MEDICAL RADIOGRAPHIC TECHNIC

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MEDICAL RADIOGRAPHIC TECHNIC

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Preface

As I see it now, this book is somewhat like Topsy—"It just grew and grew."

In the beginning, members of the Technical Service Department wanted a handbook for their own guidance in formulating a standard method of teaching x-ray operative procedure. These men were brought together for the purpose of deciding on an outline of class procedure, which, with minor changes, could and would be used by all of us.

It is only natural that certain variations in the teaching of any subject depends upon the individual; nevertheless, the fundamental principles, based upon facts, is the baseline of all instruction.

As the ideas grew in number (and in scope), it was finally decided that instead of merely having an interdepartmental notebook for instructors, it would be more worthwhile to make our information available to all. So, from such a beginning, this reference book is made available.

Our greatest appreciation is expressed to the organization which has provided us with the opportunities, facilities and finances for making this effort possible.

It is a book written by technicians for technicians, an accumulation of material based upon facts now available which have proven to be an aid in producing a "better end result" and the reasons why.

G. W. F.

Acknowledgments

The following people contributed particularly special work to MEDICAL RADIOGRAPHIC TECHNIC.

The chapter on anatomy is the work of Mr. H. O. Mahoney. The illustrations are from actual skeletal material obtained, in part, from the Department of Anatomy of Northwestern University Medical School, following throughout the proportions established by Charles Schroeder.

Chapters one to four, inclusive, were written by Mr. Morton Fagen, and the illustrations drawn by Miss Carolyn Ogle. Mr. M. J. Gross rendered valuable assistance in checking the various formulas, equations, etc.

The illustrations of positioning are the photographic contributions of Mr. Frank Cooke and Mr. George Ashworth.

Mr. George Martin, Mr. C. B. Minnich and Mr. C. H. Buckingham did special work on the text.

The transcribing and proof reading were the responsibility of Miss Jeanne Minnema.

Mr. John R. Armstrong and Miss Idylle Saffran compiled the index.

To list the many others who contributed is not feasible. But my thanks to all, mentioned by name or not, for their valuable assistance and guidance.

G. W. F.

Contents

MEDICAL RADIOGRAPHIC TECHNIC

Fundamental Electrical Concepts

THE BASIS for the generation of x-rays is essentially electrical in nature since the energy input to the x-ray tube is electrical energy. For this reason no clear understanding of the controlling factors can be had without some acquaintance with such fundamental electrical concepts as electromotive force, resistance, direct current, alternating current, transformers, capacitance, etc.

Electric Potential and Current

An electric current will flow through a circuit or through two points of a circuit between which an electric potential exists. The current of electricity is assumed to be a movement of negatively charged particles called electrons. Their occurrence may be as free electrons within the structure of the material of which the conductors are composed, or as bound constituents of the atom itself. The electric potential may be established by a variety of agents, among which are friction, chemical action, pressure, heat, and magnetic induction, the last of these being of particular interest in subject matter to follow. The effect of the electromotive force, due to the difference of potential, is to cause an electric current to flow which is directly proportional to the electromotive force and inversely proportional to the impeding elements in the circuit. The general nature of the electromotive force is the same whatever the agency by which it is produced, but the specific characteristics of the resultant current will depend on the form of its origin. This relationship may be expressed as

$$i = \frac{e}{z}$$

in which i = instantaneous value of the electric current
e = instantaneous value of the electromotive force
z = a factor expressing the impeding forces

The potential difference produced by contact of dissimilar substances, thermo-electric action, friction between dissimilar substances, and chemical action, is continual and constant, assuming that activity is proceeding at a constant rate. In the case of a simple voltaic cell, as shown in Figure 1, there will be a voltage established at the terminals which will be constant as long as the surfaces in the solution are pure and uncontaminated so that no secondary chemical action will take place. If an electrical circuit is completed externally, as shown in Figure 2, an electric current will flow in the direction indicated from the positive terminal through an indicating meter, through the remainder of the circuit symbolically represented by the resistance R and back to the source. The current will continue to flow as long as the circuit is complete and its direction and magnitude will remain constant.

