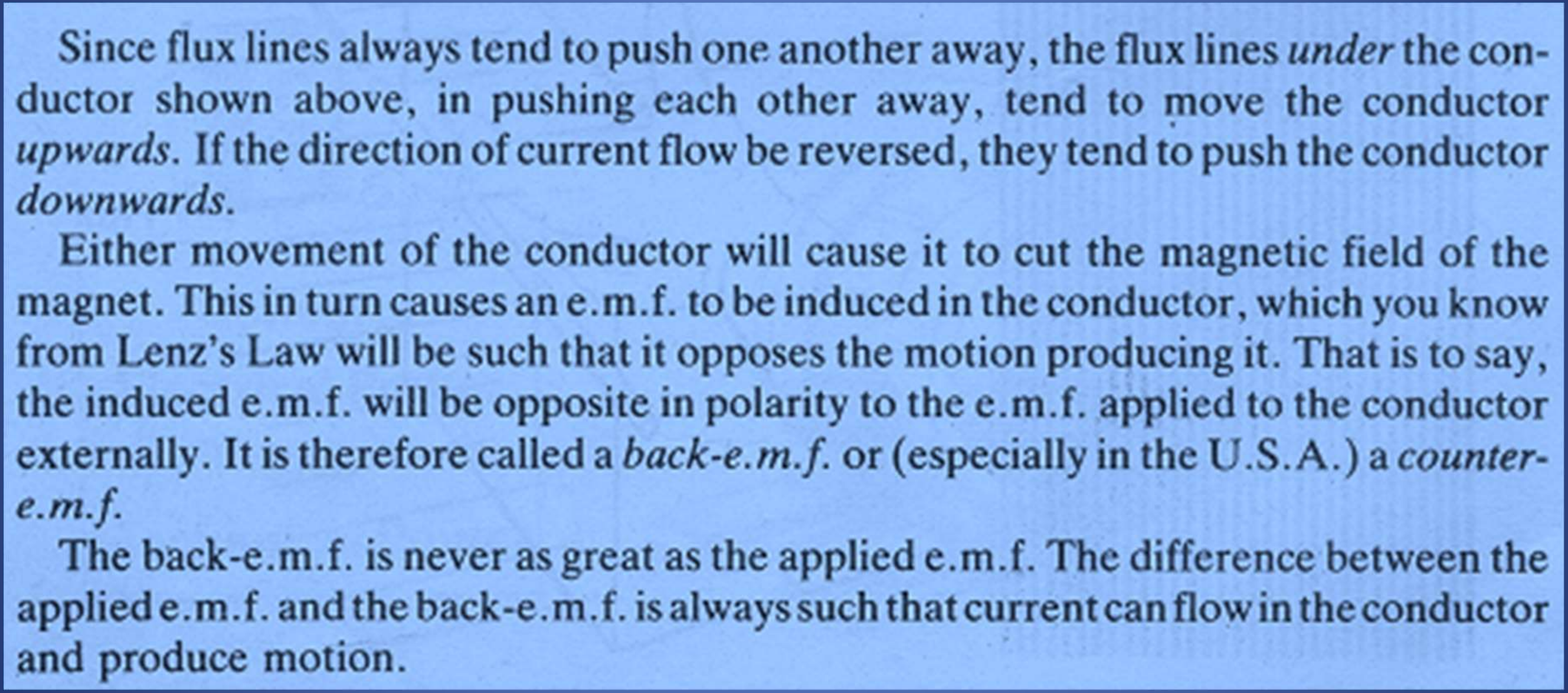


The Principles of D.C. Motor Operation *(continued)*

A conductor which carries a current is surrounded by a magnetic field. If the conductor lies in another magnetic field, the two fields will interact.

Since magnetic fields never cross, the lines of the two fields crowd together on one side of the conductor and cancel one another out on the other side, producing either strong or weak resultant fields respectively.

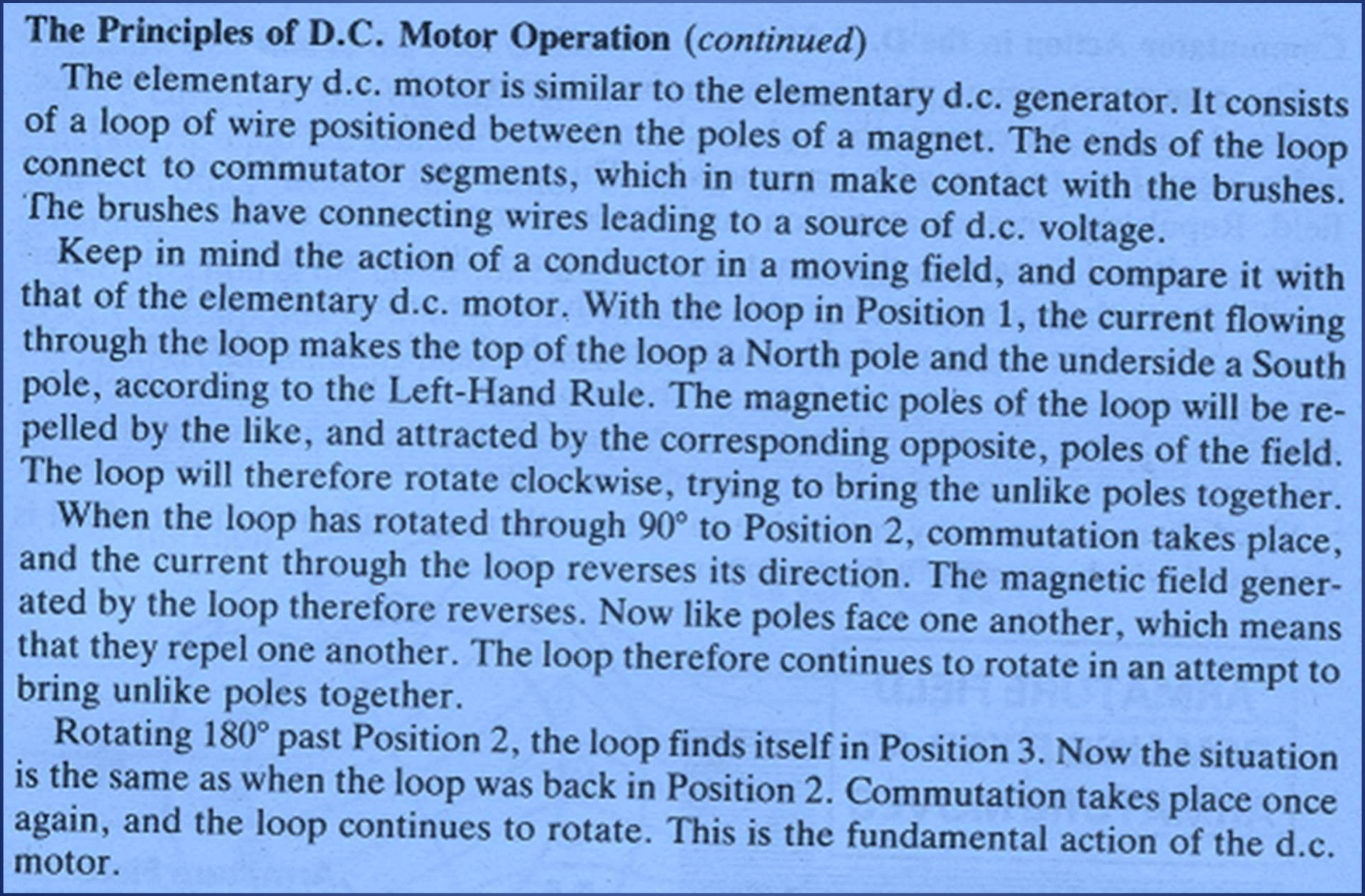

N
S
Field Caused by Induced Current Flow
INTERACTION Between MAGNETIC FIELDS
Motion Up
Motion Down
N
S
N
S



Since flux lines always tend to push one another away, the flux lines *under* the conductor shown above, in pushing each other away, tend to move the conductor *upwards*. If the direction of current flow be reversed, they tend to push the conductor *downwards*.

Either movement of the conductor will cause it to cut the magnetic field of the magnet. This in turn causes an e.m.f. to be induced in the conductor, which you know from Lenz's Law will be such that it opposes the motion producing it. That is to say, the induced e.m.f. will be opposite in polarity to the e.m.f. applied to the conductor externally. It is therefore called a *back-e.m.f.* or (especially in the U.S.A.) a *counter-e.m.f.*

The back-e.m.f. is never as great as the applied e.m.f. The difference between the applied e.m.f. and the back-e.m.f. is always such that current can flow in the conductor and produce motion.



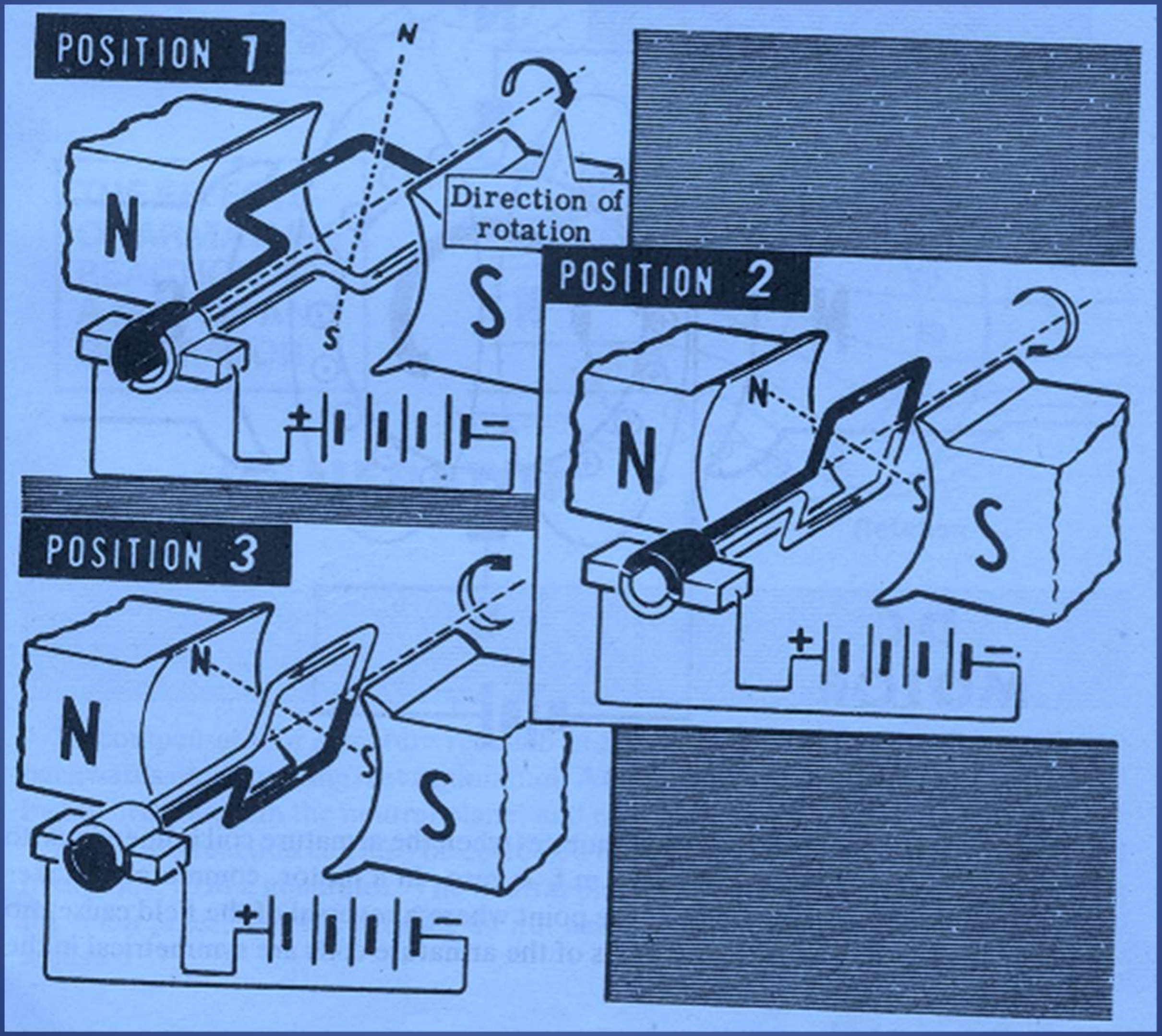
The Principles of D.C. Motor Operation (*continued*)

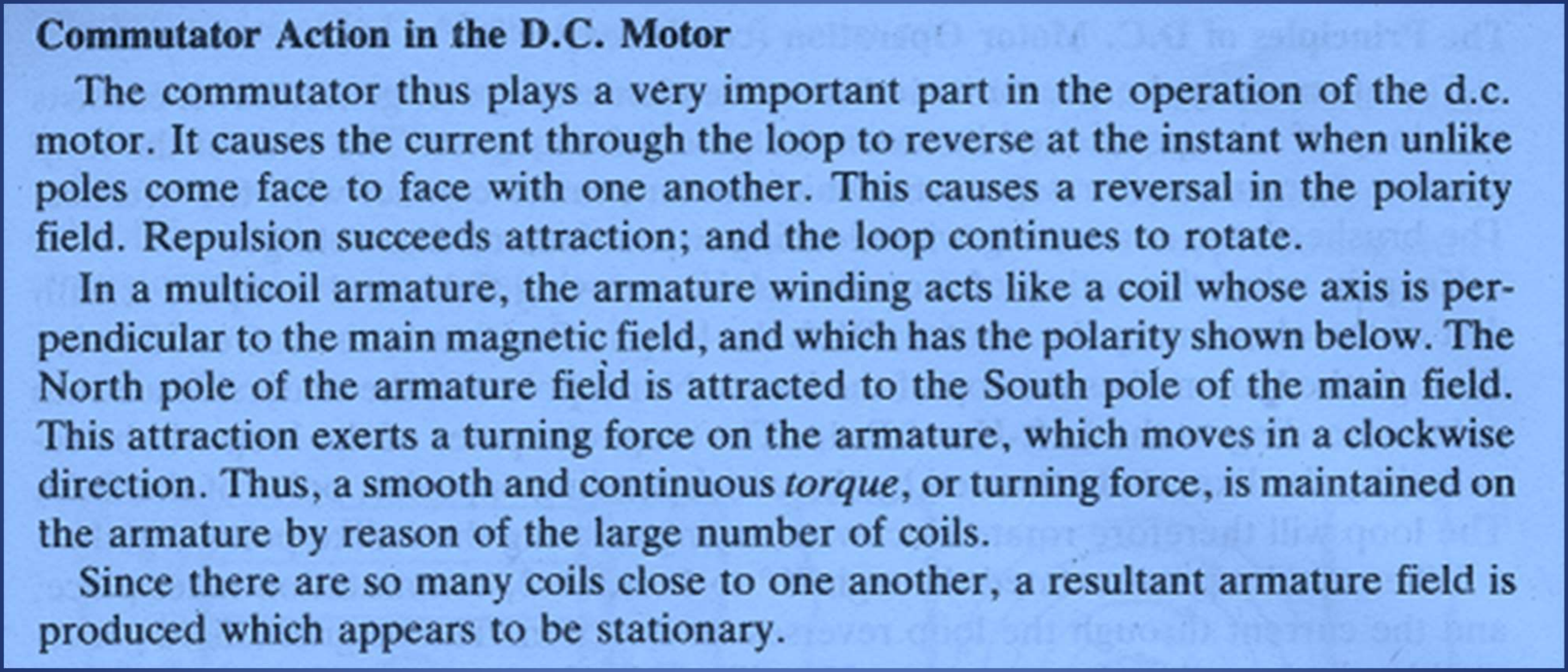
The elementary d.c. motor is similar to the elementary d.c. generator. It consists of a loop of wire positioned between the poles of a magnet. The ends of the loop connect to commutator segments, which in turn make contact with the brushes. The brushes have connecting wires leading to a source of d.c. voltage.

Keep in mind the action of a conductor in a moving field, and compare it with that of the elementary d.c. motor. With the loop in Position 1, the current flowing through the loop makes the top of the loop a North pole and the underside a South pole, according to the Left-Hand Rule. The magnetic poles of the loop will be repelled by the like, and attracted by the corresponding opposite, poles of the field. The loop will therefore rotate clockwise, trying to bring the unlike poles together.

When the loop has rotated through 90° to Position 2, commutation takes place, and the current through the loop reverses its direction. The magnetic field generated by the loop therefore reverses. Now like poles face one another, which means that they repel one another. The loop therefore continues to rotate in an attempt to bring unlike poles together.

Rotating 180° past Position 2, the loop finds itself in Position 3. Now the situation is the same as when the loop was back in Position 2. Commutation takes place once again, and the loop continues to rotate. This is the fundamental action of the d.c. motor.


POSITION 1
N
S
N
S
Direction of rotation
+
−
POSITION 2
N
S
N
S
+
−
POSITION 3
N
S
N
S
+
−

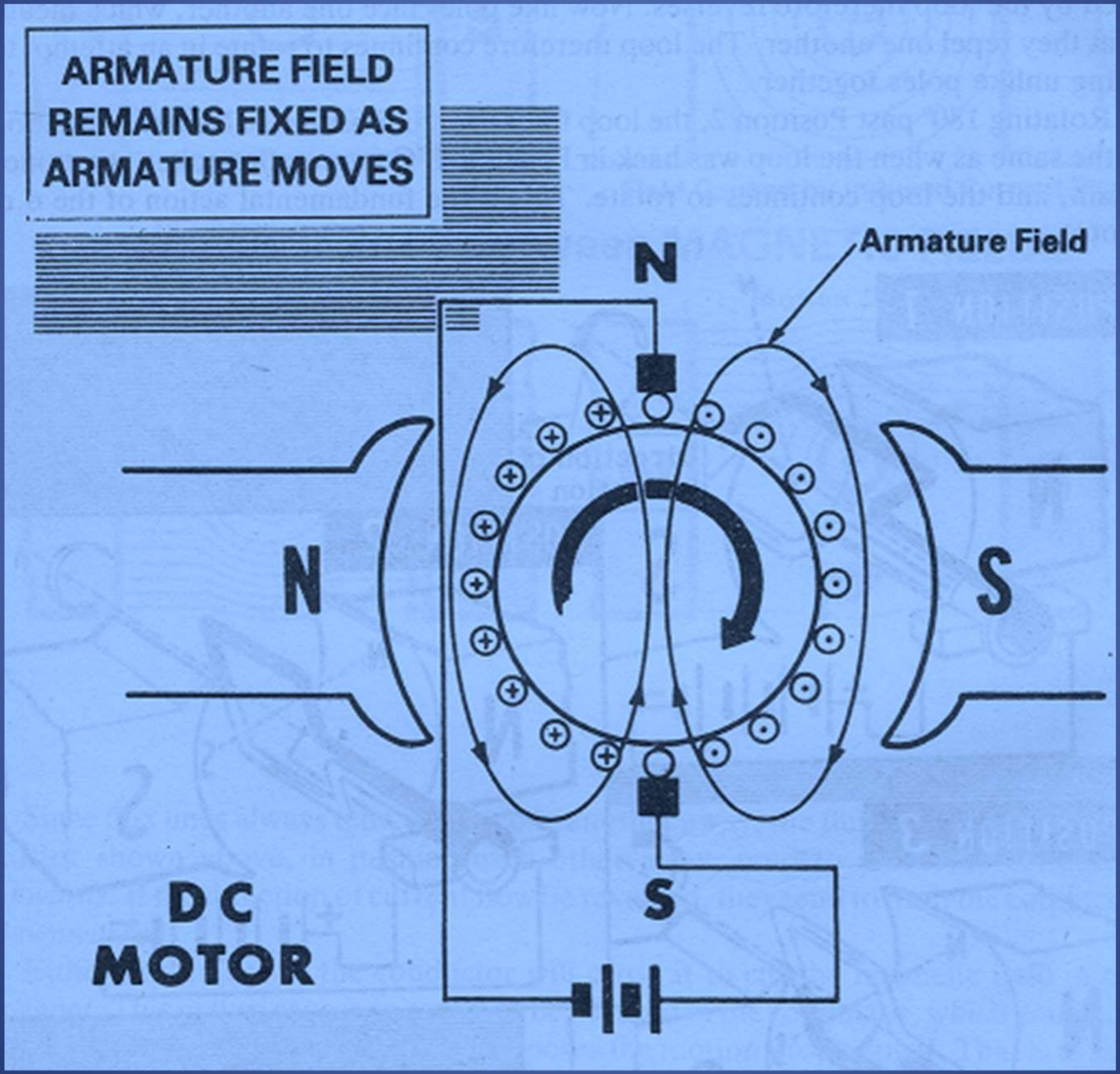


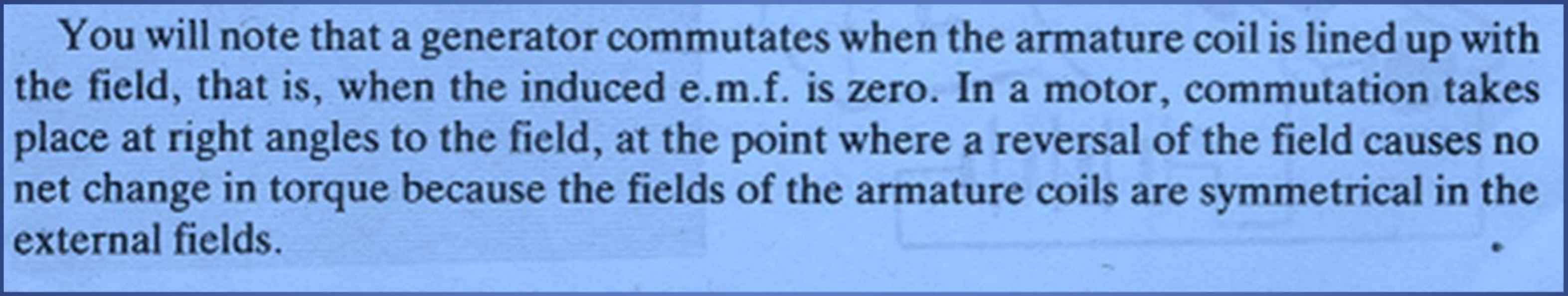
Commutator Action in the D.C. Motor

The commutator thus plays a very important part in the operation of the d.c. motor. It causes the current through the loop to reverse at the instant when unlike poles come face to face with one another. This causes a reversal in the polarity field. Repulsion succeeds attraction; and the loop continues to rotate.

