Basics of Electric Motors

Including Polyphase Induction and Synchronous Motors

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Preface

Electric motors have made possible industrial exploits that were not considered feasible with human, animal, and steam power. Yet their operation, the variety of types, their applications, and associated problems have remained somewhat of a mystery to those outside the engineering fraternity.

That the basis of motors is the phenomenon of magnetism, familiar to anyone who has at some time toyed with a horseshoe magnet, may indeed be surprising. The simple concept of the action of a motor is that of one set of magnets chasing another set attached to a shaft, causing it to rotate and perform work.

In this text we have deliberately avoided highly technical explanations and procedures, and have made only limited use of mathematics. The material presented is divided into two parts. One part deals exclusively with motors, their types and characteristics, and their operation and maintenance. Another part delves into other properties of electricity and magnetism associated with motor action. The many illustrations help in the understanding of this important and interesting subject.

Mechanics, electricians, technicians, sales and maintenance personnel, and others engaged in dealing with motors will find this work helpful. Others whose interest may also be pertinent will find it instructive. Earlier success with similar presentations concerning power delivery systems and equipment provided the motivation and experience needed to pursue this undertaking.

Grateful acknowledgment is made to the General Electric Co., Westinghouse Electric Co., U.S. Navy, and the Long Island Lighting Co. for their contributions of drawings, diagrams, and other descriptive material. Chapters seven through twelve of Part B are extracted from *Essentials of Electricity* by this author and are reproduced courtesy of Long Island Lighting Company. Thanks, too, are due to many of my friends and associates for their generous aid and encouragement, to the staff of Prentice-Hall and especially to Mrs. Jean Hunter Lapidus for constructive suggestions and criticisms, and not least, to my beloved wife for her patience and support.

Waco, Texas *Anthony J. Pansini*

chapter 1

Electromagnetic Basis

INTRODUCTION

Electric motors convert electrical energy into mechanical work, employing the same phenomenon of magnetism that is exhibited by the small horseshoe magnet, a novelty or toy familiar to almost everyone. The rotation of an elementary motor, producing the mechanical work, is caused by the interaction of the magnetic fields of a fixed magnet, called a *stator*, and a movable magnet, called a *rotor* (or sometimes an *armature*). At least one of the magnetic fields involved is produced by the electrical energy input. The repulsion action between the magnetic fields of the stator and rotor cause the rotor to revolve; the revolving rotor is harnessed to perform mechanical work. (A similar action takes place in electric generators, except that mechanical work is applied as input and electrical energy produced as output.) It is well, therefore, that the phenomena concerning magnetism and electromagnetism be understood.

MAGNETISM

Some substances exhibit a power to attract materials such as iron, steel, nickel, cobalt, and some alloys made of those materials; these substances are known as *magnets* or *magnetic materials*. If suspended so that they may swing or rotate

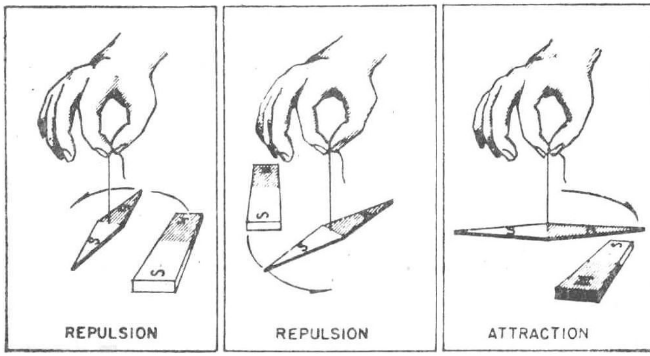


Figure 1–1 Laws of attraction and repulsion. (Courtesy U.S. Navy.)