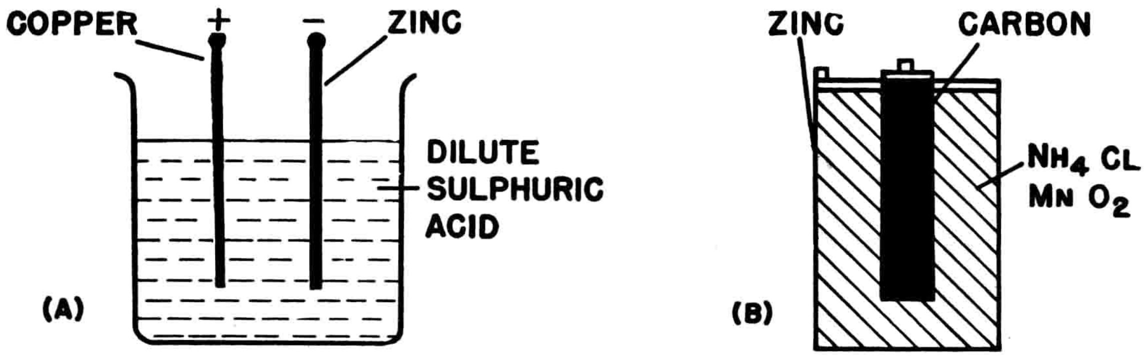

FIG. 1. Electro-chemical sources of electromotive force showing (a) simple voltaic cell and (b) "dry" cell.

Such a current is known as a *direct current* and is represented in Figure 3, in which units of current are plotted against time. This graphic representation is a convenient one since it indicates the direction of magnitude of the current at any time, T. The current I is defined as the rate of flow of electricity

$$I = \frac{Q}{T}$$

in which Q = quantity of electricity in coulombs
I = current in amperes
T = time in seconds

As indicated above, the relationship of the intensity of the current to the electromotive force producing it is linearly proportional. For a direct current circuit, Ohm's law is

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

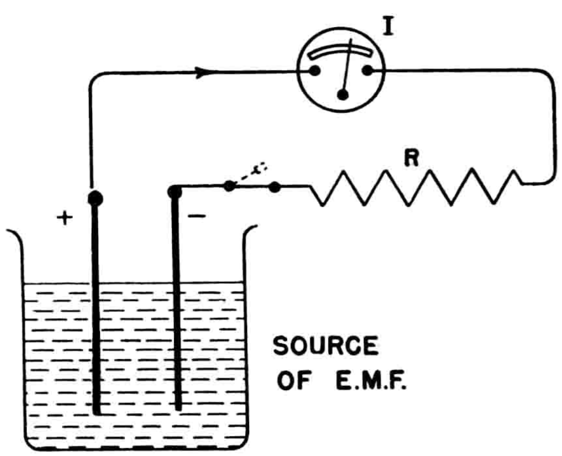

FIG. 2. Complete electrical circuit showing conventional direction of current flow.

in which I = current in amperes
E = electromotive force in volts
R = a constant of proportionality termed resistance (ohm)

The term R is a measure of the characteristic property of the circuit which resists the flow of

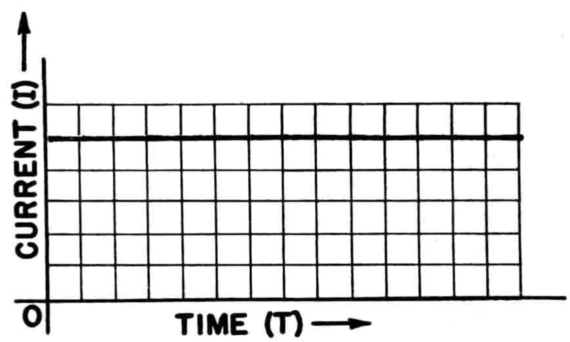

FIG. 3. Relation of current to time in a constant current circuit.

current. It depends on the material which forms the electrical path, the length of the path, and its cross-sectional area. The formula is

$$R = \rho \frac{L}{A}$$

in which R = resistance (ohms)
L = length of circuit
A = cross-sectional area
ρ = resistivity of the material forming the circuit

The nature of ρ is important. Materials differ widely in their ability to conduct electricity, varying from practically non-conductors like glass and mica to excellent conductors like copper and silver. The non-conductors offer very high resistance to the flow of electricity and are called insulators, though it is recognized that such a classification is relative, not absolute. The best conductors offer some resistance to the flow of electricity and the best insulators under certain conditions permit the flow of some electricity. The question of insulation and conduction is further complicated by the effects of temperature, pressure, surface conditions, and even the magnitude of the applied voltage, so that some materials may be reasonably good insulators under a given set of conditions, but very poor insulators under another.