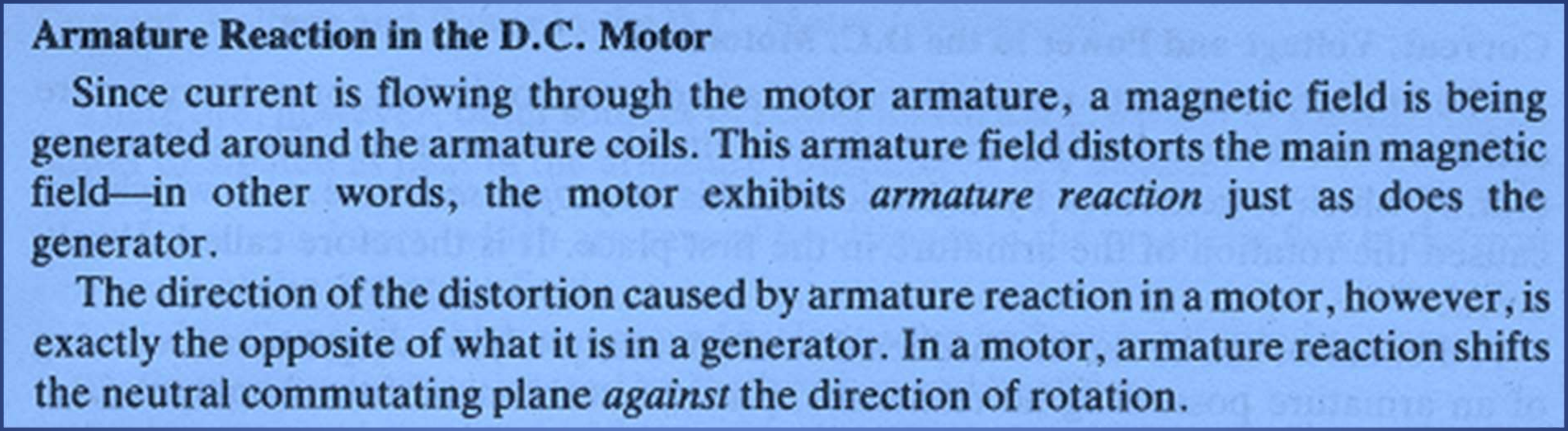
In a multicoil armature, the armature winding acts like a coil whose axis is perpendicular to the main magnetic field, and which has the polarity shown below. The North pole of the armature field is attracted to the South pole of the main field. This attraction exerts a turning force on the armature, which moves in a clockwise direction. Thus, a smooth and continuous *torque*, or turning force, is maintained on the armature by reason of the large number of coils.

Since there are so many coils close to one another, a resultant armature field is produced which appears to be stationary.


ARMATURE FIELD REMAINS FIXED AS ARMATURE MOVES
Armature Field
N
N
S
S
D C MOTOR



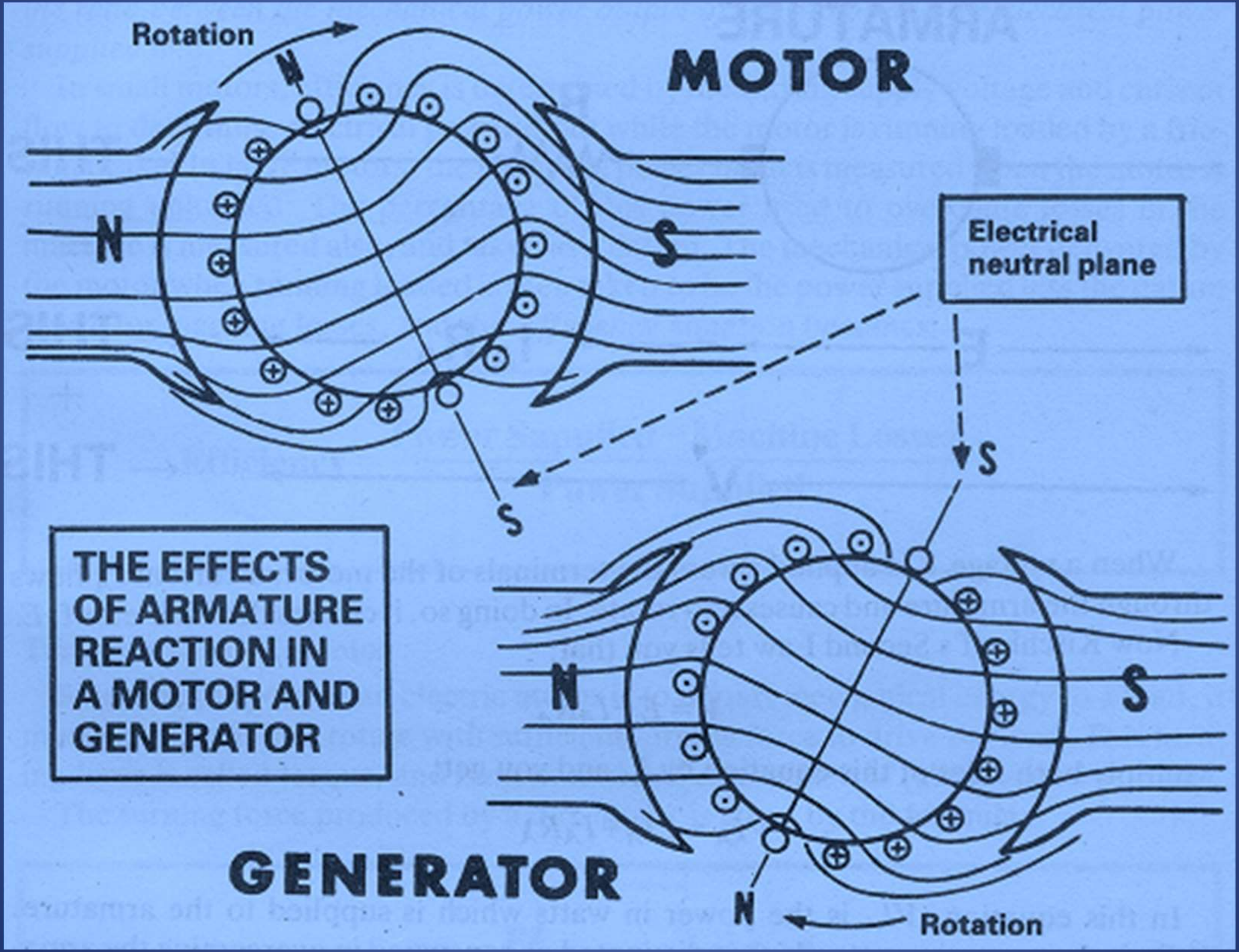
You will note that a generator commutates when the armature coil is lined up with the field, that is, when the induced e.m.f. is zero. In a motor, commutation takes place at right angles to the field, at the point where a reversal of the field causes no net change in torque because the fields of the armature coils are symmetrical in the external fields.

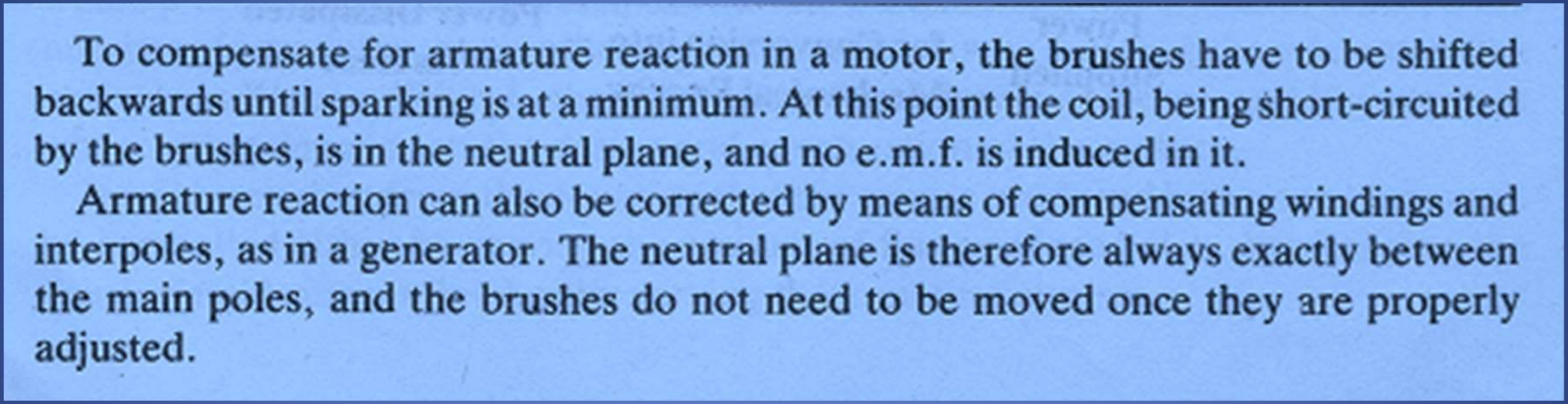


Armature Reaction in the D.C. Motor

Since current is flowing through the motor armature, a magnetic field is being generated around the armature coils. This armature field distorts the main magnetic field—in other words, the motor exhibits *armature reaction* just as does the generator.

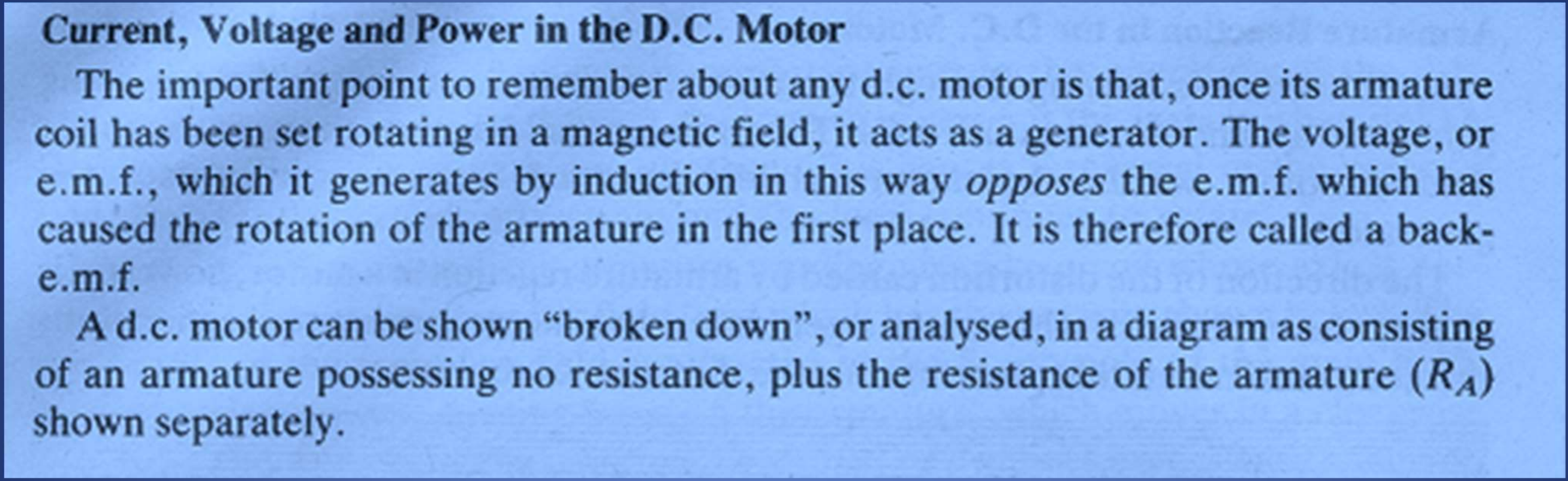
The direction of the distortion caused by armature reaction in a motor, however, is exactly the opposite of what it is in a generator. In a motor, armature reaction shifts the neutral commutating plane *against* the direction of rotation.


THE EFFECTS OF ARMATURE REACTION IN A MOTOR AND GENERATOR



To compensate for armature reaction in a motor, the brushes have to be shifted backwards until sparking is at a minimum. At this point the coil, being short-circuited by the brushes, is in the neutral plane, and no e.m.f. is induced in it.

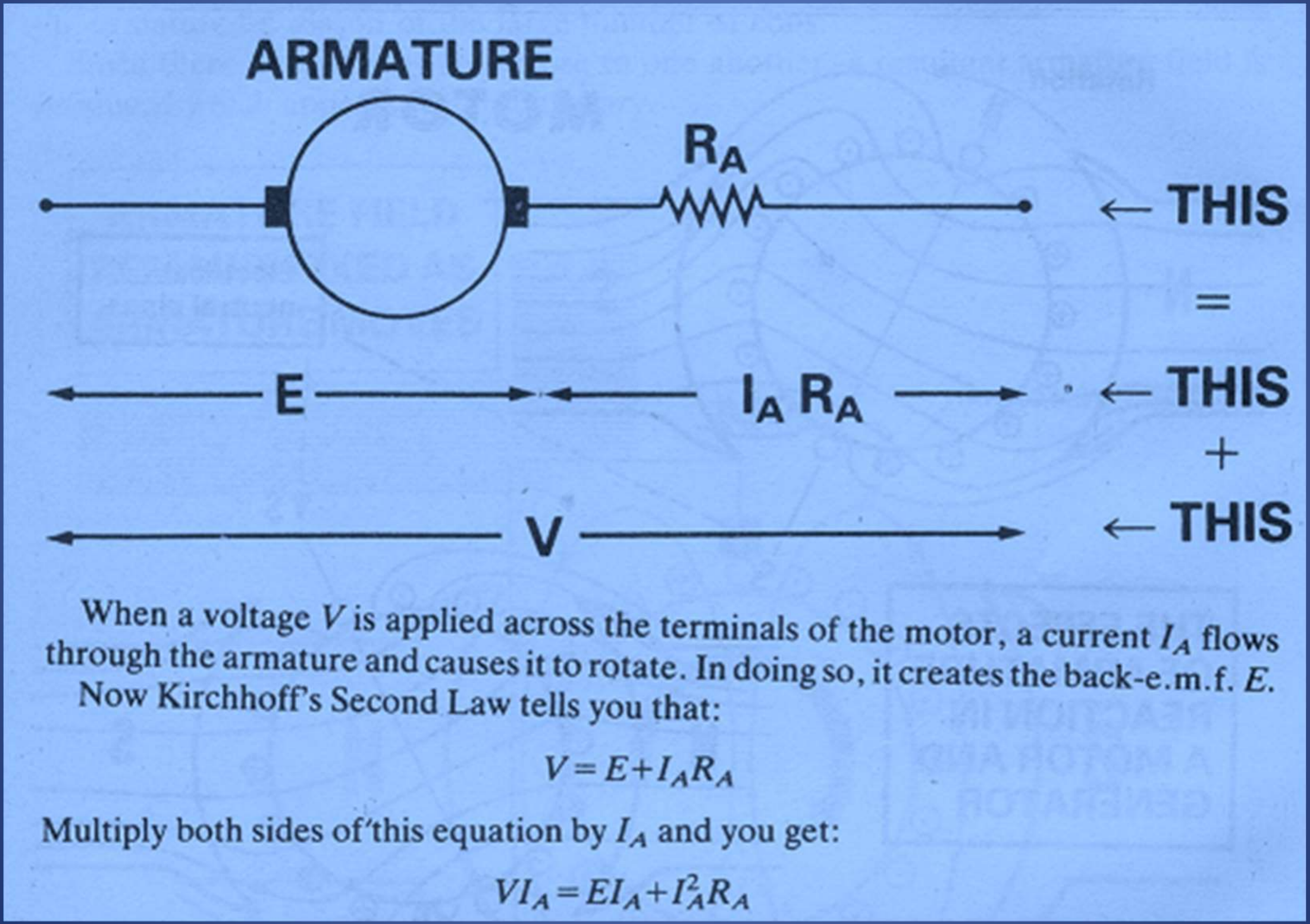
Armature reaction can also be corrected by means of compensating windings and interpoles, as in a generator. The neutral plane is therefore always exactly between the main poles, and the brushes do not need to be moved once they are properly adjusted.



Current, Voltage and Power in the D.C. Motor

The important point to remember about any d.c. motor is that, once its armature coil has been set rotating in a magnetic field, it acts as a generator. The voltage, or e.m.f., which it generates by induction in this way *opposes* the e.m.f. which has caused the rotation of the armature in the first place. It is therefore called a back-e.m.f.

A d.c. motor can be shown "broken down", or analysed, in a diagram as consisting of an armature possessing no resistance, plus the resistance of the armature (R_A) shown separately.



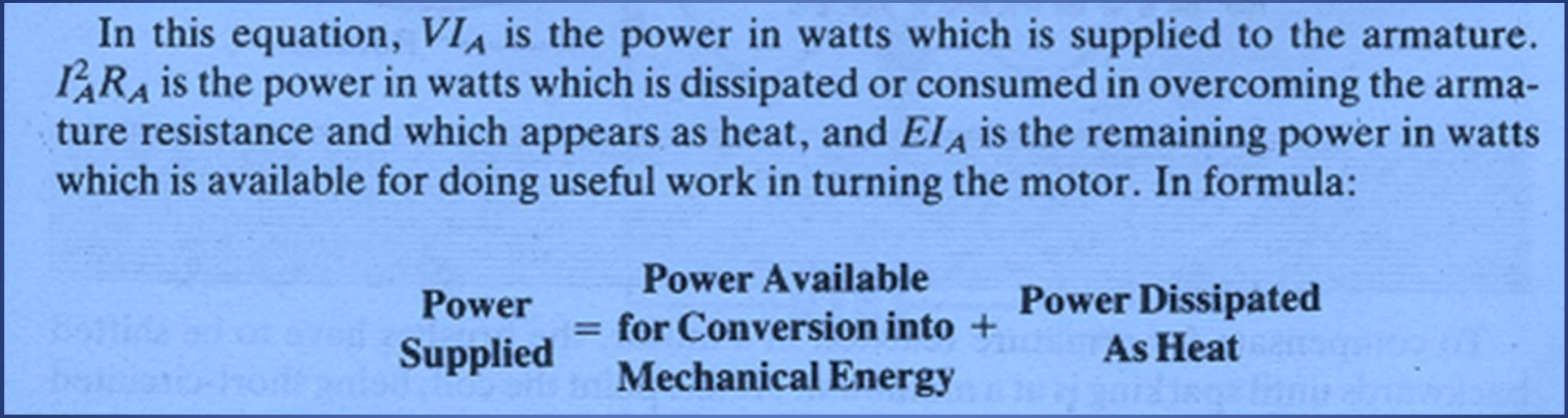
When a voltage V is applied across the terminals of the motor, a current I_A flows through the armature and causes it to rotate. In doing so, it creates the back-e.m.f. E.