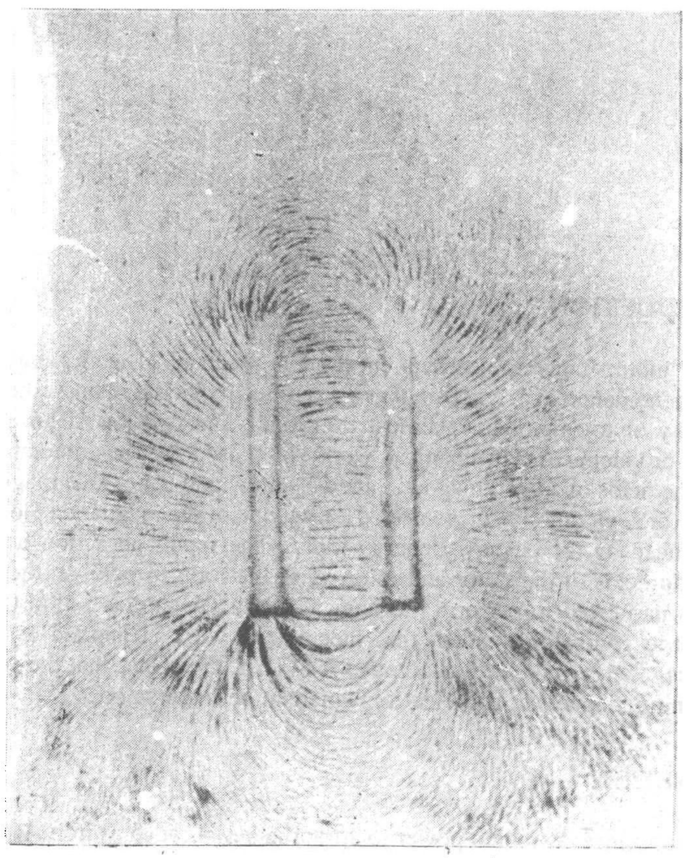


Figure 1–2 Magnet shapes and magnetic lines of force: (a) horseshoe magnet; (b) bar magnet.

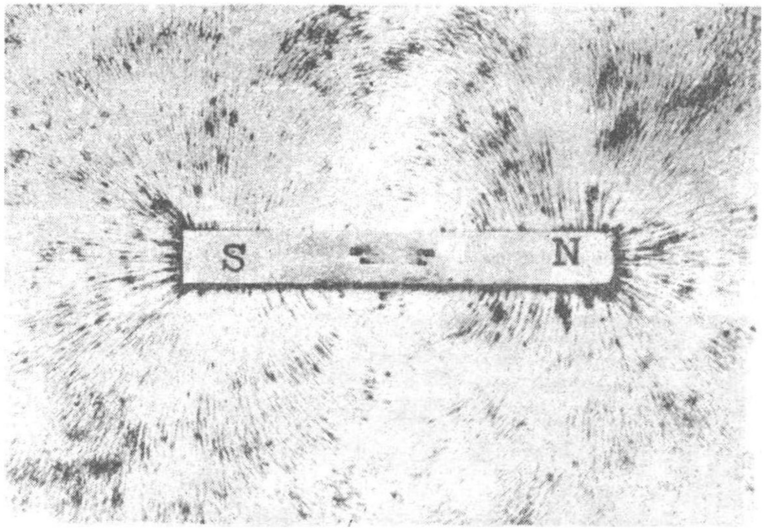


Figure 1–2 (*Continued*)

freely, pieces of such substances will come to rest in an approximately north–south line of direction. The same end will always point in one direction; that pointing toward the geographic north is referred to as the *north pole* of the magnet, and the other end the *south pole* (Figure 1–1).

The property of attraction can be illustrated by the horseshoe magnet mentioned earlier. Looking at Figure 1–2a, a magnetic field consisting of imaginary (invisible) lines of force may be theorized. For convenience, these lines may be said to emanate from the north pole and enter the south pole, then proceed through the magnet back to the north pole; the path of these lines of force constitutes a complete magnetic circuit. The same phenomenon exists in a bar shaped magnet and in magnets of other shapes (Figure 1–2b).

The phenomenon of magnetism is not well understood. Looking at Figure 1–3, one theory assumes that each of the molecules of some substances are tiny

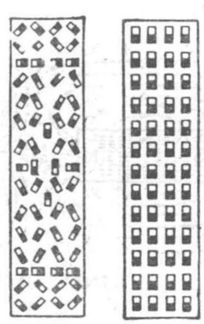
a

b

Figure 1–3 Molecular theory of magnetism: (a) unmagnetized iron; (b) magnetized iron.