Electromotive Force by Magnetic Induction

One source of electromotive force which is of particular importance in understanding the principle of the alternating current transformer is that of magnetic induction. If a wire is moved across a magnetic field, a potential difference will be produced between the end points of the wire. Figure 4 illustrates the principle and the

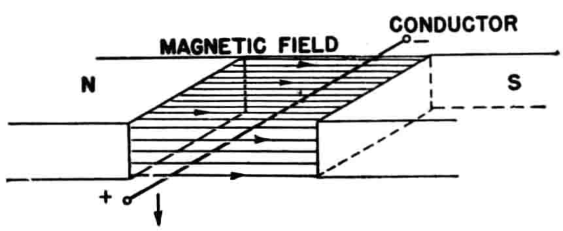

FIG. 4. Electromotive force produced by magnetic induction in a conductor moving across a field.

direction of tne induced electromotive force for a conductor moving downward in a left to right field. The electromotive force is proportional to the strength of the magnetic field, the length of the wire, and the velocity of the conductor. The formula is:

$E = kBlv$ volts

in which B = density of the magnetic flux (Gausses)
l = length of the conductor (centimeters)
v = velocity of the conductor (centimeters per second) with respect to the field
$k = 10^{-8}$

Conversely, if the magnetic field is moving with respect to the conductor, there will be an electromotive force produced in the conductor, its direction dependent upon the direction of the motion of the field and of the magnetic lines of force.

If both field and conductor are stationary, and if the magnetic field changes in intensity, there will be an electromotive force induced in the conductor which is proportional to the rate at which the field is changing. In such a case,

$$E = K \frac{\varphi_2 - \varphi_1}{t}$$

in which φ_1 = original magnetic flux
φ_2 = final magnetic flux
t = time over which the change takes place
E = average induced voltage
K = constant

The Heating Effect of an Electric Current

The current I flowing in the simple circuit of Figure 2 manifests itself by an evolution of heat in all parts of the circuit which is proportional to the square of the current and to the resistance of the portion of the circuit being considered. In the resistance R, for instance, $P = I^2 R\, 10^7$ ergs per second. If the current continues to flow for a time, T, the energy supplied to the resistance will appear as heat, equal to $W = I^2 RT$ Joules. This expression is known as Joule's law, and may conveniently be written $W = 0.24\ I^2\ RT$ calories, by introduction of a mechanical equivalent of heat, 4.19×10^7 ergs = 1 calorie. Use will be made of Joule's law in a later section for computation of the total energy input into the anode of an x-ray tube.

Magnetic Effect of an Electric Current

An electric current flowing through a conductor will produce a magnetic field in the vicinity of the conductor. The lines of magnetic force will surround the wire in concentric circles as shown in Figure 5, which lie in planes perpendicular to the axis of the conductor, and which have their centers on this axis. If the conductor is wound in the form of a solenoid, the magnetic intensity is increased with the field distribution as shown in Figure 6. The lines of force are similarly distributed in three dimensions of space, each of them being closed curves, linked with one or more turns of the coil in which the current is flowing. The magnetic intensity within the solenoid is given by:

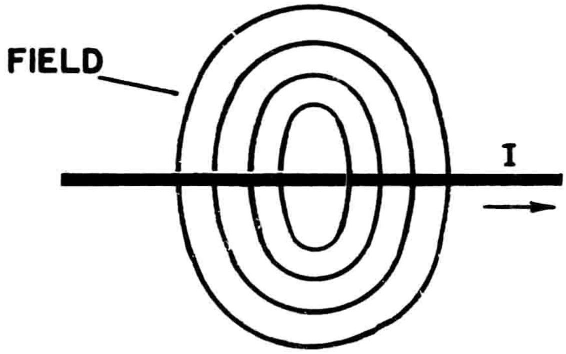

Fig. 5. Lines of magnetic force surrounding a wire carrying an electric current.