Now Kirchhoff's Second Law tells you that:

$$V = E + I_A R_A$$

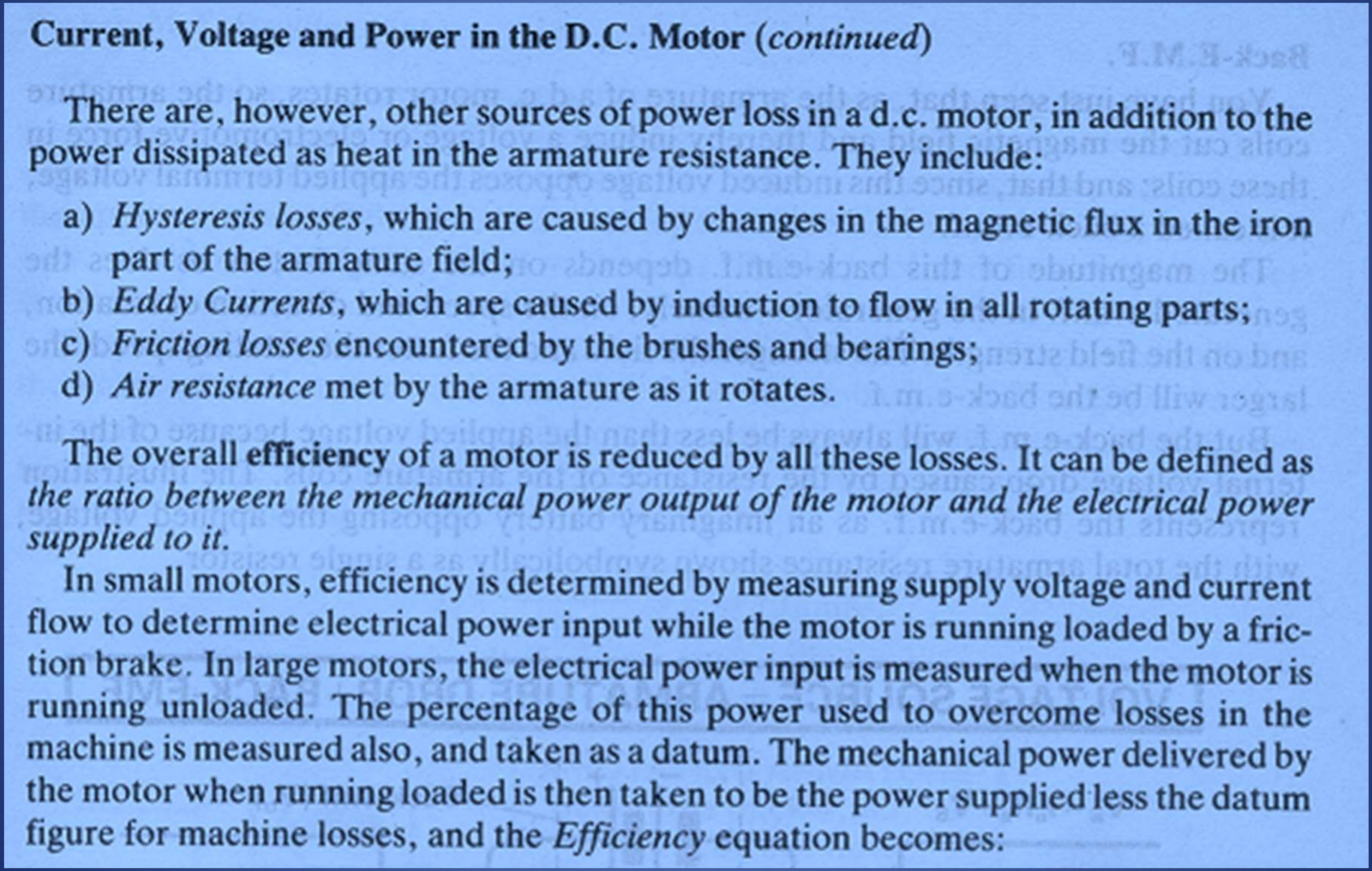
Multiply both sides of this equation by I_A and you get:

$$VI_A = EI_A + I_A^2 R_A$$



In this equation, VI_A is the power in watts which is supplied to the armature. $I_A^2R_A$ is the power in watts which is dissipated or consumed in overcoming the armature resistance and which appears as heat, and EI_A is the remaining power in watts which is available for doing useful work in turning the motor. In formula:

$$\begin{array}{c}\textbf{Power}\\\textbf{Supplied}\end{array} = \begin{array}{c}\textbf{Power Available}\\\textbf{for Conversion into}\\\textbf{Mechanical Energy}\end{array} + \begin{array}{c}\textbf{Power Dissipated}\\\textbf{As Heat}\end{array}$$



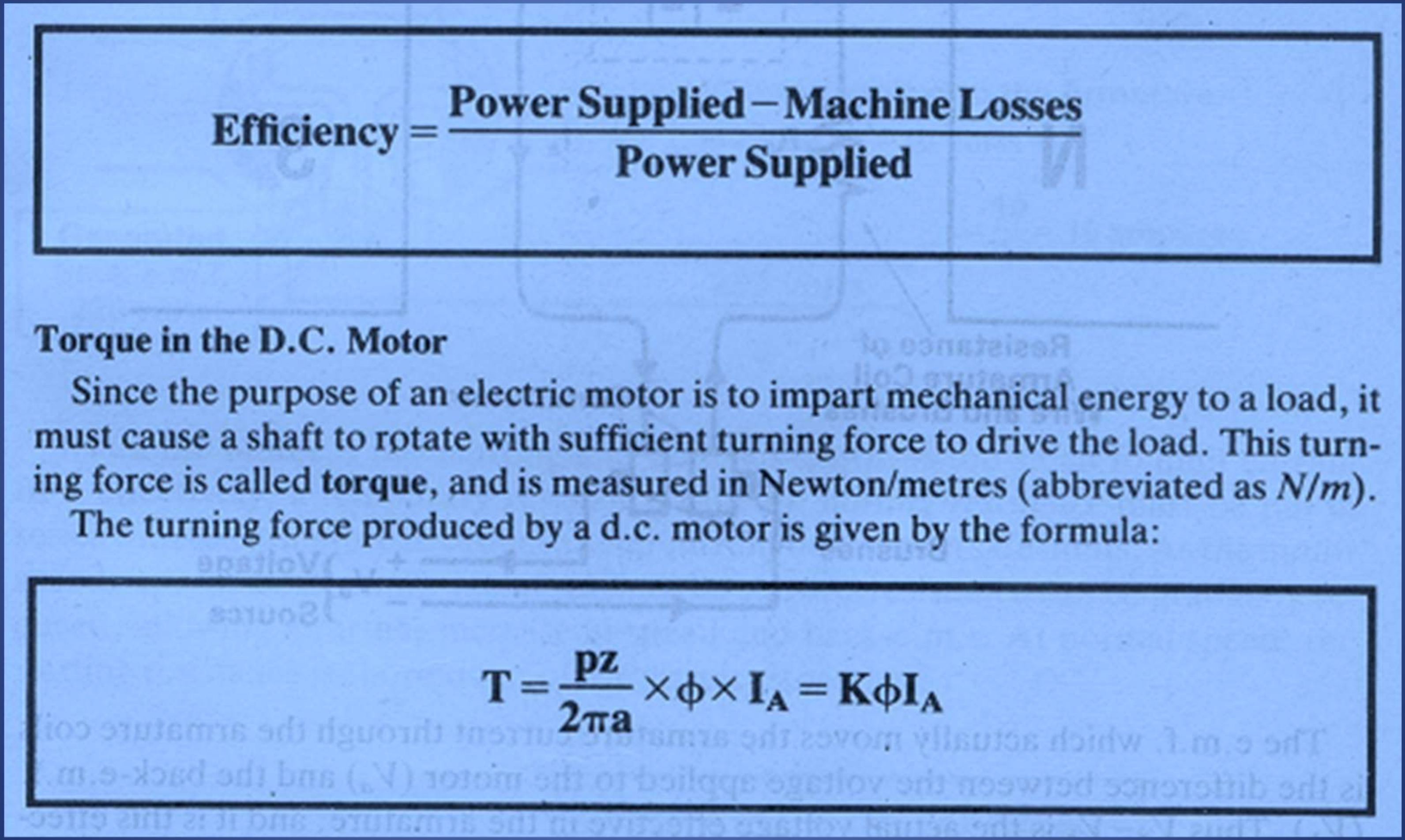
Current, Voltage and Power in the D.C. Motor (*continued*)

There are, however, other sources of power loss in a d.c. motor, in addition to the power dissipated as heat in the armature resistance. They include:

a) *Hysteresis losses*, which are caused by changes in the magnetic flux in the iron part of the armature field;
b) *Eddy Currents*, which are caused by induction to flow in all rotating parts;
c) *Friction losses* encountered by the brushes and bearings;
d) *Air resistance* met by the armature as it rotates.

The overall **efficiency** of a motor is reduced by all these losses. It can be defined as *the ratio between the mechanical power output of the motor and the electrical power supplied to it.*

In small motors, efficiency is determined by measuring supply voltage and current flow to determine electrical power input while the motor is running loaded by a friction brake. In large motors, the electrical power input is measured when the motor is running unloaded. The percentage of this power used to overcome losses in the machine is measured also, and taken as a datum. The mechanical power delivered by the motor when running loaded is then taken to be the power supplied less the datum figure for machine losses, and the *Efficiency* equation becomes:



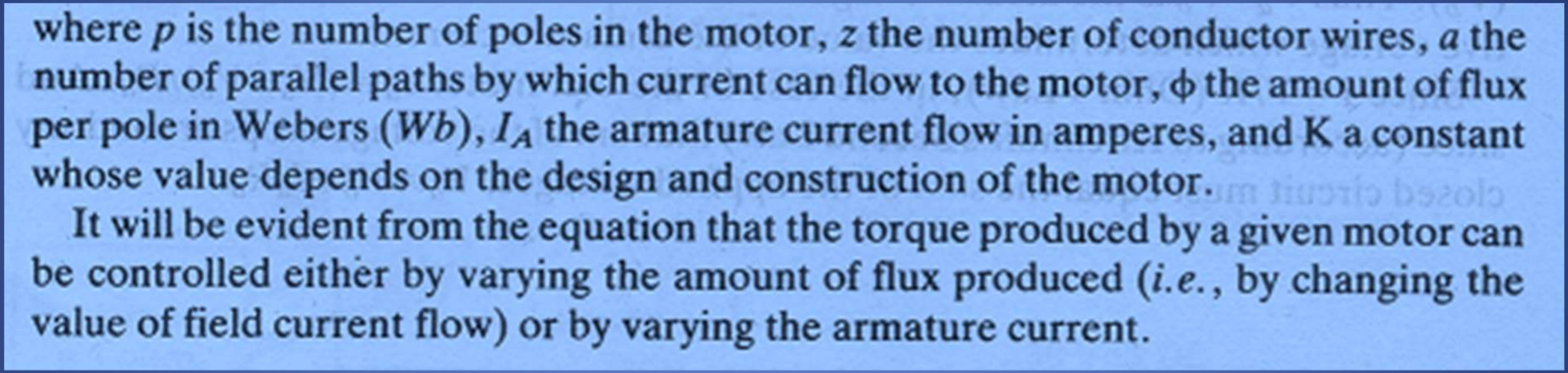
$$\text{Efficiency} = \frac{\text{Power Supplied} - \text{Machine Losses}}{\text{Power Supplied}}$$

Torque in the D.C. Motor

Since the purpose of an electric motor is to impart mechanical energy to a load, it must cause a shaft to rotate with sufficient turning force to drive the load. This turning force is called **torque**, and is measured in Newton/metres (abbreviated as *N/m*).

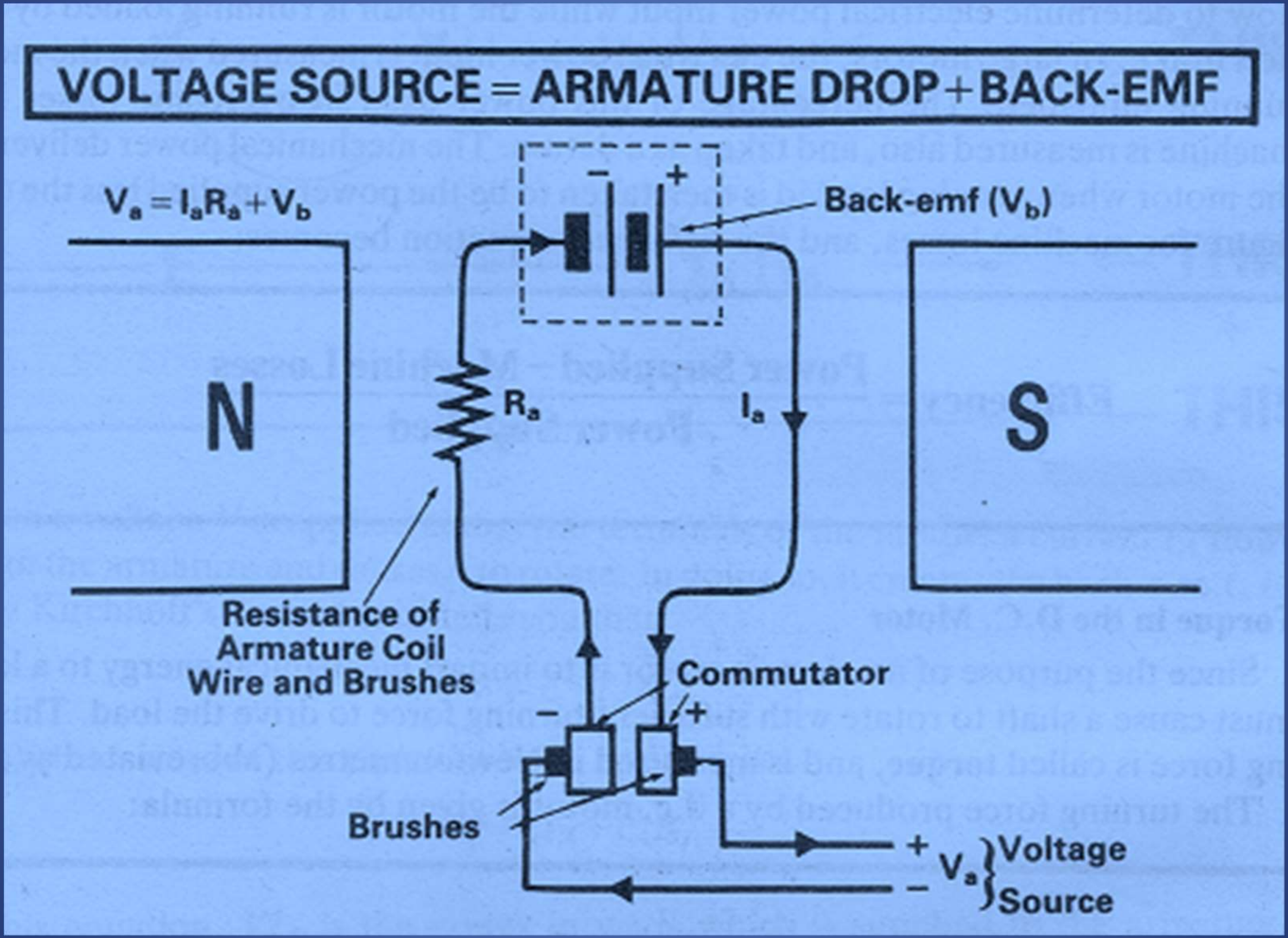
The turning force produced by a d.c. motor is given by the formula:

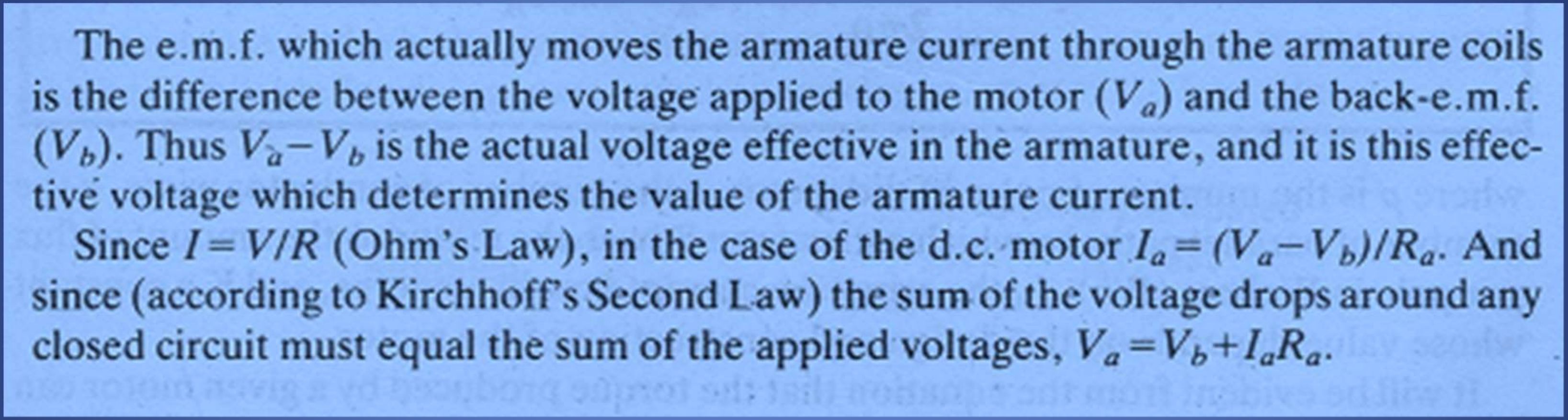
$$T = \frac{pz}{2\pi a} \times \phi \times I_A = K\phi I_A$$



where p is the number of poles in the motor, z the number of conductor wires, a the number of parallel paths by which current can flow to the motor, ϕ the amount of flux per pole in Webers (Wb), I_A the armature current flow in amperes, and K a constant whose value depends on the design and construction of the motor.

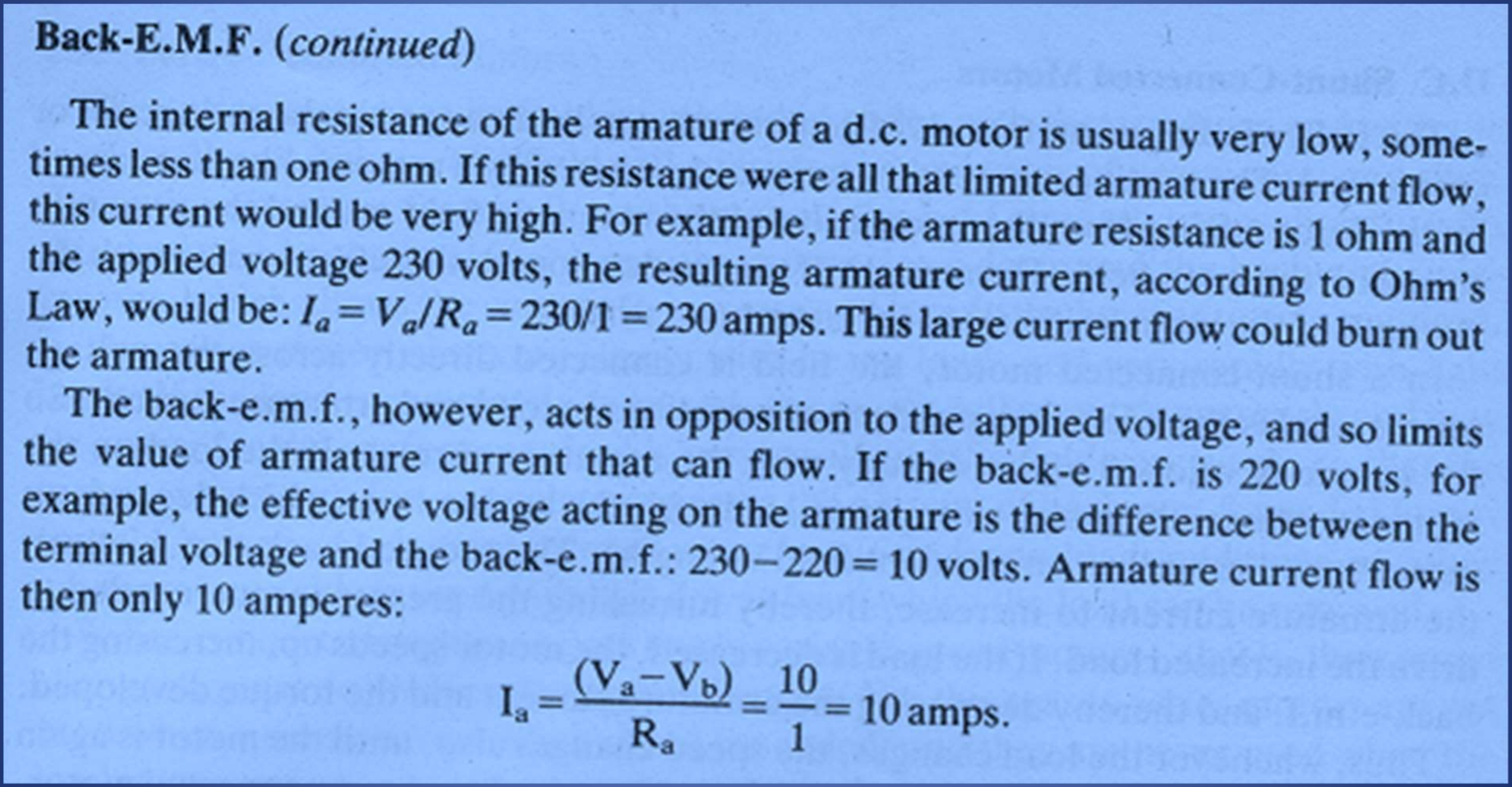
It will be evident from the equation that the torque produced by a given motor can be controlled either by varying the amount of flux produced (*i.e.*, by changing the value of field current flow) or by varying the armature current.