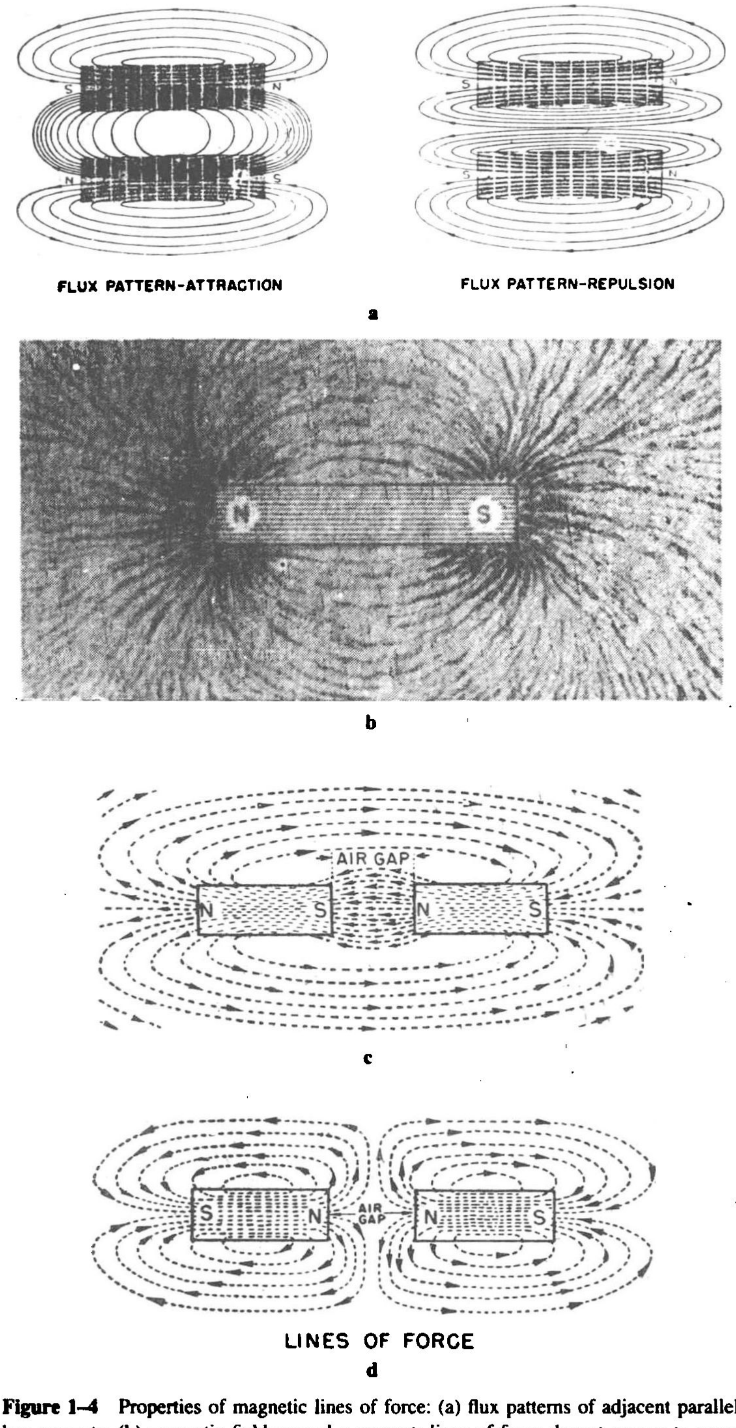


Figure 1–4 Properties of magnetic lines of force: (a) flux patterns of adjacent parallel bar magnets; (b) magnetic field around a magnet; lines of force do not appear to cross each other. (c) Unlike poles attract; (d) like poles repel. (Courtesy U.S. Navy.)

magnets which, when arranged at random, produce no magnetic effect, and when arranged so that the north poles of each of the tiny molecular magnets point in the same direction, produce an external magnetic field or magnetic lines of force (Figure 1–3).

From observation of the behavior of magnets by sprinkling iron filings around a magnet, several facts can be deduced:

1. The magnetic field around a magnet can be considered symmetrical but can be disturbed by the magnetic field of a nearby magnet (Figure 1–4a).
2. The lines of force appear to emanate from one end, or north pole, and enter the other end, or south pole, with the greatest intensity found near the pole surfaces and diminish with increased distance from the poles; the magnetic lines of force appear not to cross each other at any point (Figure 1–4b).
3. Opposite or unlike poles tend to attract each other; like poles tend to repel each other (Figure 1–4c and d). The force of attraction or repulsion varies directly as the product of the separate pole strengths, and inversely as the square of the distance separating the poles. *For example*: If either pole strength is *doubled*, the distance between poles remaining the *same*, the force between the poles will be *doubled*. If the distance between two north poles is *doubled*, the force of repulsion is decreased to *one-fourth* of the original value.

ELECTROMAGNETISM

In 1819, Hans Christian Oersted, a Danish physicist, found that a definite relationship exists between magnetism and electricity. He discovered that an electric current is accompanied by certain magnetic effects.

A current of electricity flowing through a wire produces not only heat but also a magnetic field about the wire; this may be proved by placing a compass needle in the vicinity of the current-carrying wire (Figure 1–5).