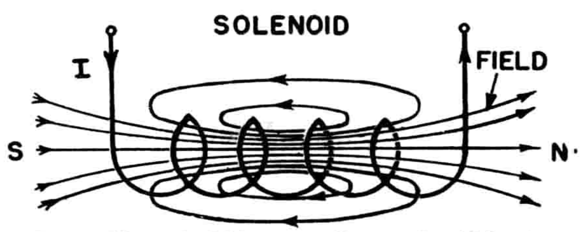

Fig. 6. Magnetic field surrounding a solenoid in air.

$$H = \frac{4\pi NI}{10}$$

in which H = magnetic field intensity (gilberts per centimeter)
N = number of turns per centimeter
I = current (amperes)

If an iron core is introduced within the solenoid, the field intensity will be greatly increased since the iron will become magnetized by induction and will add a magnetic flux to the original, and the field will be changed as shown in Figure 7. Within the core, the number of lines of force per unit area or magnetic flux density, is greatly increased, the factor for a good grade of magnetic iron being 3,000 times that for air. This characteristic is called the permeability of the magnetic medium, and is defined as:

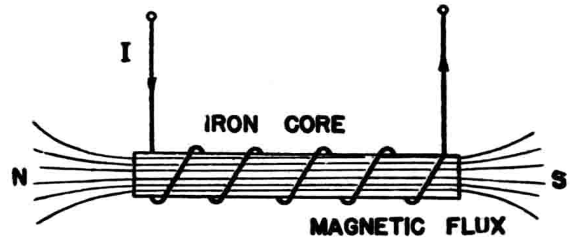

Fig. 7. Magnetic field around a solenoid with an iron core.

$$\mu = \frac{B}{H}$$

in which μ = permeability

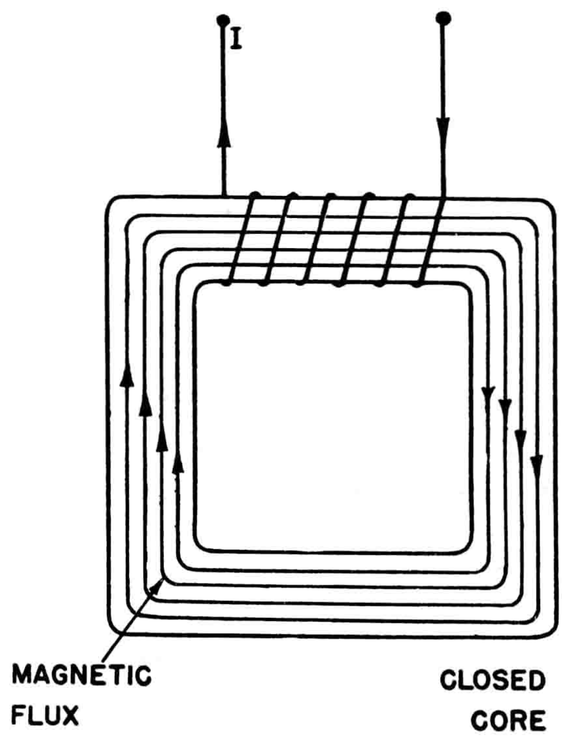

Fig. 8. Magnetic field in a closed iron core produced by current flowing through a solenoid.

H = magnetic field intensity
B = flux density

In Figure 7, the magnetic circuit is completed in air which has a comparatively high magnetic reluctance. Forming the solenoid over a closed iron core, as shown in Figure 8, the flux density is still further increased since the magnetic lines of force have a complete circuit in a material of good magnetic characteristics. The relation of the electric current I to the magnetic flux φ which it produces is given by:

$$\varphi = \frac{4\pi}{10} \frac{NI}{L} \mu A$$

in which φ = flux (maxwells)
N = number of turns in the coil
I = current (amperes)
L = mean length of core (centimeters)
A = cross-section of the core (centimeters^2)
μ = permeability of the core.