VOLTAGE SOURCE = ARMATURE DROP + BACK-EMF
$V_a = I_aR_a + V_b$
Back-emf (V_b)
−
+
N
S
R_a
I_a
Resistance of Armature Coil Wire and Brushes
Commutator
−
+
Brushes
+
−
V_a
Voltage Source



The e.m.f. which actually moves the armature current through the armature coils is the difference between the voltage applied to the motor (V_a) and the back-e.m.f. (V_b). Thus $V_a - V_b$ is the actual voltage effective in the armature, and it is this effective voltage which determines the value of the armature current.

Since $I = V/R$ (Ohm's Law), in the case of the d.c. motor $I_a = (V_a - V_b)/R_a$. And since (according to Kirchhoff's Second Law) the sum of the voltage drops around any closed circuit must equal the sum of the applied voltages, $V_a = V_b + I_a R_a$.

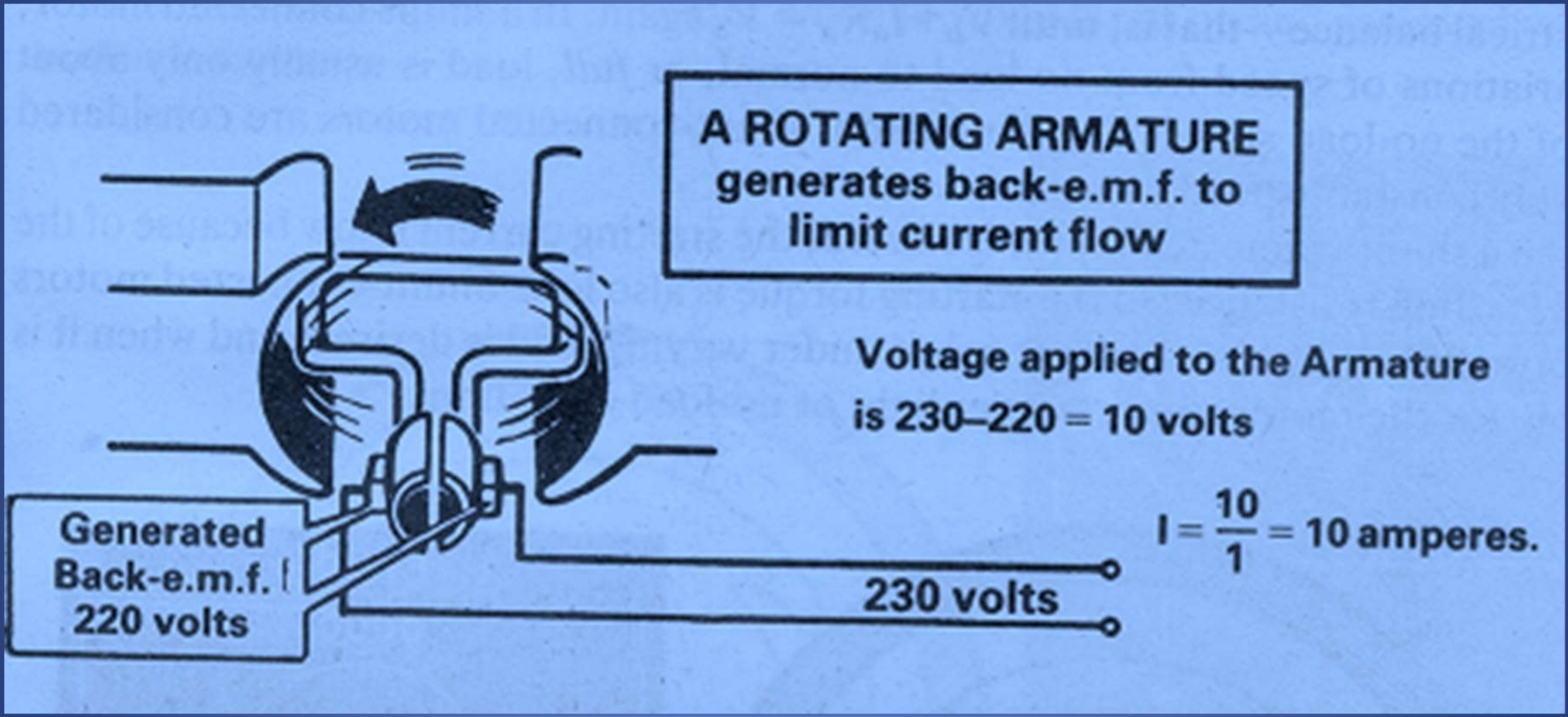


Back-E.M.F. (*continued*)

The internal resistance of the armature of a d.c. motor is usually very low, sometimes less than one ohm. If this resistance were all that limited armature current flow, this current would be very high. For example, if the armature resistance is 1 ohm and the applied voltage 230 volts, the resulting armature current, according to Ohm's Law, would be: $I_a = V_a/R_a = 230/1 = 230$ amps. This large current flow could burn out the armature.

The back-e.m.f., however, acts in opposition to the applied voltage, and so limits the value of armature current that can flow. If the back-e.m.f. is 220 volts, for example, the effective voltage acting on the armature is the difference between the terminal voltage and the back-e.m.f.: $230-220=10$ volts. Armature current flow is then only 10 amperes:

$$I_a = \frac{(V_a - V_b)}{R_a} = \frac{10}{1} = 10 \text{ amps.}$$

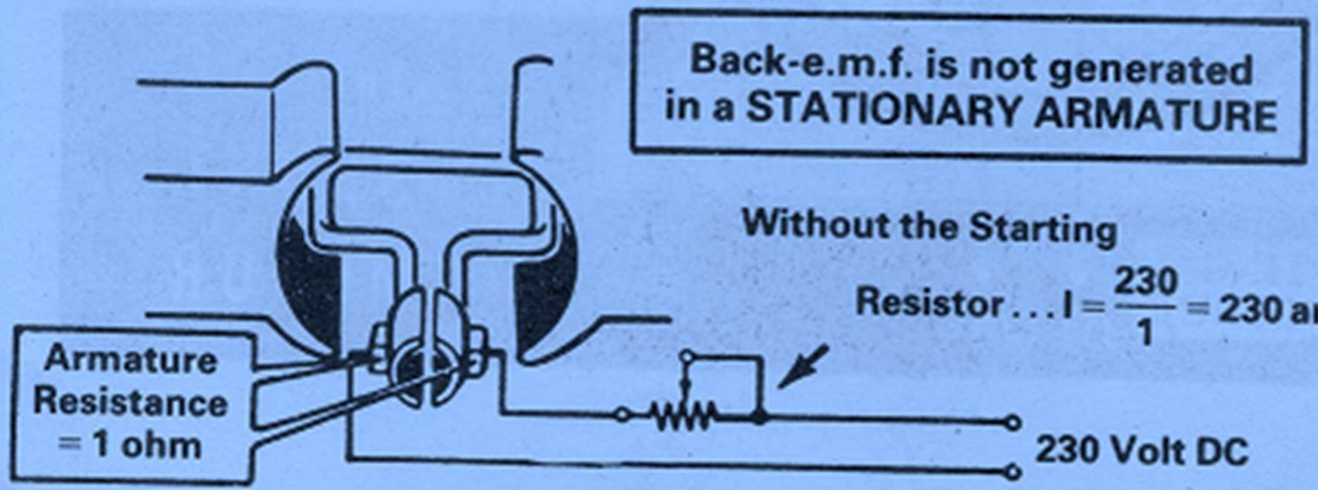


A ROTATING ARMATURE generates back-e.m.f. to limit current flow

Voltage applied to the Armature is 230–220 = 10 volts

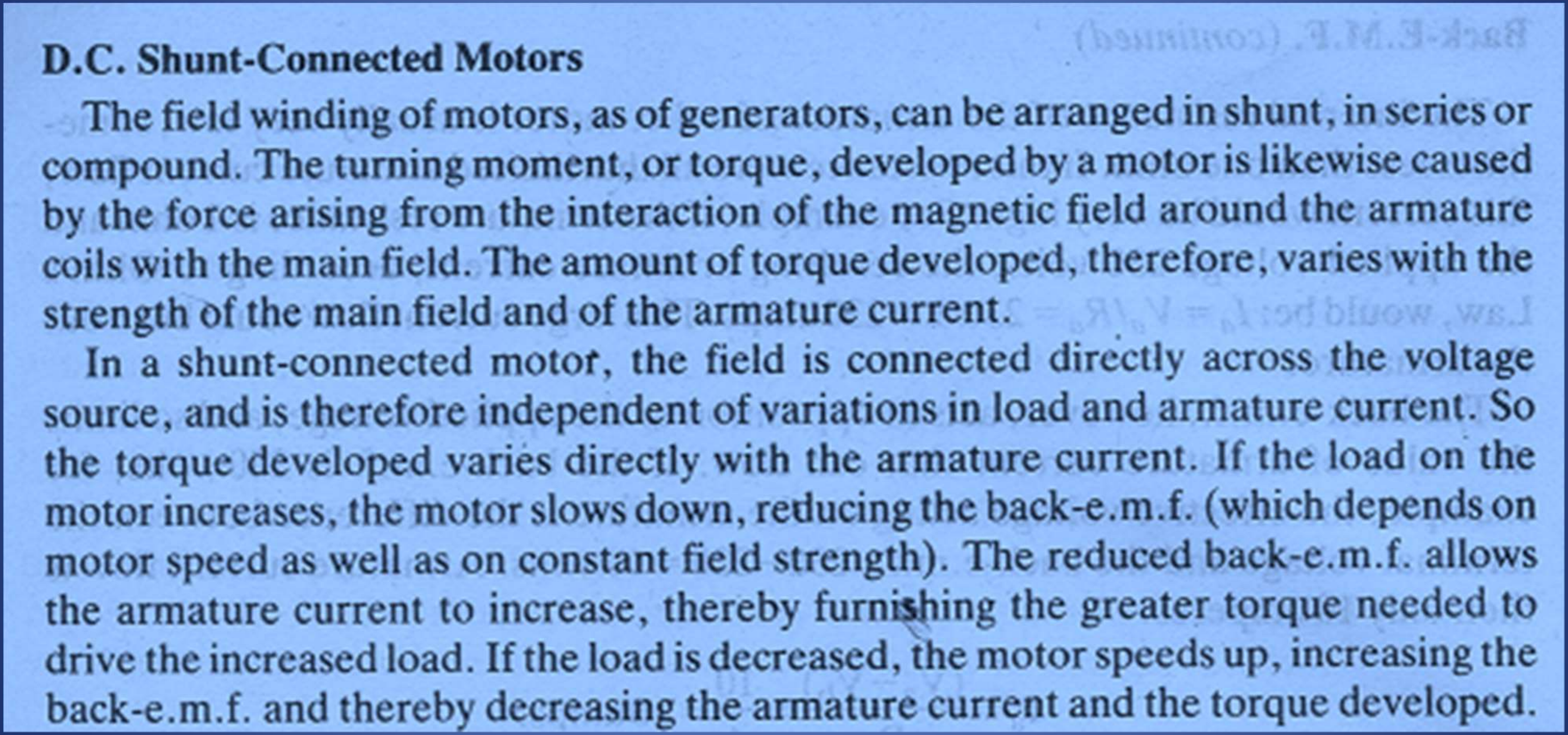
$$I = \frac{10}{1} = 10 \text{ amperes.}$$

When the motor is just starting and the back-e.m.f. is too small to limit current flow effectively, a temporary resistance called a *starting resistance* must be put in series with the armature in order to keep current flow within safe limits. As the motor speeds up, the back-e.m.f. increases and the starting resistance can be gradually reduced, allowing a further increase in speed and back-e.m.f. At normal speed, the tarting resistance is shorted out of the circuit altogether.



Back-e.m.f. is not generated in a STATIONARY ARMATURE

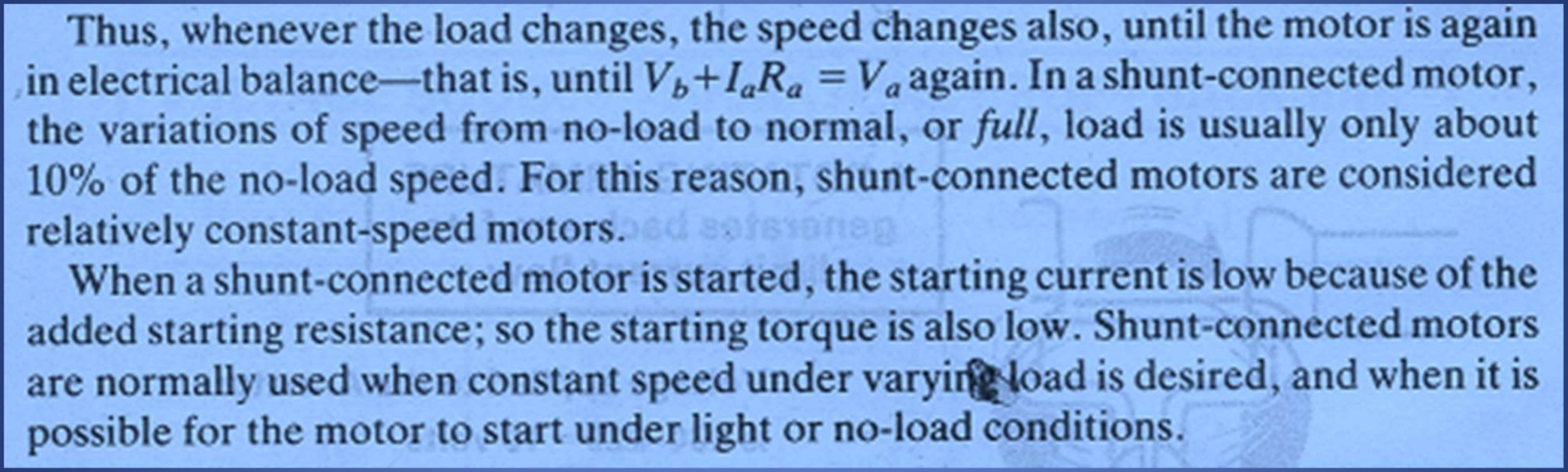
Without the Starting Resistor . . . $I = \frac{230}{1} = 230$ amperes.



D.C. Shunt-Connected Motors

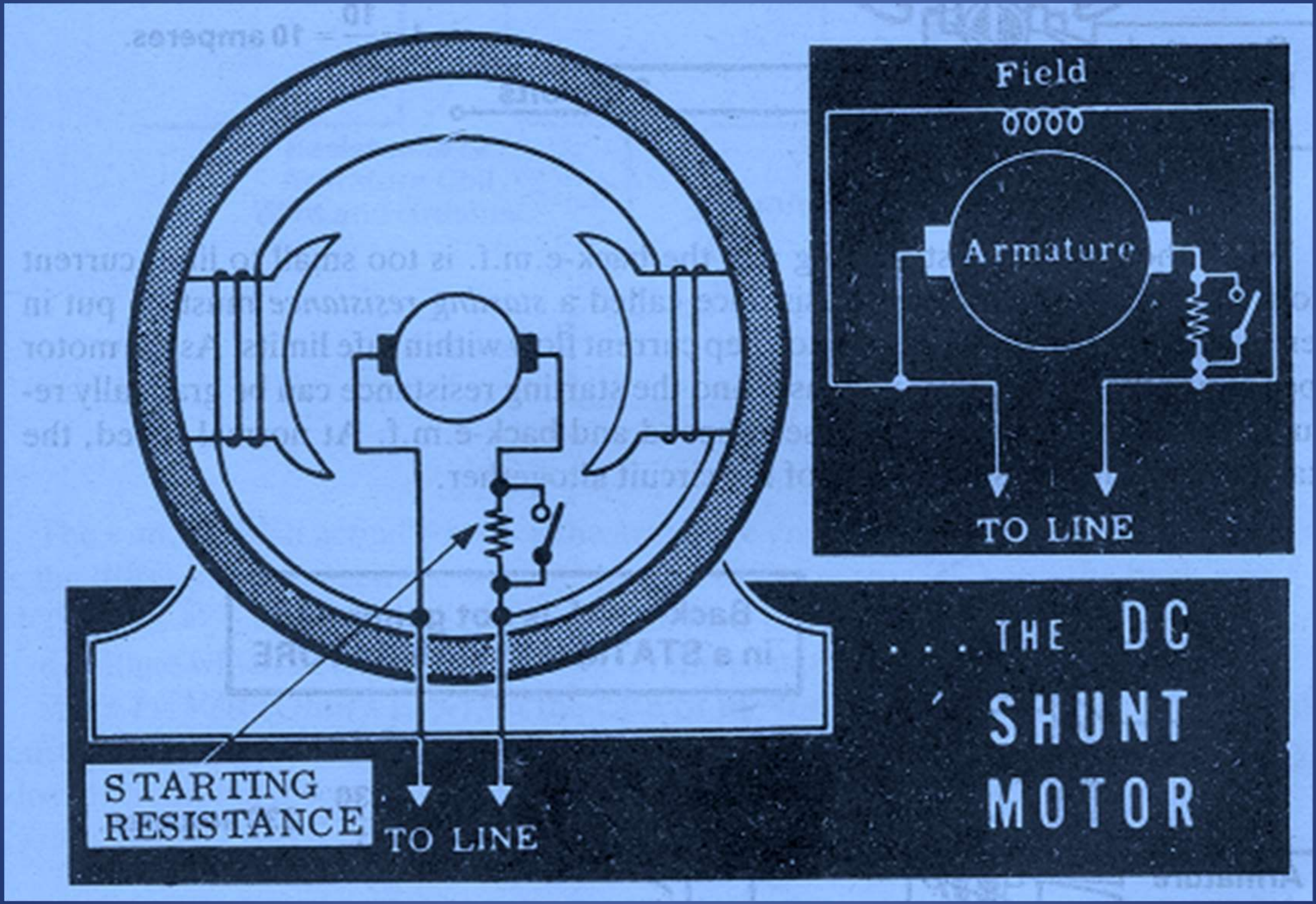
The field winding of motors, as of generators, can be arranged in shunt, in series or compound. The turning moment, or torque, developed by a motor is likewise caused by the force arising from the interaction of the magnetic field around the armature coils with the main field. The amount of torque developed, therefore, varies with the strength of the main field and of the armature current.

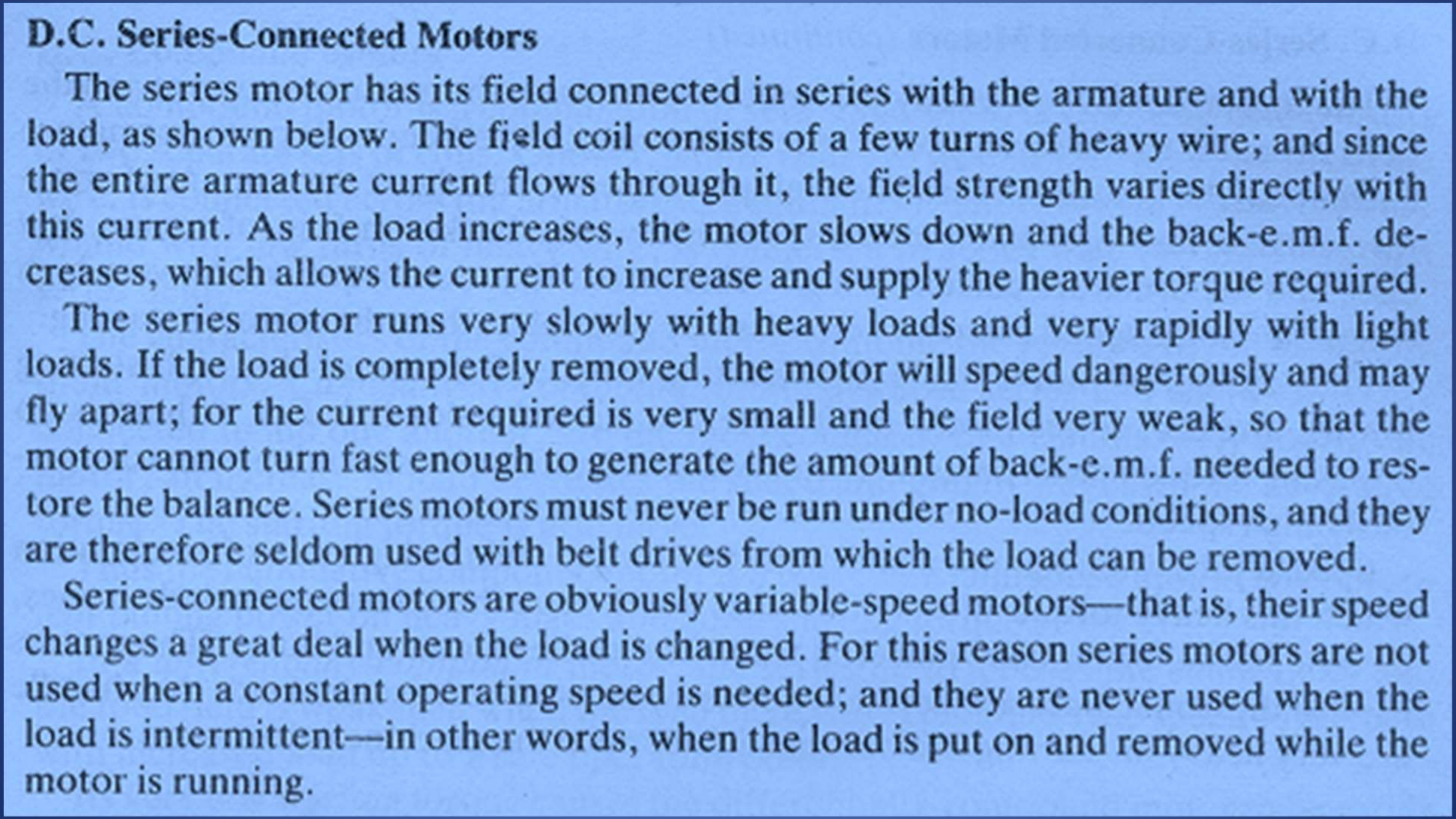
In a shunt-connected motor, the field is connected directly across the voltage source, and is therefore independent of variations in load and armature current. So the torque developed varies directly with the armature current. If the load on the motor increases, the motor slows down, reducing the back-e.m.f. (which depends on motor speed as well as on constant field strength). The reduced back-e.m.f. allows the armature current to increase, thereby furnishing the greater torque needed to drive the increased load. If the load is decreased, the motor speeds up, increasing the back-e.m.f. and thereby decreasing the armature current and the torque developed.



