Electric Motors and Their Applications

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To The Memory of Three Unsung Martyrs

Thomas Davenport of Brandon, Vermont, who invented the electric motor (U. S. Patent #132, 1837) and died penniless as a result.

Emily Davenport, his wife, who gave up her silk wedding dress for insulation on the windings of the first electric motor.

Oliver Davenport, itinerant merchant, who sold his horse and wagon to finance his brother's experiments, thereby putting himself out of business.

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Preface

In this affluent society the average American home may contain about 20 electric motors. To every member of the family they are just electric motors, although they obviously differ in size and mechanical design. Perhaps the discerning householder may have discovered that a few appear to spark inside, others make a clicking noise when started, and others do neither.

The differences go much deeper than that. These 20 motors probably represent six different principles of operation.

The number of types is further increased when one sets foot in an office building or a factory and examines the variety of motors in use there.

The operational characteristics of each can be understood with simple mathematics and some fundamental electrical theory. These characteristics form the reason for using one type of motor on the dishwasher, another on the vacuum cleaner, and still another on the electric typewriter.

A few of these devices could operate satisfactorily with a different and cheaper type of motor. A few could operate with motors that are larger or smaller, with the same horsepower output, and bought at a reduced price.

This is a challenging statement.

It is based on the belief that some engineers, who design the vast amount of motor-driven equipment found on the market, do not know enough about the motors that are available.

This situation is brought about also by the way in which many motor-driven devices apparently are designed. The process involves these steps:

The designer develops a new domestic ironer, desk calculator, dishwasher, or what not. He uses great ingenuity in producing a sample that fulfills its primary function and can be produced economically.

Little space remains inside the device for the motor.

The sample, in its prototype cabinet, is then given to the industrial designer, who smooths out the corners, "reduces the silhouette," and gives the product eye appeal.

Now there is still less space inside for the electric motor.

He then calls in the motor application engineer (salesman) and says that he needs a production motor to drive his device.

This procedure can result in the need for special motors of non-standard mechanical sizes, special motors in which the losses must be minimized because of overheating, and in general a more expensive product than might have been required had the motor supplier been called in at the inception of the development.

The above account is exaggerated, of course, but it happens occasionally to the full degree as described and more often to a lesser degree.

A more widespread knowledge of motor types, operation, and standards might result in reduced costs.

It is hoped that this book, which is the outgrowth of a number of courses and talks I have given over many years, will help to bring this about. My audiences consisted of salesmen, factory superintendents and foremen, technicians, and laboratory assistants. All of these people had been involved in various phases of production, sales, and testing of electric motors.

As an engineering executive, however, I had a natural interest in helping the sales department to supply engineering information on electric motors to prospects and customers. Some of the chapters in this book therefore are based on almost identical information supplied to purchasing agents and engineers of various backgrounds who were in a position to buy and/or specify electric motors for their products. They became curious about how motors work and about the relative merits of the various types.

Three generations of electrical engineers have burned midnight oil to develop the theory and mathematics for analyzing and designing electric motors. Today's designers are working equally hard with computers in an attempt to design motors to meet the almost infinite variety of performances sought by motor users.

I owe them all an apology for minimizing their mathematical wizardry and attempting to make their achievements appear simple.

Acknowledgement is due to many former associates at Robbins &

Myers, Inc., who helped to supply data for this book or who sat patiently through the lectures that formed the material used. Special mention should be made of John A. Zimmerman, Manager of Marketing, who for many years goaded me into writing it.

Yellow Springs, Ohio

T. C. LLOYD

Contents

Chapter 1

Electrical Fundamentals, Electric and Magnetic Circuits, Generator and Motor Action

To understand electric motors it is necessary to have a knowledge of the terms used and the nature of the electric and magnetic circuits. These terms are introduced by considering direct-current (dc) circuits and the magnetic circuit as set up by direct currents.

Interaction of the electric and magnetic circuits leads to a basic understanding of motor and generator action.

The concepts of direct current are useful not only for their own sake (for dc equipment has seen a revival in recent years) but also because they provide an introduction to the more complex alternating-current (ac) circuits.

1-1 The DC Circuit

If we connect a long loop of wire to the terminals of a battery, an electric current will flow through the wire. It is forced through the circuit by the electric pressure which is measured in *volts* (v). This pressure is also called *electromotive force* (emf). The rate of current flow is measured in *amperes* (amp). The current is limited by the *resistance* of the wire and this resistance is measured in *ohms* (Ω).

The resistance to current flow is determined by the material of which the wire is made, its length, and its cross-sectional area. To a lesser extent it also depends on the temperature of the wire. Thus, if we double the length of the wire, one-half as much current would flow. In general we can represent many natural phenomena by this expression:

$$\text{effect} = \frac{\text{effort}}{\text{opposition}}. \tag{1-1}$$

The effect we obtain in this electric circuit is a flow of current. The effort is through the pressure or voltage built up by the battery and the opposition is the resistance of the wire.