Electromotive Force of Self-Induction and Inductance

It was shown earlier that if the magnetic field changes in intensity, there will be an electromotive force induced in the conductors linked by the field which is proportional to the rate at which the field is changing. In the case of the coil shown in Figure 8, an electromotive force will be induced in each turn of its winding by the changing flux which links its turns. As a result, a voltage will be produced across its terminals in an opposite direction to that which is applied from an external source in order to produce the original flux. This electromotive force is expressed as:

$$E = -N \frac{\alpha\varphi}{\alpha t} 10^{-8} \text{ volts}$$

and is known as an electromotive force of self-induction.

This characteristic of the coil, which is responsible for the induced electromotive force, is called its inductance, and is measured in henries, which is defined as that inductance which, when a current is changing at the rate of one ampere per second, will produce an induced electromotive force of one volt. Inductance can be considered also in terms of the magnetic flux which is produced by the current flowing through the coil. It is then defined as the flux linkages per ampere of current producing the flux:

$$L = \frac{\text{flux linkages}}{\text{current}} 10^{-8} \text{ henries}$$

$$= \frac{N\varphi}{I} 10^{-8} \text{ henries}$$

Capacitors

The ability to store electricity is a characteristic of certain combinations of conductors and insulators which are called capacitors. Whenever an insulator, usually called a dielectric, separates two conductors between which a difference of potential can exist, a quantity of electricity may be stored in the combination which is a function of the area of the conducting plate, the space between them, and the potential difference between them. Figure 9 shows such an arrangement. Applying a voltage between the plates will cause an electric charge to flow into them which, for the case shown, will cease when the poten-

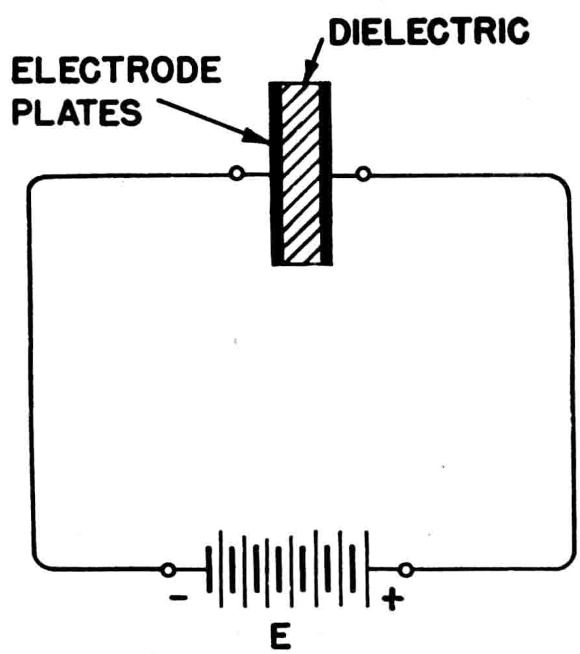

FIG. 9. Electric circuit showing capacitor and direct current source of electromotive force.

tial of the plates is the same as the potential of the charging source. The charge stored in a capacitor is given by the equation:

$$Q = CE$$

in which Q = charge in coulombs
C = capacitance in farads
E = potential difference between the plates in volts

Since the current changes with time, it is equal at any instance to the rate of change of the charge. This rate of change with respect to time is mathematically expressed as:

$$I = \frac{dQ}{dt} = C\frac{dE}{dt}$$

For a pair of parallel plates, the capacity in microfarads is given by the equation:

$$C = 0.08842\, K\frac{A}{d}$$

in which A = area of the plate (centimeters)
K = a constant called the dielectric constant which is a function of the material separating the plates. For air, K = 1.

Alternating Current

Thus far in consideration of fundamental electrical concepts, the current has been unidirectional and either constant in magnitude or varying in intensity with time. There is another kind of current which is of very great importance in the theory of x-ray generation and, in particular, the power supply to the x-ray tube. This is *alternating current* which is defined as one which reverses its direction at regularly recurring intervals, most generally with the positive and negative portions symmetrical in shape and area when instantaneous values of current are plotted against time. An understanding of the nature of alternating current can best be obtained by examining the principle of the alternating current electrical generator, the device in which an alternating current is produced.