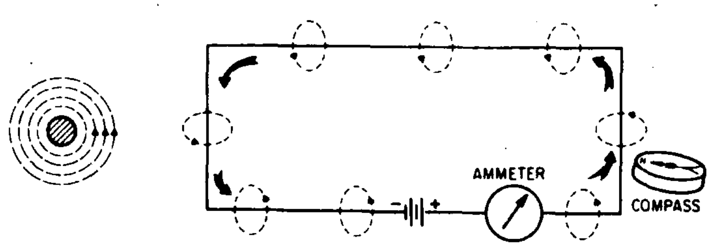


Figure 1–5 Magnet field around a current-carrying conductor.

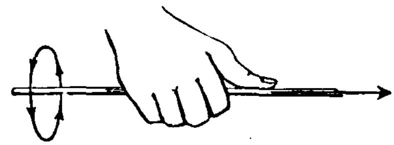


Figure 1–6 Right-hand-thumb rule.

If the direction of the electric current is assumed to be from negative to positive, it will be observed that the magnetic needle placed adjacent to the conductor will always point with its "north" pole in a certain definite direction. The needle is forced into this position by the magnetic lines of force, sometimes also referred to as the *magnetic field*, and sometimes as *magnetic flux*.

Right-Hand-Thumb Rule

This observation leads to a general rule known as the right-hand-thumb rule. If the wire is grasped in the right hand with the thumb outstretched pointing to the direction of the electric current, the fingers curled around the wire will indicate the direction of the magnetic lines of force (Figure 1–6).

FIELD ABOUT A COIL

A magnetic field around a single wire carrying a current is rather weak. By winding the wire into a ring, the magnetic lines are concentrated in the small space inside the ring or coil and the magnetic effect is much increased. The lines of force are grouped, resulting in a magnetic field stronger than that around the single wire (Figure 1–7a).

A coil of wire may be considered as a succession of these rings stacked one after the other. Each adds its quota to the magnetic field. Most of the magnetic lines of force pass straight through the coil. Each line makes a complete circuit, returning by a path outside the coil. A coil carrying a current is in fact a magnet. Where the lines come out is the "north" pole; where they enter is the "south" pole (Figure 1–7b).

The right-hand-thumb rule may also be applied in determining the polarity of a coil. If the coil is grasped in the right hand with the fingers pointing in the direction of the current flowing around the coil, the outstretched thumb points toward the north pole of the coil (Figure 1–6).

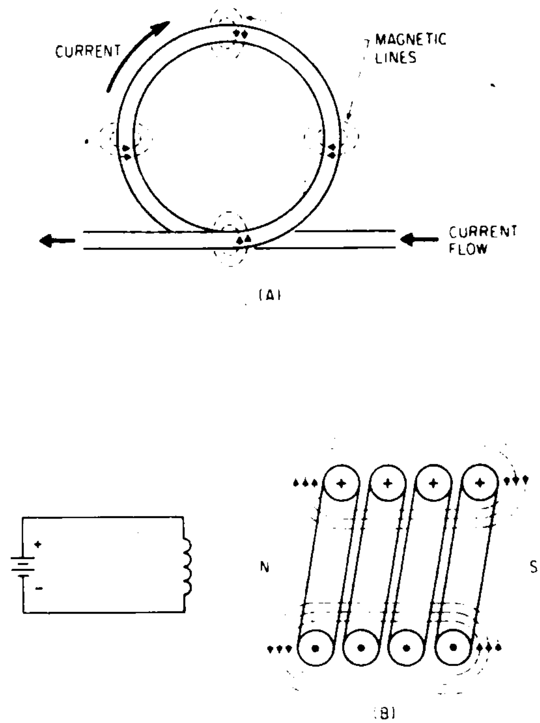


Figure 1–7 (a) Magnetic field about a loop; (b) magnetic field about a coil. (Courtesy Long Island Lighting Co.)

Strength of the Magnetic Field

The strength of the magnetic field inside a coil depends on the strength of the current flowing and the number of turns. It is therefore expressed in *ampere-turns*, that is, amperes multiplied by the number of turns. Thus a single turn carrying a very large current may produce the same effect as a great many turns carrying a small current.

A coil with an air core, however, produces a comparatively weak magnetic field. Its strength can be increased enormously by inserting an iron or steel core.

inside the coil. This arrangement is generally referred to as an *electromagnet* (or sometimes, *solenoid*).