To apply this general expression specifically,

$$\text{amperes} = \frac{\text{volts}}{\text{ohm}}. \tag{1-2}$$

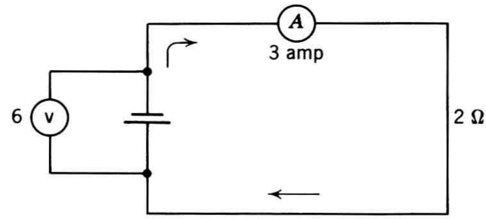

Figure 1-1. A loop of wire is connected to a 6-v battery. The resistance of the wire is 2 Ω. By Ohm's law we can calculate that the current in the wire would be 3 amp as measured by the ammeter, in a series with the line. Voltmeters are connected *across* various points in a circuit as they measure the difference in electrical potential between those points.

Using the common symbols, I for amperes, and R for ohms, we have

$$I = \frac{V}{R}. \tag{1-3}$$

This is known as *Ohm's law*. Our forefathers were kind enough to define these units so that we can say that 1-v causes 1 amp to flow against 1 Ω resistance without introducing other numbers as constants (See Figure 1-1).

Ohm's law applies not only to an entire circuit but also to the parts thereof. Suppose a concentrated resistance such as a light bulb of 1 Ω is connected to the battery through lead wires each of $\frac{1}{2}$-Ω resistance (see Figure 1-2). Now the total resistance of the circuit is

$$1 + \tfrac{1}{2} + \tfrac{1}{2} = 2 \text{ ohms}.$$

The current is then,

$$I = \frac{V}{R} = \frac{6}{2} \text{ or } 3 \text{ amp.}$$

Since $I = V/R$, it follows by simple algebra that

$$V = IR, \tag{1-4}$$

that is, the voltage across a part of a circuit will equal the product of amperes and ohms (refer again to Figure 1-2). If a voltmeter were connected from a to b, it would read

$$3 \times \tfrac{1}{2} = 1\tfrac{1}{2} \text{ v.}$$

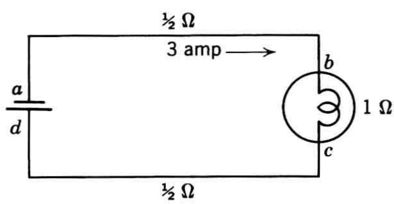

Figure 1-2. A lamp of 1-Ω resistance is connected to a battery by leads, each having a resistance of ½ Ω.

Connected from c to d it would read the same. Connected from b to c it would read

$$3 \times 1 = 3 \text{ v.}$$

We have applied 6 v to this circuit. Of this, 1½ v are "used up" in overcoming the resistance of one lead wire, 3 v are applied to the lamp, and the other lead wire "uses up" the remaining 1½ v. Thus, of the 6 v applied, all are represented by an equal number of "voltage drops" around the circuit. This is always the case. It is an example of action and reaction being equal and opposite.

If we used a 12-v battery on this circuit, the current would double and the "voltage drops" would double, equaling the 12 vs applied. Note that the current, being the *effect* in this phenomenon, adjusts itself to bring about this balance.

Note also that, although we applied 6 v to this circuit, only 3 v appeared at the lamp terminals. This is an exaggerated case of what might happen when a large electric motor is connected to the end of a long line in which the wire cross section is too small and, therefore, has a high resistance. The motor would not get the benefit of full line voltage.

1-2 Power in the DC Circuit

Power is the rate at which work is done. In the electric circuit this is measured in *watts* (w) and it ties into horsepower (hp) by ratio of 746 w being equal to 1 hp. In dc calculations, watts equal the product of current and voltage.

It must be emphasized that power is a *rate.* Thus, if we consider a 100-w lamp or a 400-w motor, these terms measure the rate at which power is being used. The total *energy* used involves *time* and power, measured as kilowatthours (kwhr), which is what the electric user pays for, as it represents the total amount of work done, electrically, in a given period.

Refer to Figure 1-2. Here we had a voltage drop of $1\frac{1}{2}$ v in each wire when 3 amps were flowing.

$$\text{watts in each} = 1\tfrac{1}{2} \times 3 = 4.5 \text{ w.}$$

In the lamp itself

$$\text{watts} = 3 \times 3 = 9 \text{ w.}$$

Total watts of circuit:

$$4.5 \text{ (one wire)} + 9 \text{ in lamp} + 4.5 \text{ (other wire)} = 18 \text{ w.}$$

This can also be calculated from the battery output. It supplied 3 amps at 6-v pressure.

$$3 \times 6 = 18 \text{ w.}$$

Hence the battery puts out energy at exactly the same rate at which it was being used in the circuit.