Figure 10 illustrates the basic principle of an alternating current generator. A loop of wire is

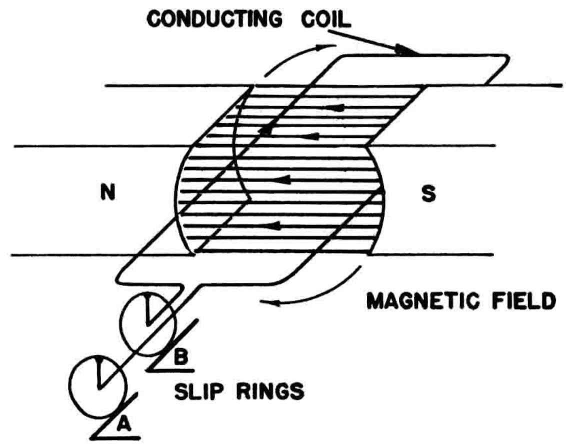

FIG. 10. The basic principle of an alternating current generator.

made to rotate in a magnetic field which passes from pole N to pole S, produced by the passage of direct current through field coils wound on the poles. The ends of the coil are connected to conducting rings insulated from one another upon which stationary contacts, A and B, complete the electrical circuit to the terminals of the machine.

The direction of the current in the wires will be at right angles to the direction of the magnetic lines and the direction of motion, usually expressed by Fleming's rule.

If the thumb, forefinger, and middle finger of the right hand are perpendicular one to another and the thumb is pointed in the direction of motion of the wire relative to the field, the forefinger in the direction of the magnetic lines of force, then the middle finger will point in the direction of the induced voltage. In Figure 10, an electromotive force will be induced in the wire passing under the N pole in a direction away from the reader, while for the wire passing under the S pole, the direction will be toward the reader. The electromotive force in the conductors A and B forming opposite sides of the coil add together in such a direction that A is the positive terminal and B is the negative terminal when the coil is in the position shown. Now consider the coil rotated half a revolution or 180°: conductor B is then under the S pole and A is under the N pole. The electromotive force reverses and B is the positive terminal with A the negative. The polarity thus reverses itself twice for each revolution of the coil.

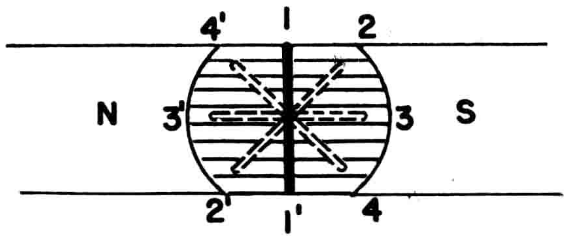

FIG. 11. Reference position of plane of coil in the magnetic field.

The magnitude of the generated voltage is proportional to the rate of change of the magnetic flux through the coil. In Figure 11, when the coil is in position 1, the flux enclosed is a maximum, but the rate at which the number enclosed is changing is zero. Thus the induced voltage is zero. In position 3, similar to that of Figure 10, the flux enclosed is a minimum but the rate at which it is varying is a maximum, so the induced voltage is a maximum. In position 2 the voltage is some intermediate value depending on the angle between the plane of the coil and the plane of the magnetic lines. It can be shown that the rate at which the flux linkages change in a uniform magnetic field cut by a rotating loop conductor is a sine function[1] of the angle through which the coil has passed, beginning from position 1. Figure 12 shows the variation of φ, the enclosed flux, with time and the resultant induced voltage E.

It is not the magnitude of the enclosed flux which determines the voltage, but the *rate* at which it is changing as the coil rotates clockwise from the original position. With the coil in position 1, the voltage generated is zero. It increases until position 3 is reached at which it is a maximum, the angle traversed being 90°. Then the voltage decreases in magnitude until it reaches

[1] The sine of an angle is the ratio b/c so that C sine α becomes the projected length of the hypotenuse c, in the direction of b.