Thus, whenever the load changes, the speed changes also, until the motor is again in electrical balance—that is, until $V_b + I_a R_a = V_a$ again. In a shunt-connected motor, the variations of speed from no-load to normal, or *full*, load is usually only about 10% of the no-load speed. For this reason, shunt-connected motors are considered relatively constant-speed motors.

When a shunt-connected motor is started, the starting current is low because of the added starting resistance; so the starting torque is also low. Shunt-connected motors are normally used when constant speed under varying load is desired, and when it is possible for the motor to start under light or no-load conditions.


Field
Armature
TO LINE
STARTING RESISTANCE
TO LINE
. . . THE DC SHUNT MOTOR

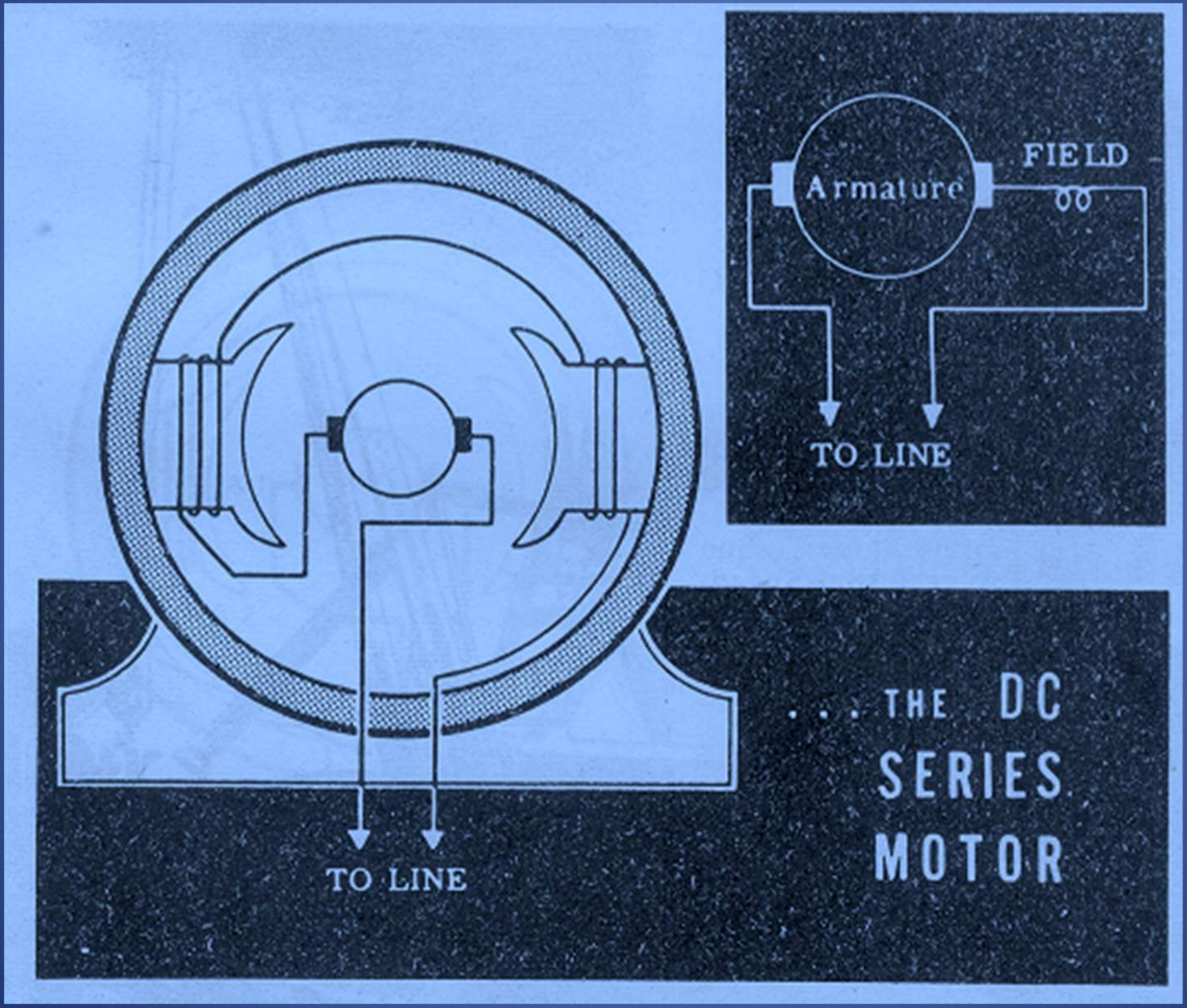


D.C. Series-Connected Motors

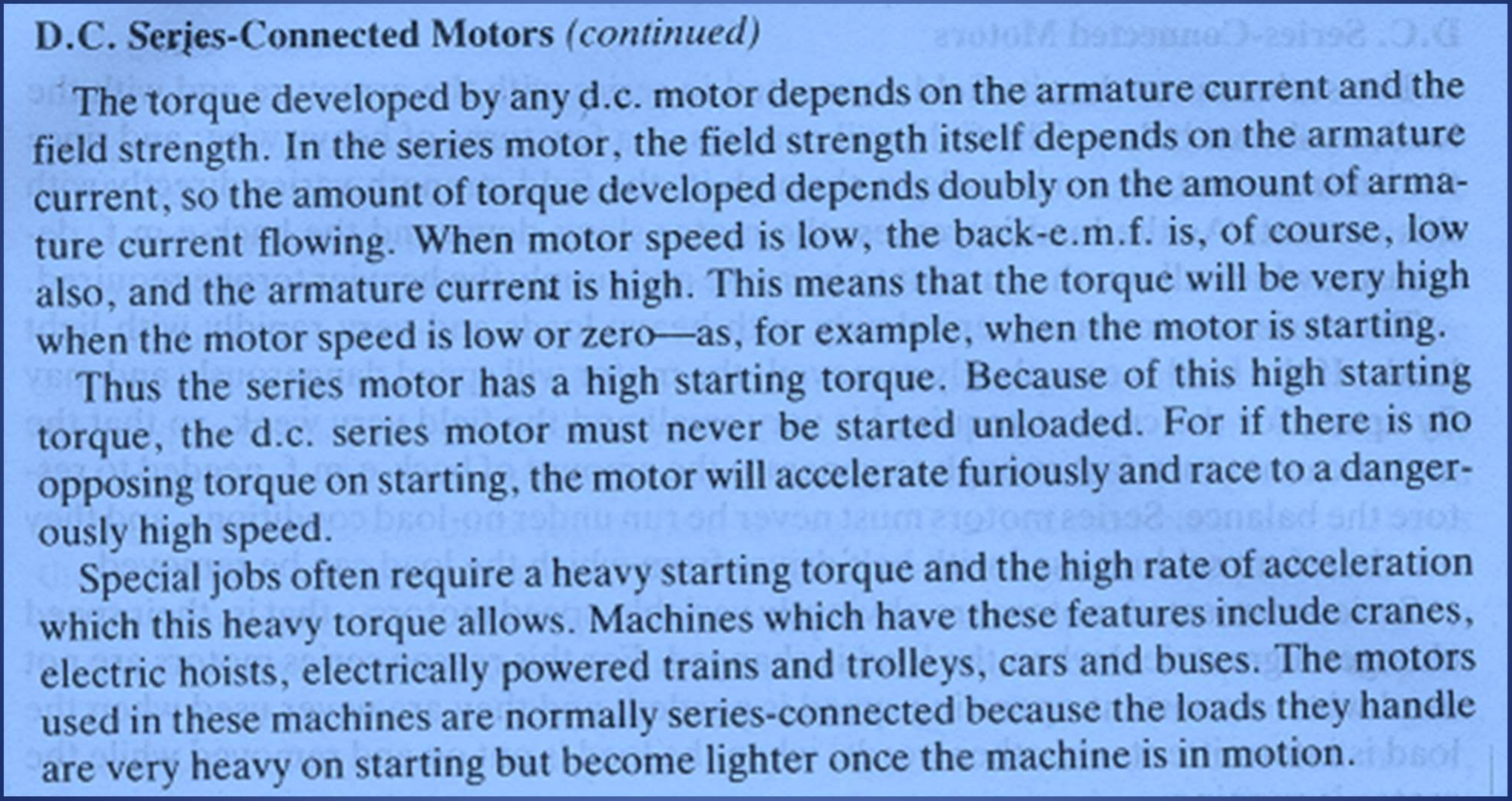
The series motor has its field connected in series with the armature and with the load, as shown below. The field coil consists of a few turns of heavy wire; and since the entire armature current flows through it, the field strength varies directly with this current. As the load increases, the motor slows down and the back-e.m.f. decreases, which allows the current to increase and supply the heavier torque required.

The series motor runs very slowly with heavy loads and very rapidly with light loads. If the load is completely removed, the motor will speed dangerously and may fly apart; for the current required is very small and the field very weak, so that the motor cannot turn fast enough to generate the amount of back-e.m.f. needed to restore the balance. Series motors must never be run under no-load conditions, and they are therefore seldom used with belt drives from which the load can be removed.

Series-connected motors are obviously variable-speed motors—that is, their speed changes a great deal when the load is changed. For this reason series motors are not used when a constant operating speed is needed; and they are never used when the load is intermittent—in other words, when the load is put on and removed while the motor is running.



. . . THE DC SERIES MOTOR

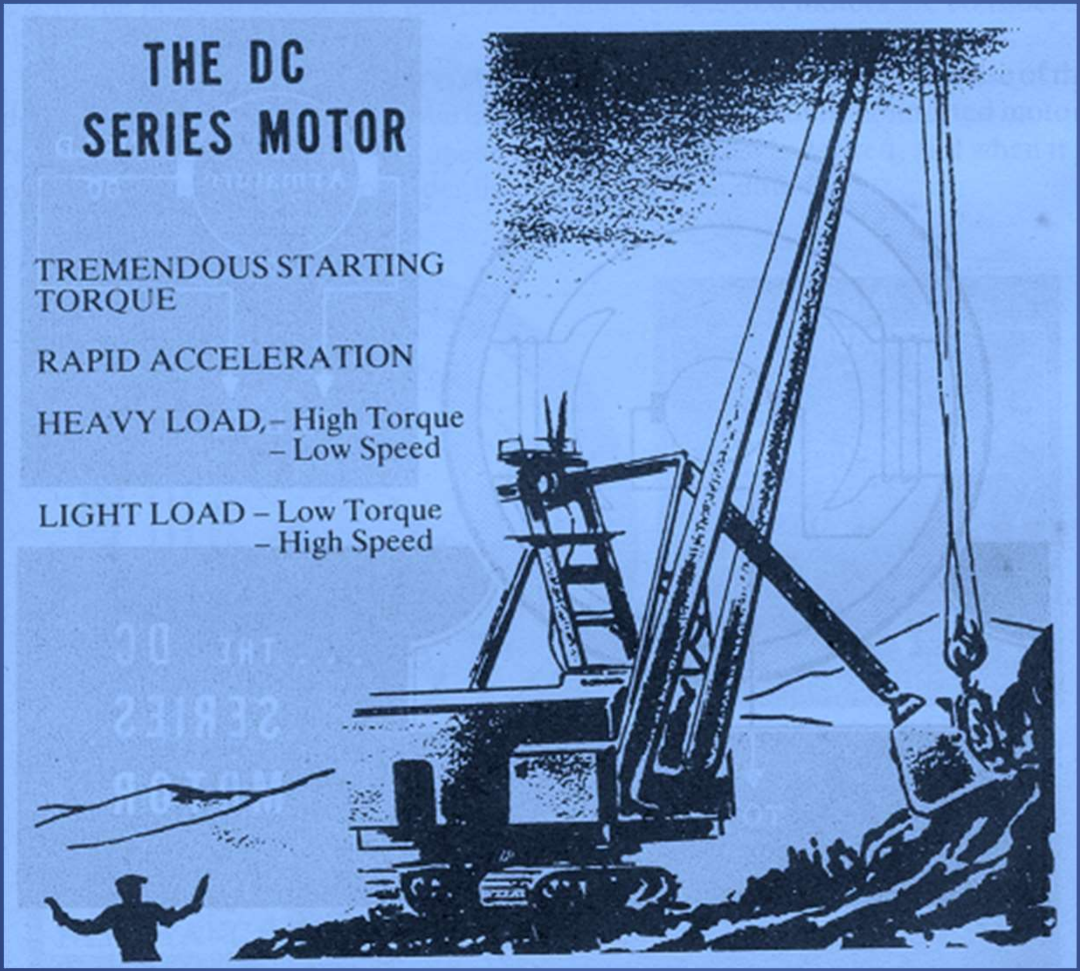


D.C. Series-Connected Motors *(continued)*

The torque developed by any d.c. motor depends on the armature current and the field strength. In the series motor, the field strength itself depends on the armature current, so the amount of torque developed depends doubly on the amount of armature current flowing. When motor speed is low, the back-e.m.f. is, of course, low also, and the armature current is high. This means that the torque will be very high when the motor speed is low or zero—as, for example, when the motor is starting.

Thus the series motor has a high starting torque. Because of this high starting torque, the d.c. series motor must never be started unloaded. For if there is no opposing torque on starting, the motor will accelerate furiously and race to a dangerously high speed.

Special jobs often require a heavy starting torque and the high rate of acceleration which this heavy torque allows. Machines which have these features include cranes, electric hoists, electrically powered trains and trolleys, cars and buses. The motors used in these machines are normally series-connected because the loads they handle are very heavy on starting but become lighter once the machine is in motion.



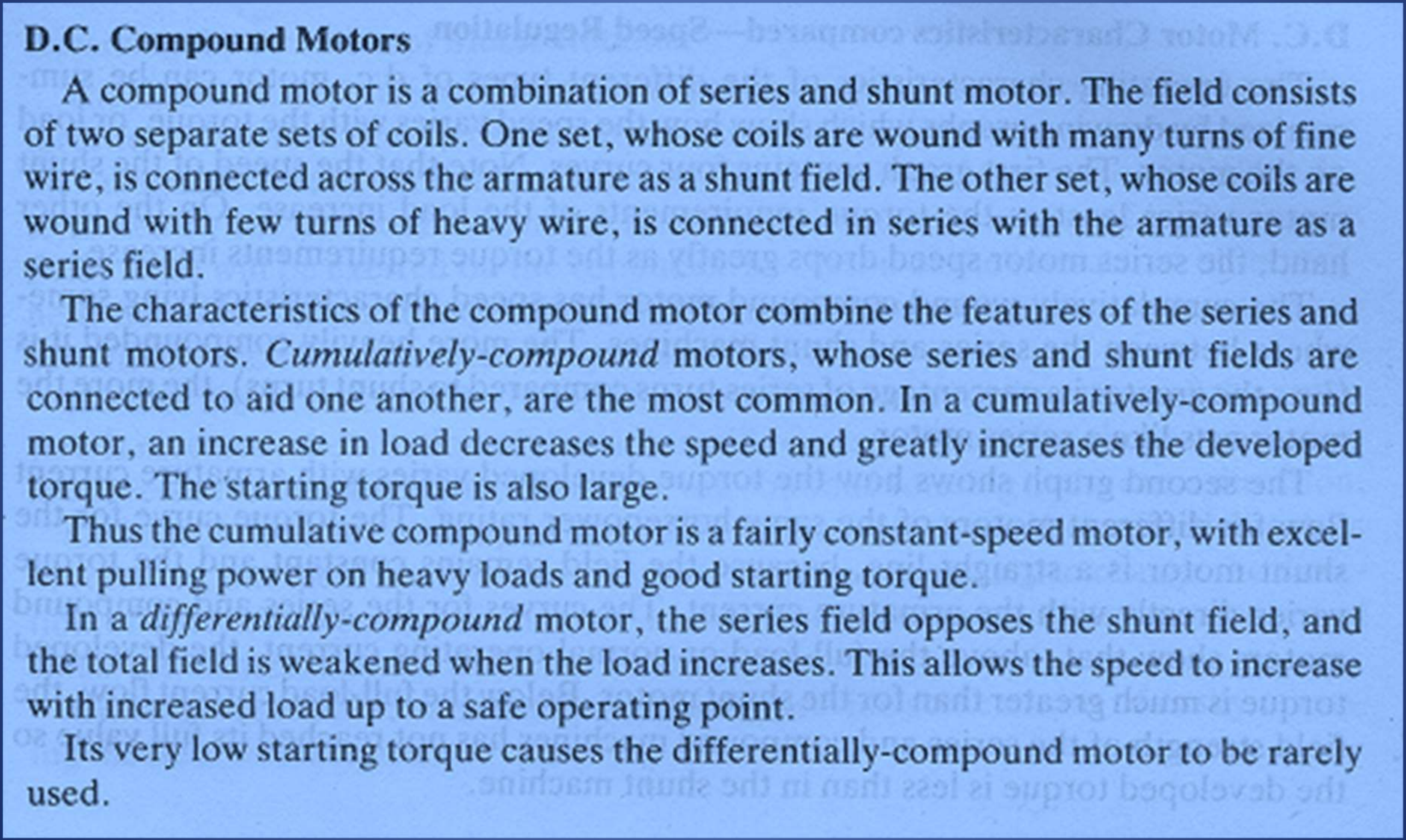
THE DC SERIES MOTOR

TREMENDOUS STARTING TORQUE

RAPID ACCELERATION

HEAVY LOAD, – High Torque
– Low Speed

LIGHT LOAD – Low Torque
– High Speed



D.C. Compound Motors

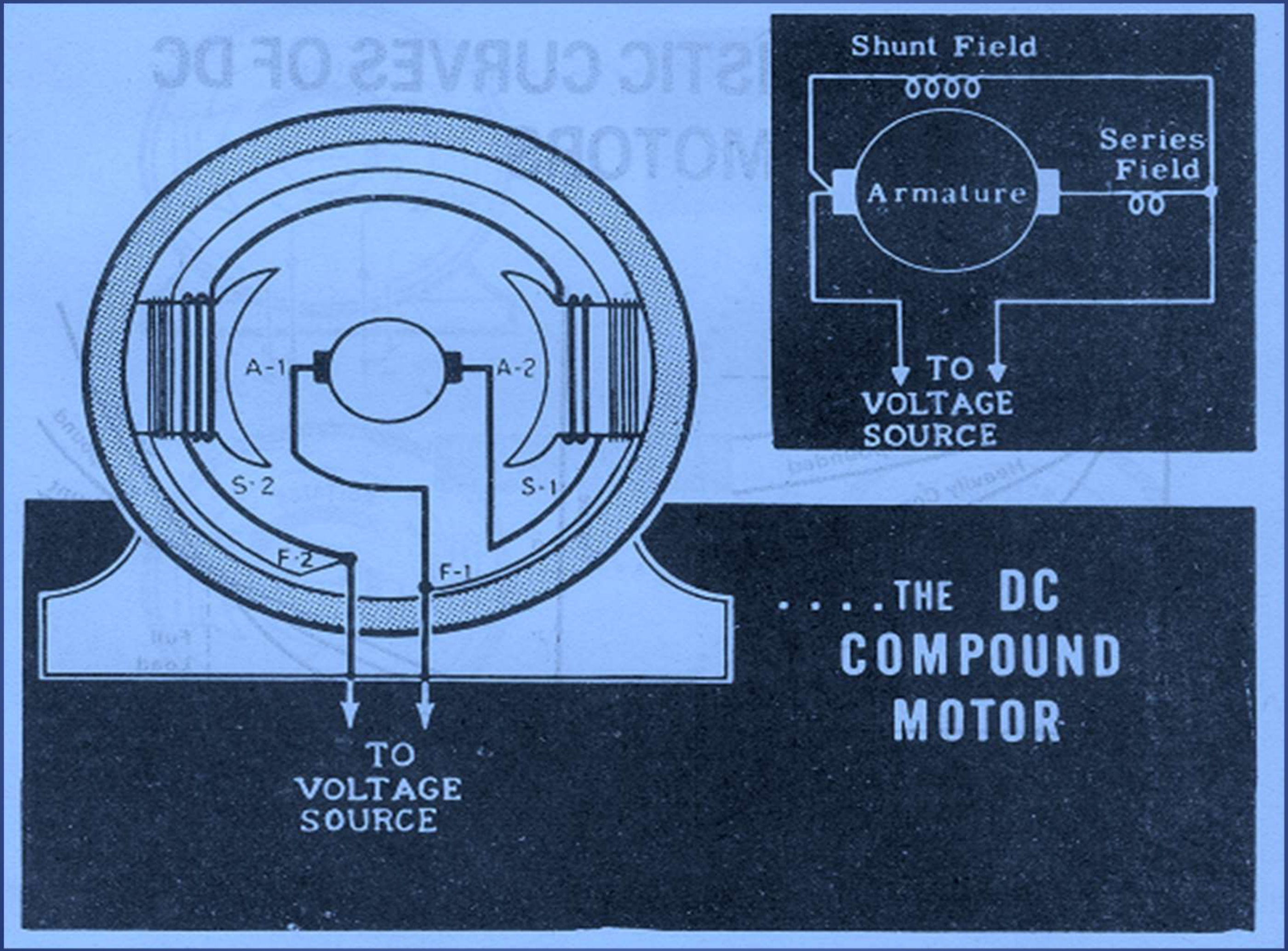
A compound motor is a combination of series and shunt motor. The field consists of two separate sets of coils. One set, whose coils are wound with many turns of fine wire, is connected across the armature as a shunt field. The other set, whose coils are wound with few turns of heavy wire, is connected in series with the armature as a series field.