Since power = $V \times I$ in watts and

$$V = I \times R,$$

it follows that

$$\begin{aligned} \text{power} &= (I \times R) \times I \\ &= I^2R. \end{aligned} \tag{1-5}$$

Consider again the lamp in Figure 1-2. Its resistance is 1 Ω. The current was 3 amps. The watts are then $I^2R = 9 \times 1$ or 9 w. This is verified by the previous calculation.

The term "I^2R loss" is frequently used in dealing with circuits and motors.

1-3 Parallel Circuits

Figure 1-2 showed what were in effect three resistances in series. The voltages varied across parts of the circuit, the current was the same throughout the entire circuit. Now refer to Figure 1-3. Here we have two resistances connected across a 100-v line in parallel. The resistance of the leads will be ignored.

What is the current in each part of this circuit?

$$I = \frac{V}{R}$$

$$= \tfrac{100}{20} = 5 \text{ amp} \qquad \text{in part } (a)$$

$$= \tfrac{100}{10} = 10 \text{ amp} \qquad \text{in part } (b)$$

$$= 5 + 10 \text{ or } 15 \text{ amp} \qquad \text{in part } (c).$$

Note that the combined effect of two resistances in parallel shows less resistance than that of any one branch.

$$R_T = \frac{V}{I} = \frac{100}{15} \text{ or } 6.66\ \Omega.$$

Resistances in parallel can be added by obtaining the sum of the reciprocals. (This sounds more complicated than it is.)

$$\frac{1}{R_T} = \frac{1}{Ra} + \frac{1}{Rb}, \tag{1-6}$$

$$\frac{1}{R_T} = \frac{1}{20} + \frac{1}{10} \text{ or } 0.05 + 0.10\ \Omega,$$

$$\frac{1}{R_T} = 0.15,$$

$$R_T = \frac{1}{0.15} \text{ or } 6.66\ \Omega.$$

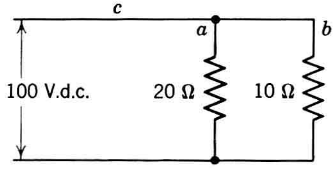

Figure 1-3. The conventional method of representing resistance employs the saw-tooth lines as shown. These two resistors are in parallel.

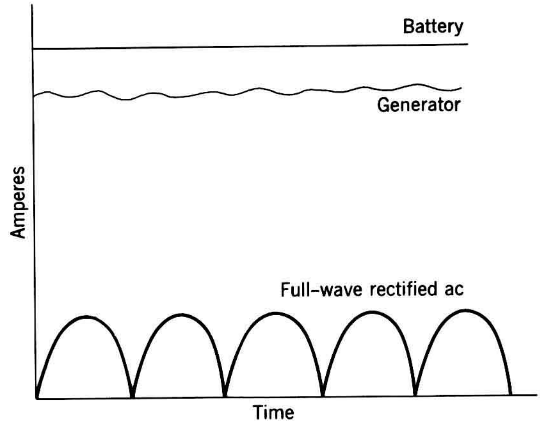

Figure 1-4. These currents are all defined as dc because they represent flow in one direction. Special considerations must be made in dealing with the lower, rectified quantity.

This checks with the resistance obtained by using the total current in the circuit (see Figure 1-4).

1-4 The Magnetic Circuit

We are all familiar with permanent magnets, but let us consider one shaped like a straight bar, as shown in Figure 1-5. Placed under a sheet of glass on which iron filings have been placed, we note some form of magnetic force which lines up the filings into the paths as shown. This magnetic field is considered as being made up of magnetic lines of force or flux lines. They are considered as coming out of one end, called the north pole, and entering the other, called the south pole. Each line must make a complete circuit, through the magnet and loop around from one end to the other. There is no motion along them; in fact, the flux line is entirely an imaginary concept. But it is inadequate in engineering work just to say that this is a strong field or a weak field. Quantitative measurements are needed. With the concept of lines we can then measure a field strength by saying it has 40,000 lines per square inch (in.^{2}), or 100,000 lines per in.^{2}. The kilogauss[1] is also a common unit, being 1,000 lines per square centimeter (cm^2). Although the "line"

[1] Named for a German mathematician, Gauss. One of his lesser known accomplishments was the development of a formula by which the date of Easter could be calculated.

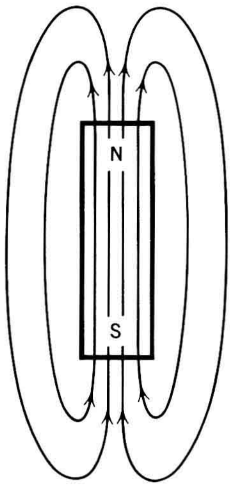

Figure 1-5. Magnetic field built up by a permanent magnet.

is imaginary, in dealing with it consistently in all related phenomena it is mathematically useful and correct. The symbol B is used to denote field intensity.