***Example*:**

Assume a coil of wire of 100 turns having an air core produces 10,000 lines of force when a current of 5 amperes flow through it, that is, by a coil magnetic strength of 5 ampere-turns. If a magnetic field of 20,000 lines of force is desired, it may be achieved by

1. Doubling the number of turns in the coil, keeping the current flowing through it constant:

   200 turns × 5 amperes = 1000 ampere-turns

2. Keeping the number of turns in the coil the same and doubling the current flowing through it:

   100 turns × 10 amperes = 1000 ampere-turns

Permeability

When an iron core is used in an electromagnet, it produces a stronger magnetic field than when no core is used; further, if a steel core is used, the magnetic field produced is even stronger than that produced when iron is used

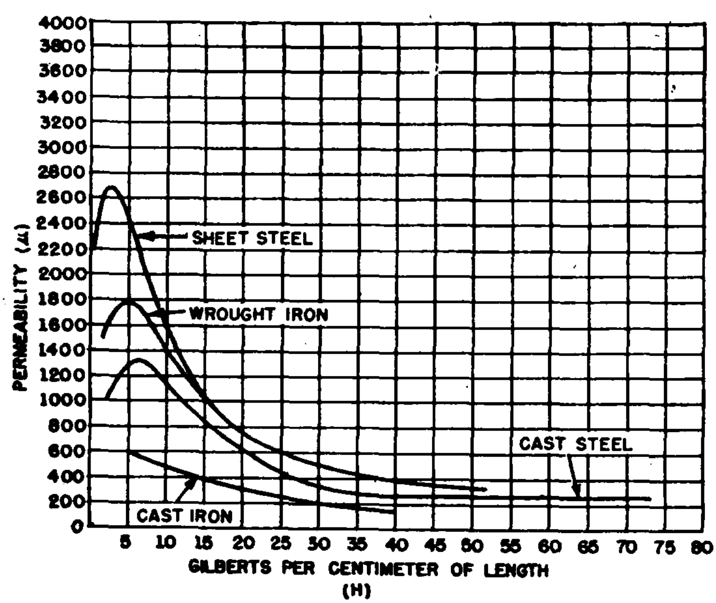


Figure 1–8 Permeability curves. (Courtesy Westinghouse Electric Co.)

as a core. The ratio of the magnetic field, or *flux*, produced by a coil when the core is iron, steel, or some other substance, to the flux produced when the core is air is called the *permeability* of that substance. The premeability of a substance is thus a measure of the relative ability to conduct magnetic lines of force, or its magnetic conductivity.

The permeability of air is taken as 1 or unity, and is essentially the same for nonmagnetic materials such as wood, aluminum, copper, and brass. The permeability of magnetic materials may range from values as low as 200 for cast iron to over 3000 for special steels (Figure 1–8).

Example:

If the coil considered above of 100 turns and 5-ampere current flow, producing 10,000 magnetic lines of force, has inserted in it a cast-iron core whose permeability is 200, the magnetic lines of force produced will be

$$10{,}000 \times 200 = 2{,}000{,}000 \text{ lines}$$

If a steel core having a permeability of 1000 is inserted in the coil, the magnetic field produced will be

$$10{,}000 \times 1000 = 10{,}000{,}000 \text{ lines}$$

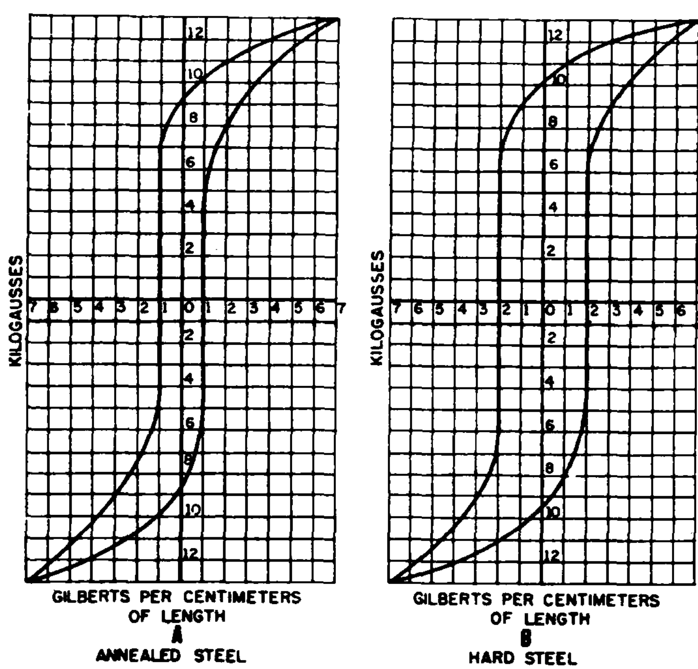


Figure 1–9 Comparison of hysteresis loops: (a) annealed steel; (b) hard steel. (Courtesy Westinghouse Electric Co.)