The characteristics of the compound motor combine the features of the series and shunt motors. *Cumulatively-compound* motors, whose series and shunt fields are connected to aid one another, are the most common. In a cumulatively-compound motor, an increase in load decreases the speed and greatly increases the developed torque. The starting torque is also large.

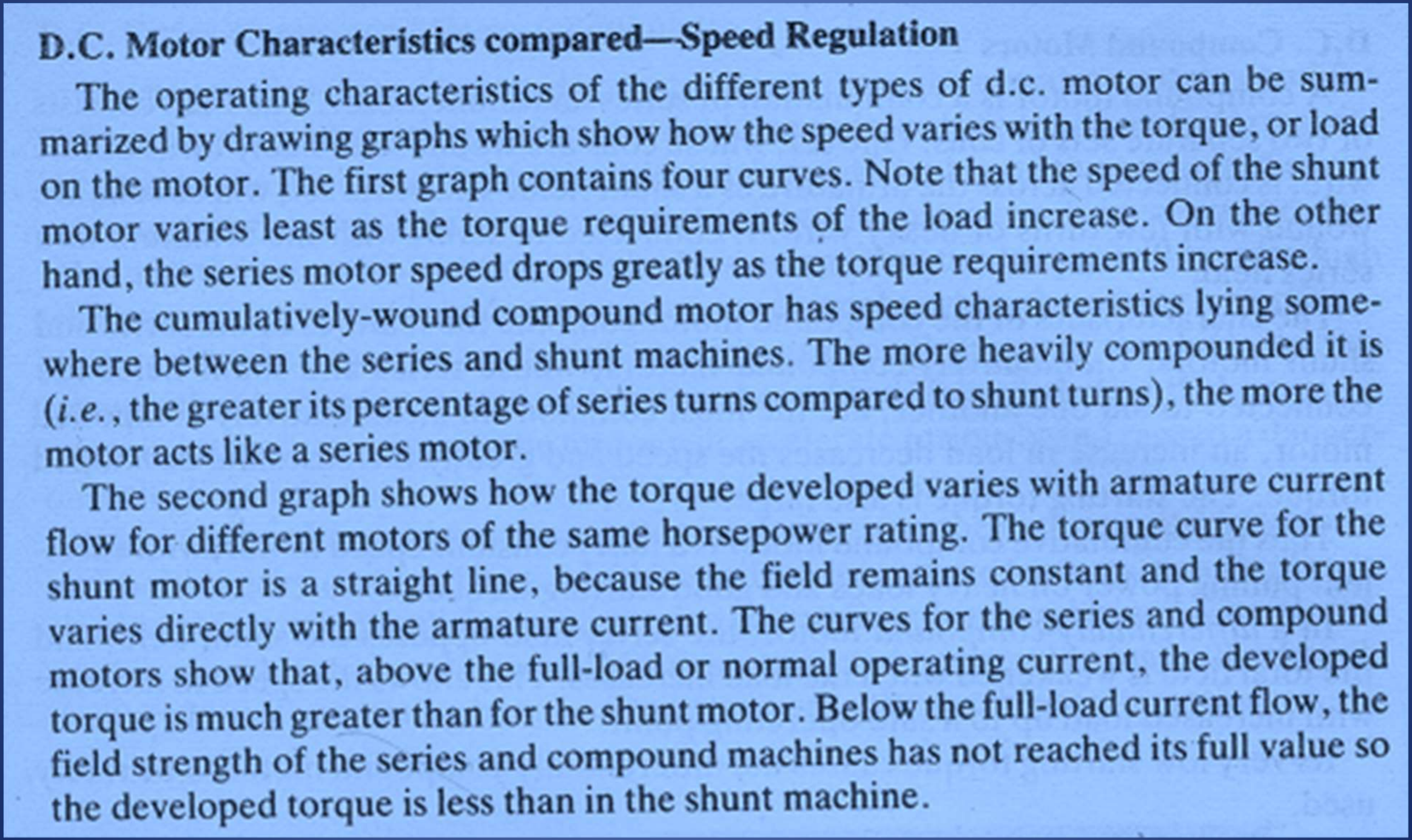
Thus the cumulative compound motor is a fairly constant-speed motor, with excellent pulling power on heavy loads and good starting torque.

In a *differentially-compound* motor, the series field opposes the shunt field, and the total field is weakened when the load increases. This allows the speed to increase with increased load up to a safe operating point.

Its very low starting torque causes the differentially-compound motor to be rarely used.



. . . . THE DC COMPOUND MOTOR



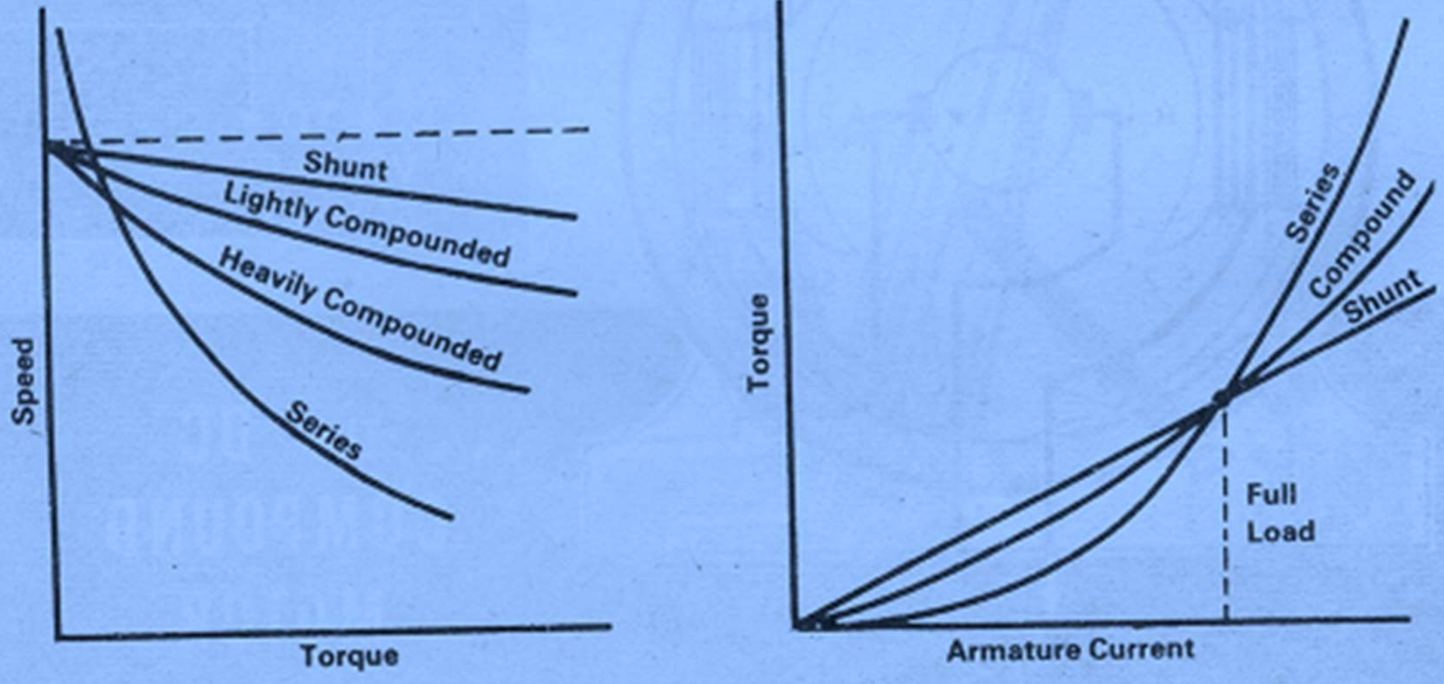
D.C. Motor Characteristics compared—Speed Regulation

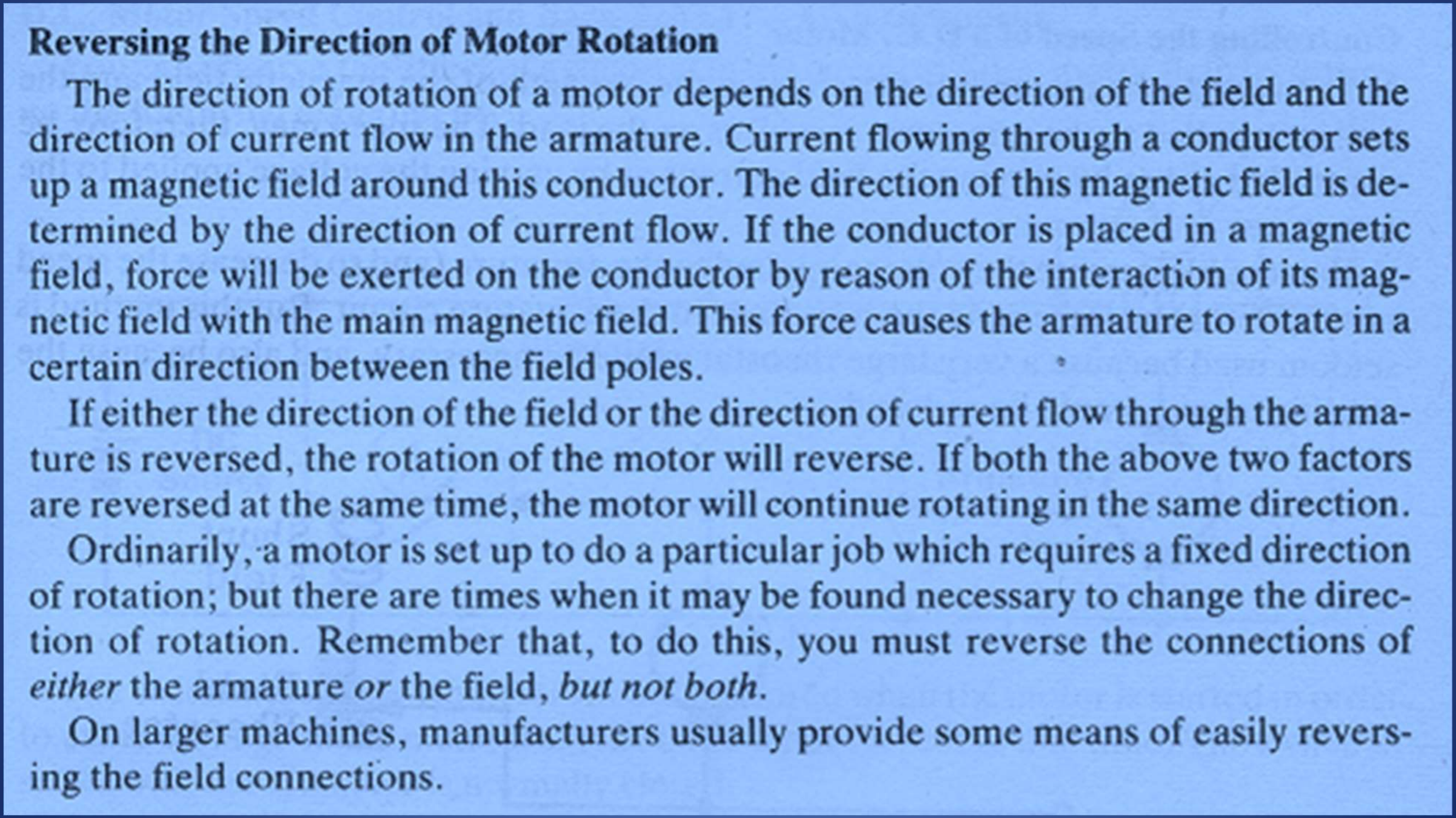
The operating characteristics of the different types of d.c. motor can be summarized by drawing graphs which show how the speed varies with the torque, or load on the motor. The first graph contains four curves. Note that the speed of the shunt motor varies least as the torque requirements of the load increase. On the other hand, the series motor speed drops greatly as the torque requirements increase.

The cumulatively-wound compound motor has speed characteristics lying somewhere between the series and shunt machines. The more heavily compounded it is (*i.e.*, the greater its percentage of series turns compared to shunt turns), the more the motor acts like a series motor.

The second graph shows how the torque developed varies with armature current flow for different motors of the same horsepower rating. The torque curve for the shunt motor is a straight line, because the field remains constant and the torque varies directly with the armature current. The curves for the series and compound motors show that, above the full-load or normal operating current, the developed torque is much greater than for the shunt motor. Below the full-load current flow, the field strength of the series and compound machines has not reached its full value so the developed torque is less than in the shunt machine.

CHARACTERISTIC CURVES OF DC MOTORS





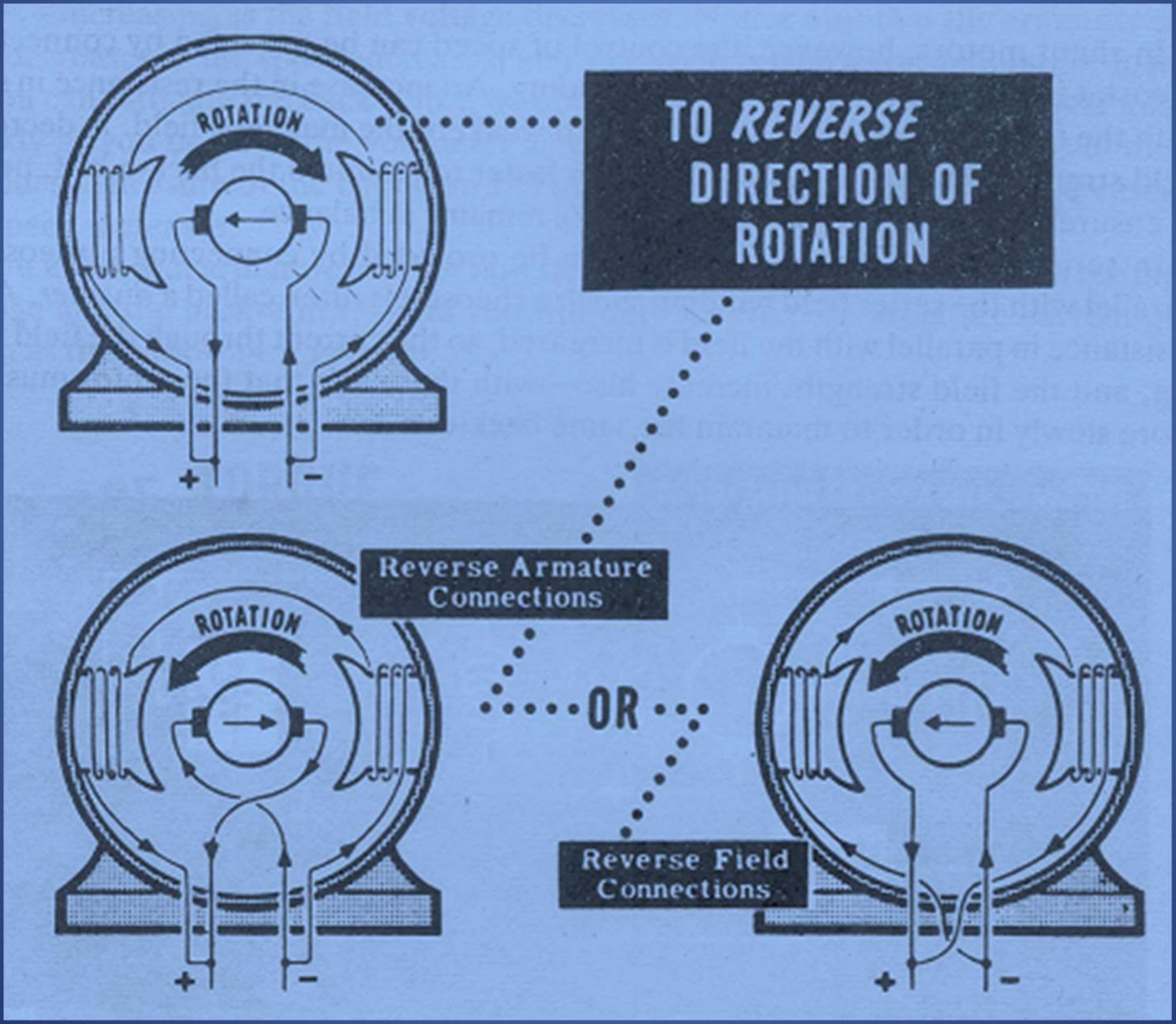
Reversing the Direction of Motor Rotation

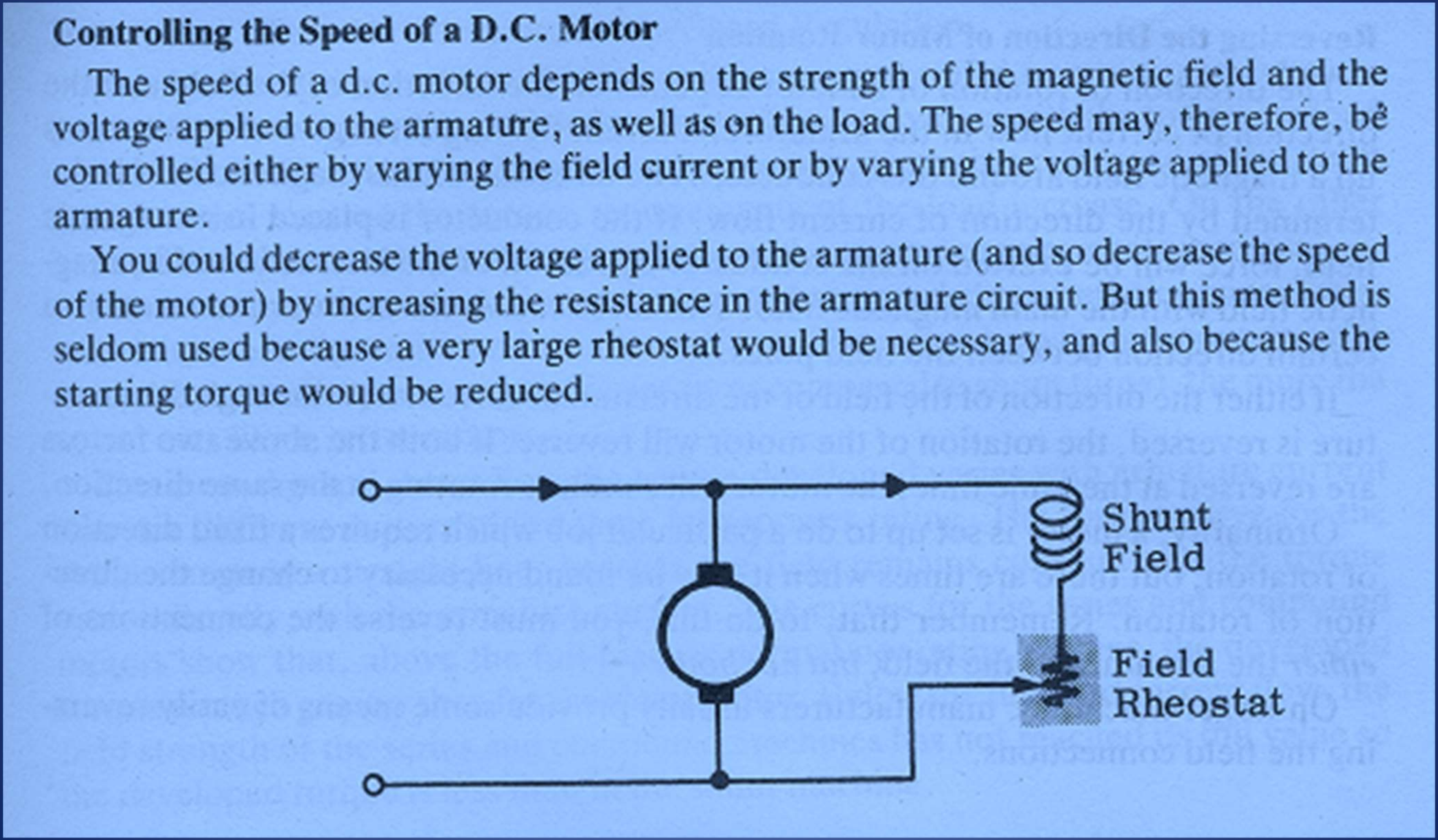
The direction of rotation of a motor depends on the direction of the field and the direction of current flow in the armature. Current flowing through a conductor sets up a magnetic field around this conductor. The direction of this magnetic field is determined by the direction of current flow. If the conductor is placed in a magnetic field, force will be exerted on the conductor by reason of the interaction of its magnetic field with the main magnetic field. This force causes the armature to rotate in a certain direction between the field poles.