1-5 Magnetic Fields and the Electric Current

Whenever a current flows in a conductor, a magnetic field is built up around it. This is a natural phenomenon. Refer to Figure 1-6. Here a

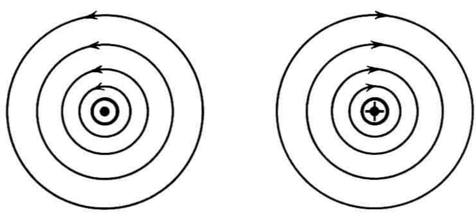

Figure 1-6. If we imagine that a conductor is clasped in the palm of the right hand, with the current flowing in the direction of the thumb, the flux is built up in the direction of the fingers. (*a*) Cross section of a conductor with the current flowing out of the page. This is represented by the dot, indicating the head of an arrow. (*b*) Cross section of a conductor with the current flowing into the page. The "cross" is the tail of an arrow.

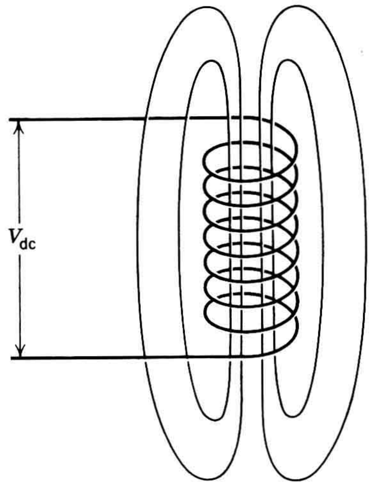

Figure 1-7. Magnetic field built up around a coil with current flowing.

current is shown flowing first in one direction and then reversed. The magnetic field has a definite direction with respect to the current as shown. If the current goes to zero, the field collapses to an imaginary line in the center of the conductor. Reversing the current reverses the field. These lines extend out indefinitely into space, but they fall off in intensity as the inverse square of the distance. That means that, if we have a field intensity of 200 lines/in.^{2} close to the conductor, at a distance of 10 times further out, the intensity will be $\frac{1}{100}$ or 2 lines/in.^{2}. This explains why amateurish "inventions" which depend upon magnets working through great distances are never successful.

If the conductor is wrapped in the form of a coil, as shown in Figure 1-7, the fields about each turn add up to a flux system similar to that displayed by the permanent magnet. For convenience we consider that, as a direct current is made to flow through this coil, the flux builds up from zero from an imaginary line through the center of the coil to a position as shown. Opening the circuit causes the flux to collapse to this line.

1-6 Effect of Iron or Steel

If we would place a piece of steel inside the coil, the flux would be greatly increased. If the steel were a complete loop so that the entire

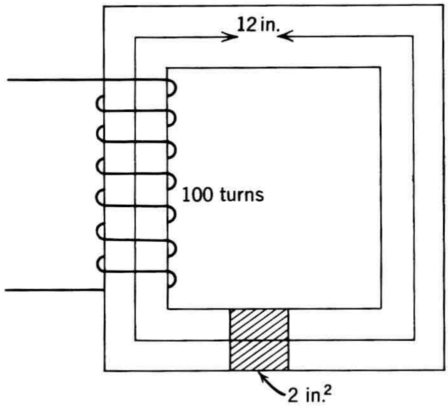

Figure 1-8. A steel core of laminations is built up to the dimensions shown and is magnetized by a coil of 100 turns.

magnetic circuit could be set up in steel, the flux would increase a great deal more. This construction is shown in Figure 1-8.

In addition, if we increase the current in the coil, more flux is built up, which also occurs if the number of turns is increased. The flux system around each added turn adds to the total. Examine the general rule:

$$\text{effect} = \frac{\text{effort}}{\text{opposition}}.$$

We can conclude that the effort expended, depending on both the number of turns and the amperes, is their product, N (turns) $\times I$. This is the magnetizing force. The effect is a flux system of ϕ lines with an intensity of B lines/in.².

By adding steel to the circuit and obtaining more flux lines thereby, we can see that it is easier to set up flux in steel than in air. The opposition to the setting up of flux is called the *reluctance*. The inverse of this, the ease with which flux is set up, is called the *permeability*.

We can now fill in our equation for the magnetic circuit:

$$\phi \text{ (flux)} = \frac{NI}{\text{reluctance}} K. \tag{1-7}$$

Magnetic circuits are cursed with many units of measurement, each requiring a different definition or value of K. We will deal only with the simplest method.