If either the direction of the field or the direction of current flow through the armature is reversed, the rotation of the motor will reverse. If both the above two factors are reversed at the same time, the motor will continue rotating in the same direction.

Ordinarily, a motor is set up to do a particular job which requires a fixed direction of rotation; but there are times when it may be found necessary to change the direction of rotation. Remember that, to do this, you must reverse the connections of *either* the armature *or* the field, *but not both*.

On larger machines, manufacturers usually provide some means of easily reversing the field connections.

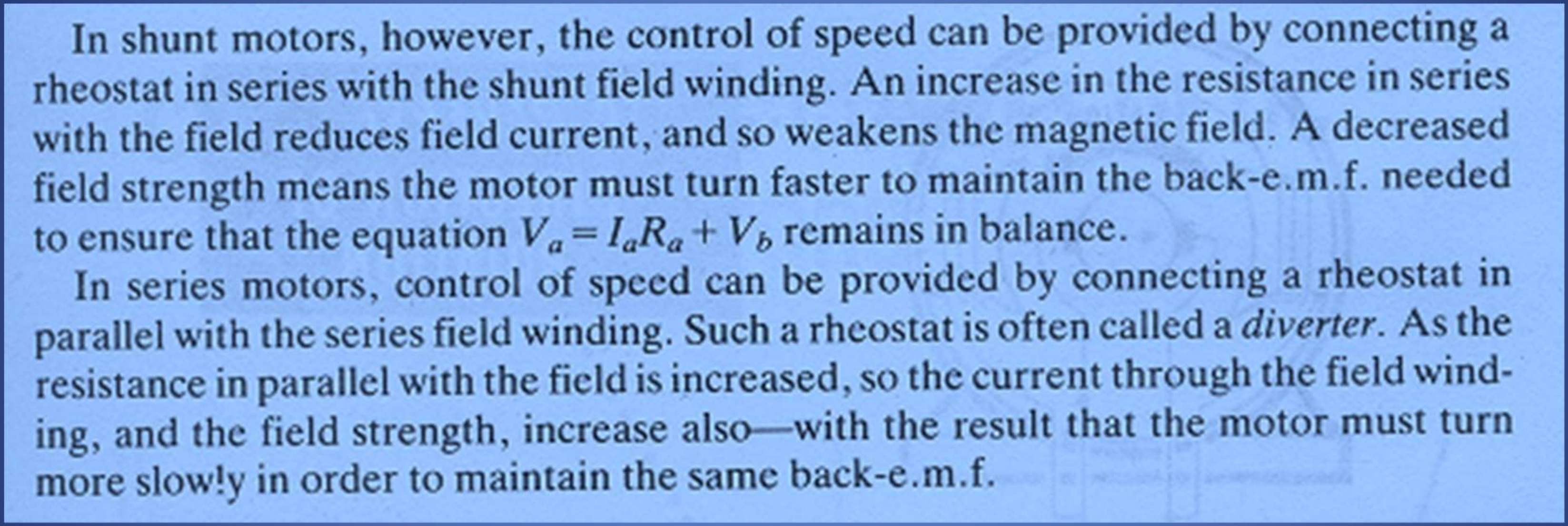

ROTATION
+
−
TO *REVERSE* DIRECTION OF ROTATION
Reverse Armature Connections
ROTATION
+
−
OR
ROTATION
Reverse Field Connections
+
−



Controlling the Speed of a D.C. Motor

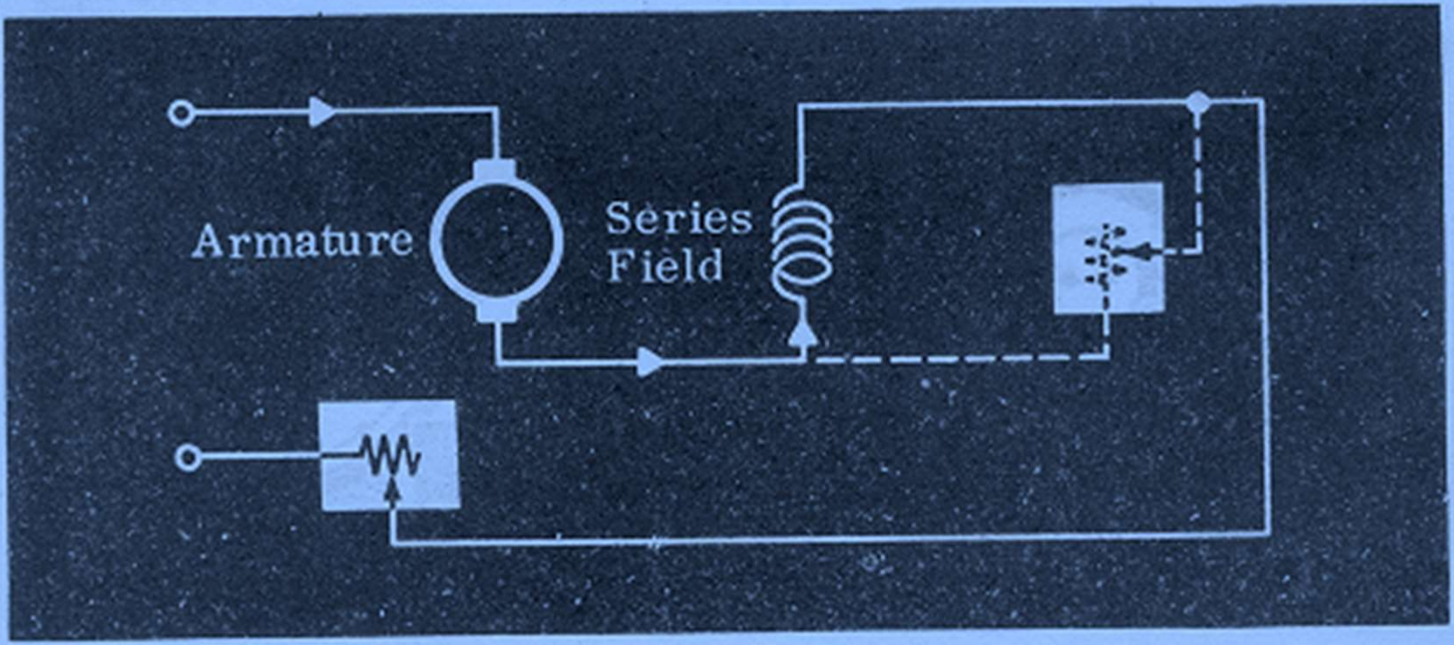
The speed of a d.c. motor depends on the strength of the magnetic field and the voltage applied to the armature, as well as on the load. The speed may, therefore, be controlled either by varying the field current or by varying the voltage applied to the armature.

You could decrease the voltage applied to the armature (and so decrease the speed of the motor) by increasing the resistance in the armature circuit. But this method is seldom used because a very large rheostat would be necessary, and also because the starting torque would be reduced.

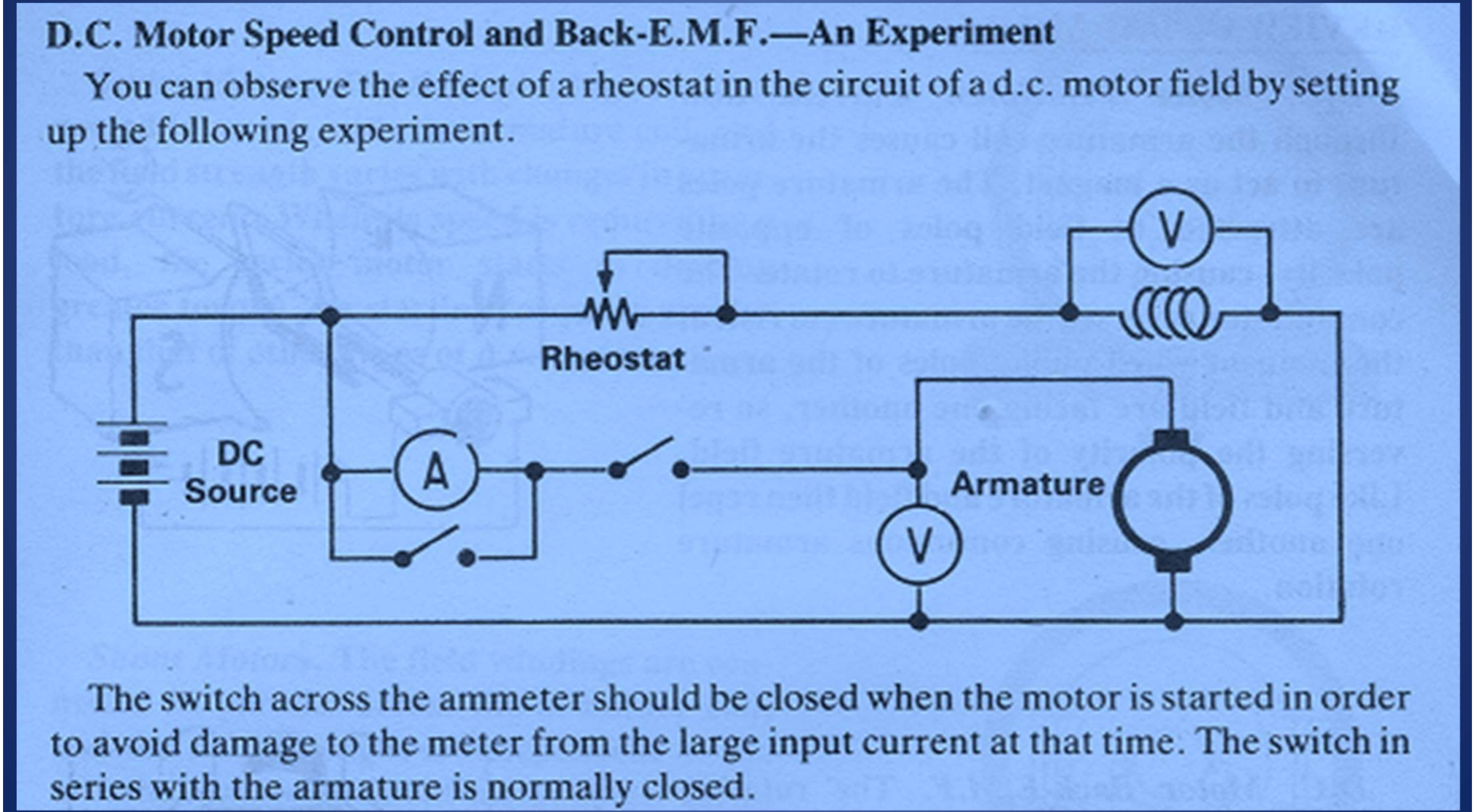


In shunt motors, however, the control of speed can be provided by connecting a rheostat in series with the shunt field winding. An increase in the resistance in series with the field reduces field current, and so weakens the magnetic field. A decreased field strength means the motor must turn faster to maintain the back-e.m.f. needed to ensure that the equation $V_a = I_a R_a + V_b$ remains in balance.

In series motors, control of speed can be provided by connecting a rheostat in parallel with the series field winding. Such a rheostat is often called a *diverter*. As the resistance in parallel with the field is increased, so the current through the field winding, and the field strength, increase also—with the result that the motor must turn more slowly in order to maintain the same back-e.m.f.



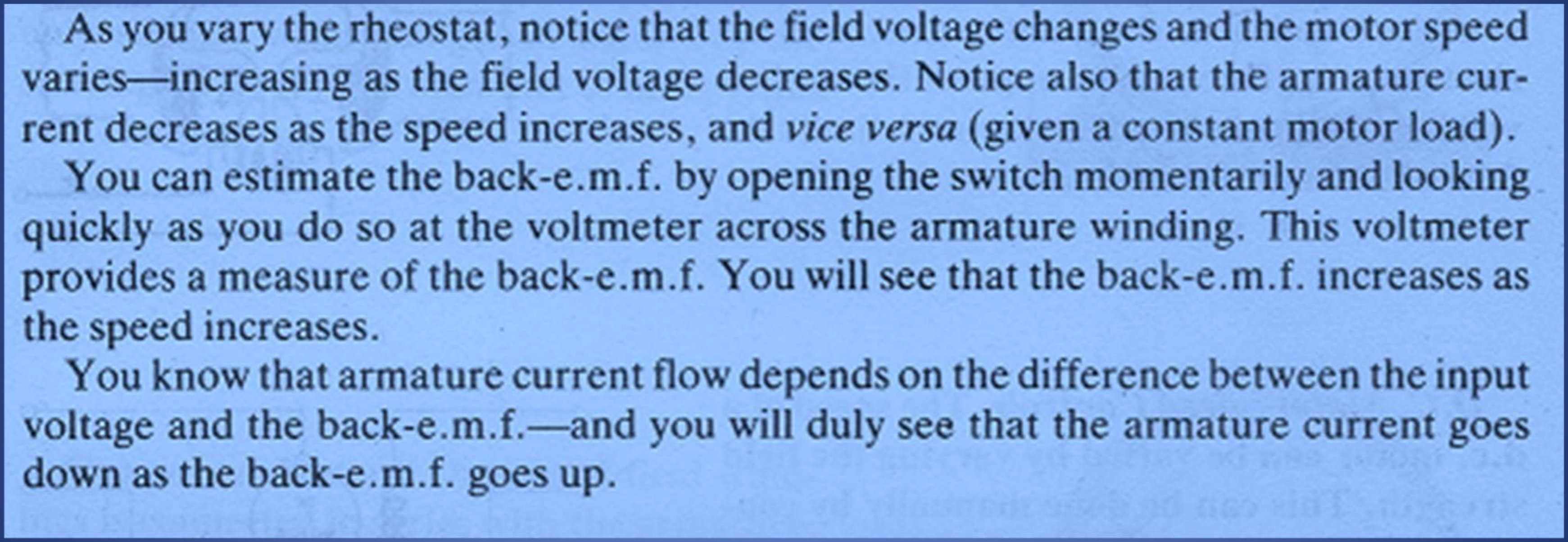
Variable-speed motors are usually of the shunt-connected type because of the ease of motor control. You will learn about automatic speed regulators later in this volume.



D.C. Motor Speed Control and Back-E.M.F.—An Experiment

You can observe the effect of a rheostat in the circuit of a d.c. motor field by setting up the following experiment.

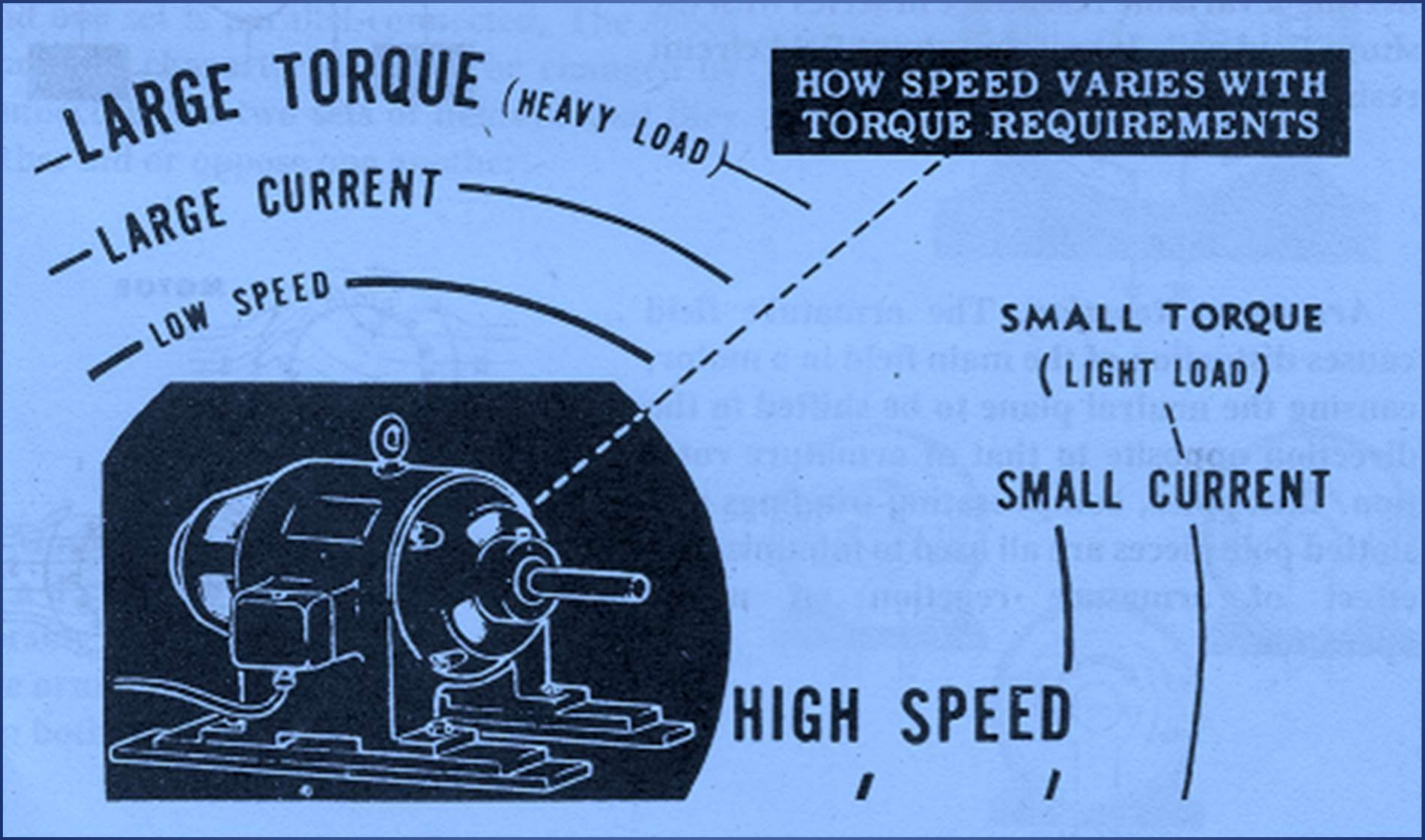
The switch across the ammeter should be closed when the motor is started in order to avoid damage to the meter from the large input current at that time. The switch in series with the armature is normally closed.

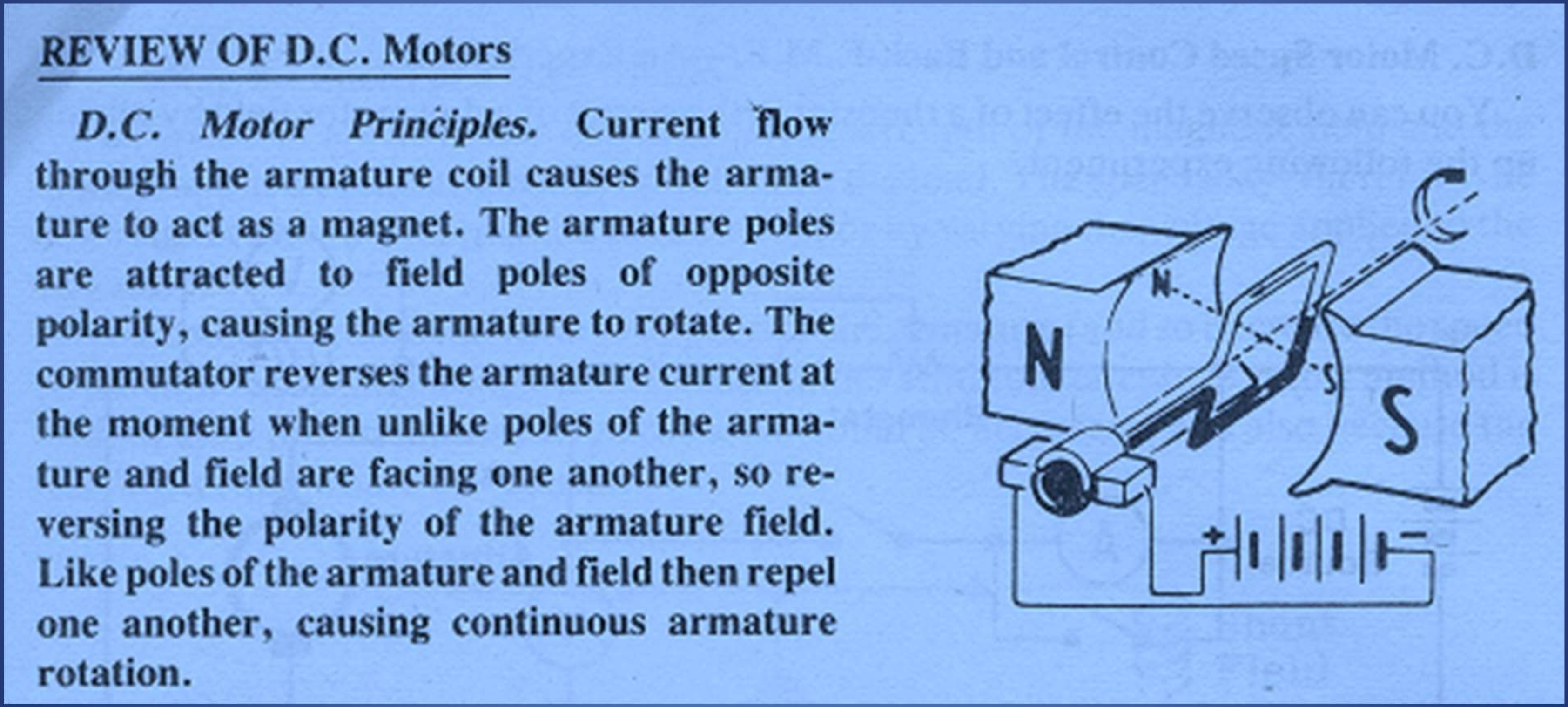


As you vary the rheostat, notice that the field voltage changes and the motor speed varies—increasing as the field voltage decreases. Notice also that the armature current decreases as the speed increases, and *vice versa* (given a constant motor load).

You can estimate the back-e.m.f. by opening the switch momentarily and looking quickly as you do so at the voltmeter across the armature winding. This voltmeter provides a measure of the back-e.m.f. You will see that the back-e.m.f. increases as the speed increases.

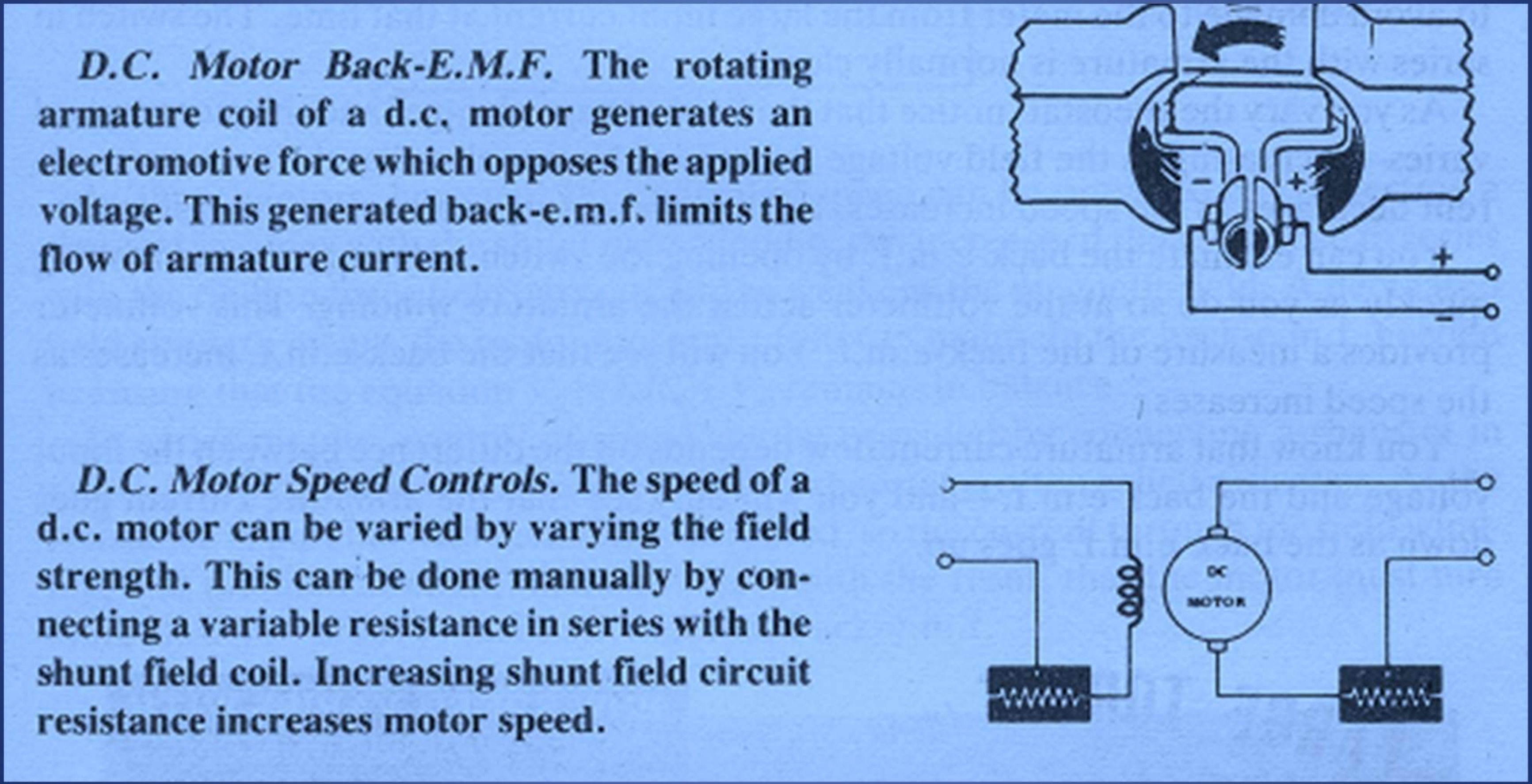
You know that armature current flow depends on the difference between the input voltage and the back-e.m.f.—and you will duly see that the armature current goes down as the back-e.m.f. goes up.


HOW SPEED VARIES WITH TORQUE REQUIREMENTS



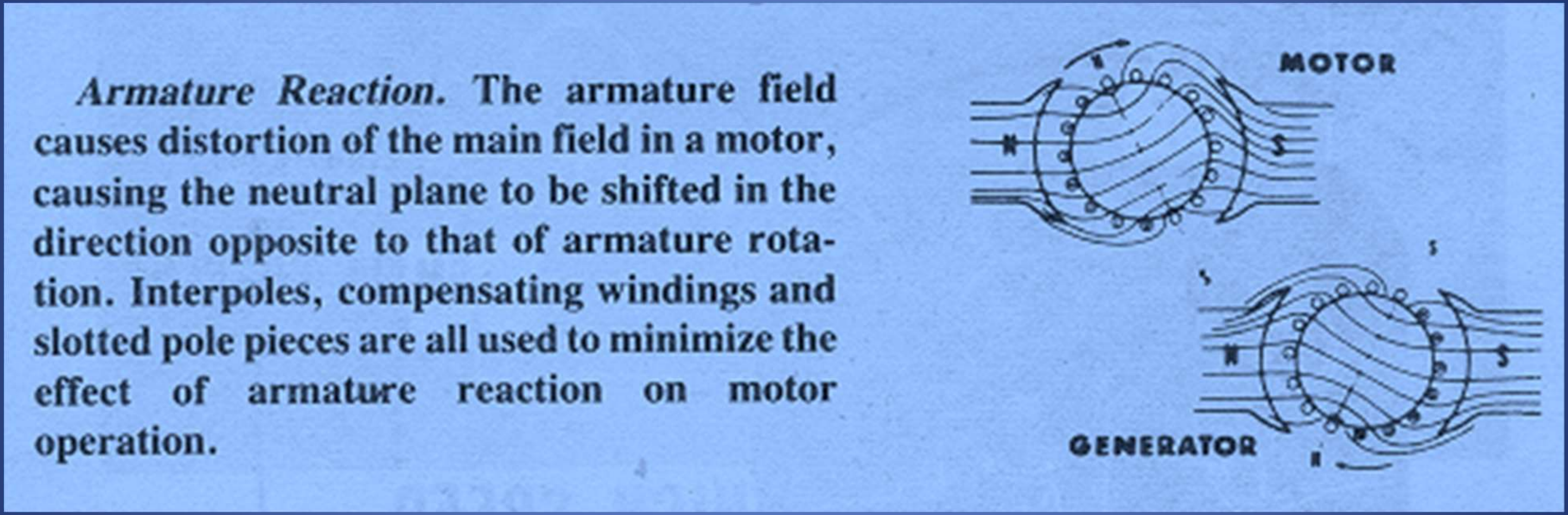
REVIEW OF D.C. Motors

D.C. Motor Principles. Current flow through the armature coil causes the armature to act as a magnet. The armature poles are attracted to field poles of opposite polarity, causing the armature to rotate. The commutator reverses the armature current at the moment when unlike poles of the armature and field are facing one another, so reversing the polarity of the armature field. Like poles of the armature and field then repel one another, causing continuous armature rotation.

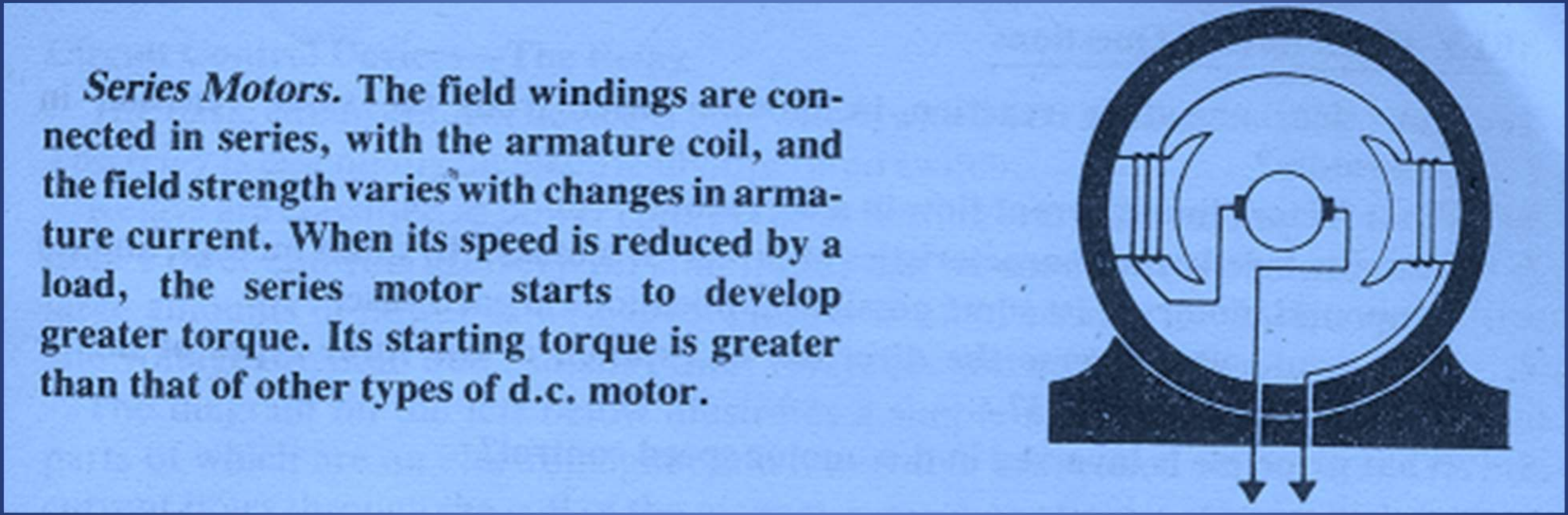


D.C. Motor Back-E.M.F. **The rotating armature coil of a d.c. motor generates an electromotive force which opposes the applied voltage. This generated back-e.m.f. limits the flow of armature current.**

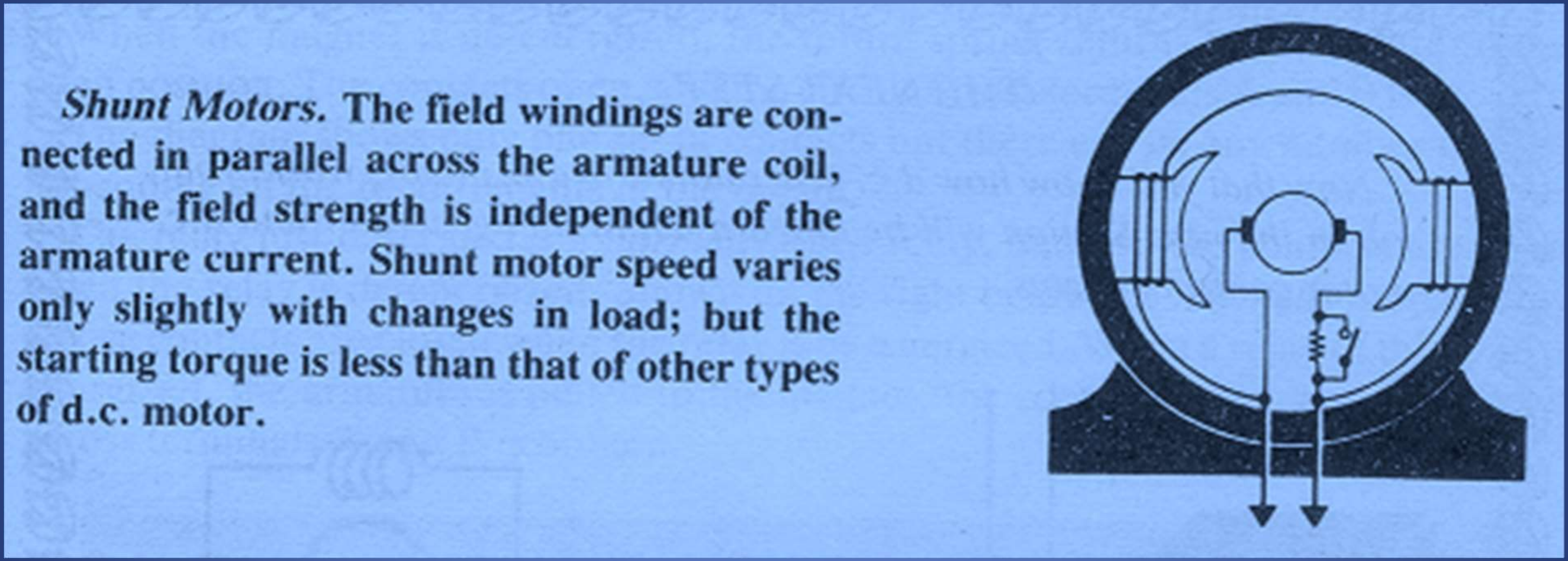
D.C. Motor Speed Controls. **The speed of a d.c. motor can be varied by varying the field strength. This can be done manually by connecting a variable resistance in series with the shunt field coil. Increasing shunt field circuit resistance increases motor speed.**



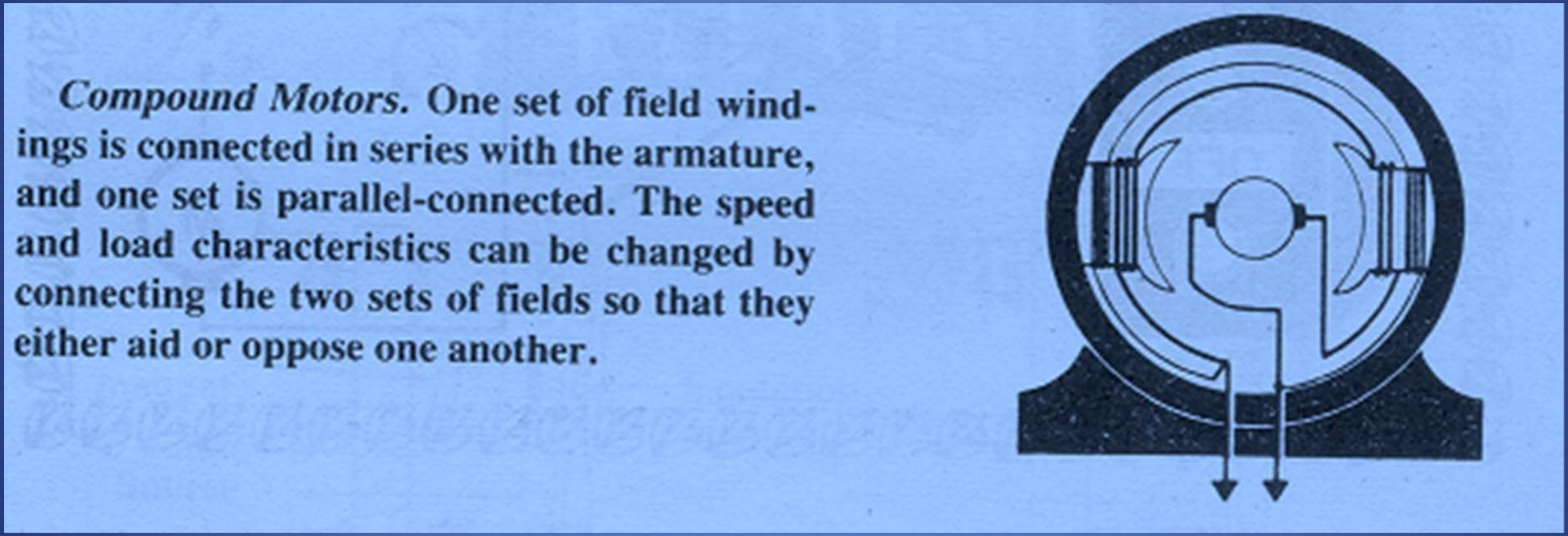
Armature Reaction. The armature field causes distortion of the main field in a motor, causing the neutral plane to be shifted in the direction opposite to that of armature rotation. Interpoles, compensating windings and slotted pole pieces are all used to minimize the effect of armature reaction on motor operation.



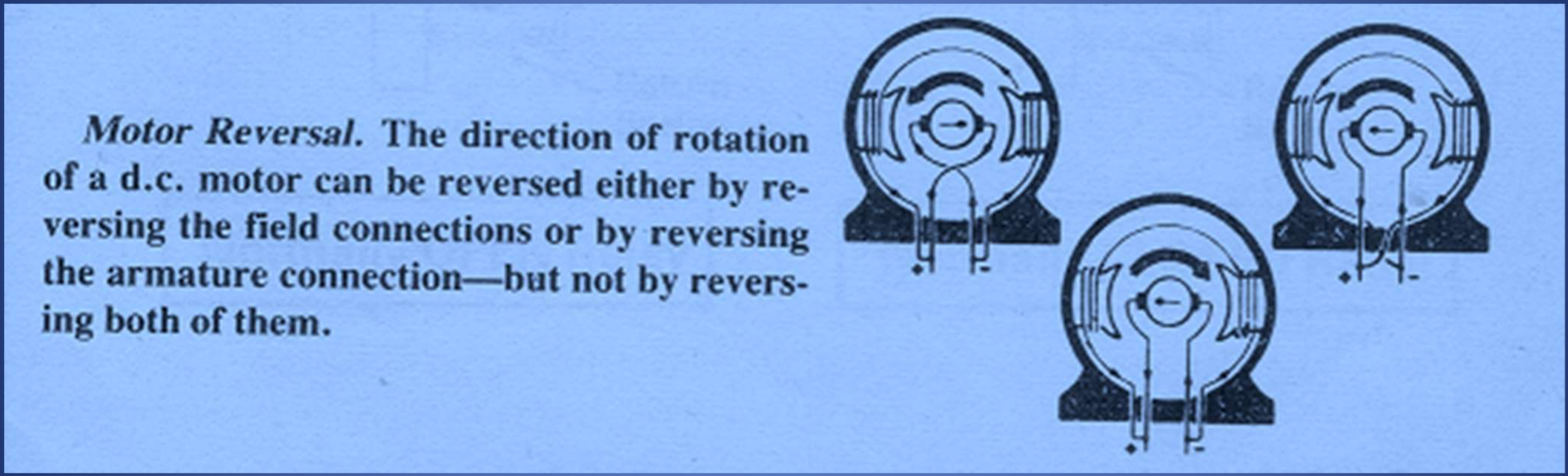
Series Motors. **The field windings are connected in series, with the armature coil, and the field strength varies with changes in armature current. When its speed is reduced by a load, the series motor starts to develop greater torque. Its starting torque is greater than that of other types of d.c. motor.**



Shunt Motors. The field windings are connected in parallel across the armature coil, and the field strength is independent of the armature current. Shunt motor speed varies only slightly with changes in load; but the starting torque is less than that of other types of d.c. motor.



Compound Motors. One set of field windings is connected in series with the armature, and one set is parallel-connected. The speed and load characteristics can be changed by connecting the two sets of fields so that they either aid or oppose one another.



Motor Reversal. **The direction of rotation of a d.c. motor can be reversed either by reversing the field connections or by reversing the armature connection—but not by reversing both of them.**