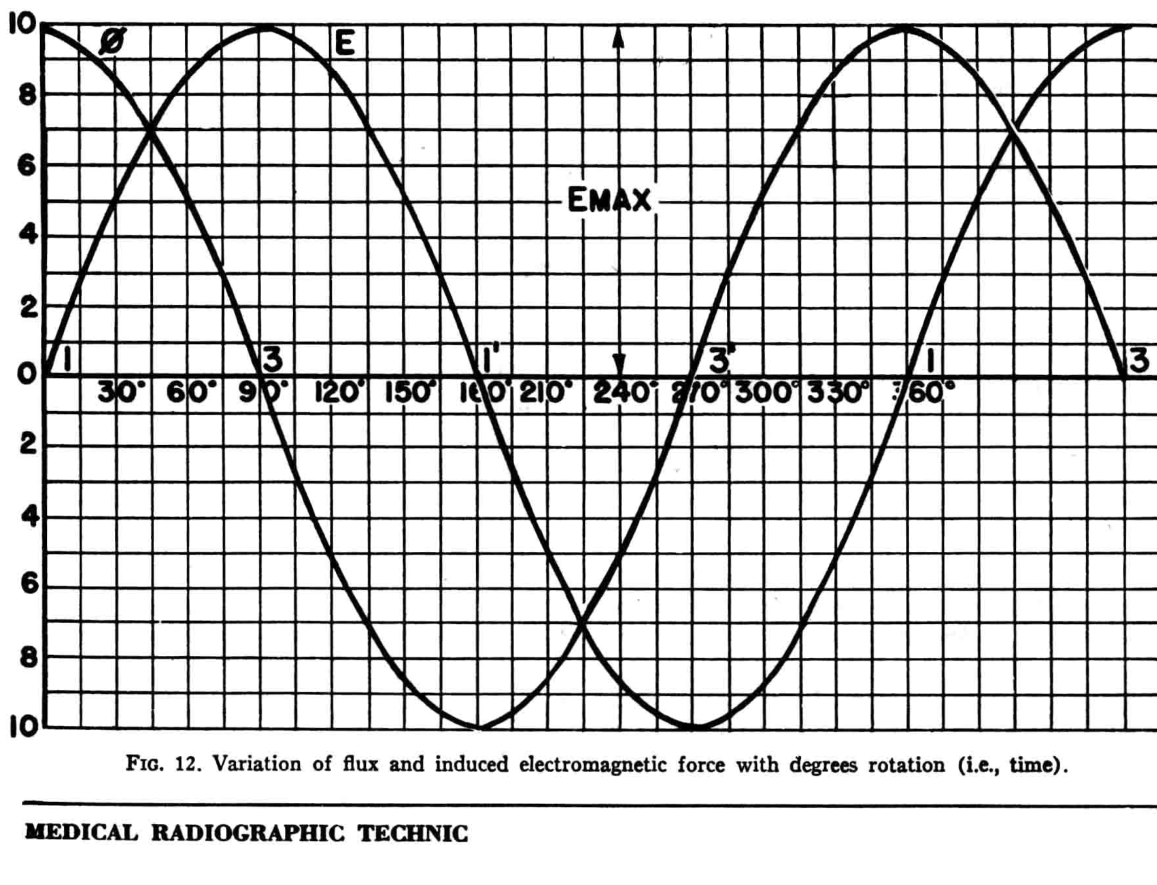

FIG. 12. Variation of flux and induced electromagnetic force with degrees rotation (i.e., time).

zero with the coil perpendicular to the field position 1′; similar to position 1 but with the coil sides reversed. The angular change is 180°. The voltage then increases, but with reversed polarity until a position 3′ is reached, at which it is a maximum, the direction of the induced voltage being opposite to that in position 3. With continued rotation, the cycle of changes repeats itself.

The electrical current produced in the manner described is known as an *alternating current* and is defined as one whose direction reverses at regularly recurring intervals, most generally with successive half waves 1 to 1′ of Figure 12 of the same shape and area when instantaneous values of current are plotted against time.

A cycle is one complete set of positive and negative values of an alternating current.

The frequency is the number of cycles through which it passes per second.

The sine wave is the simple alternating wave shown in Figure 12, for which the changes with time are expressed in terms of a function of the maximum value E_{max} and the angle α as:

$$e = E_{max} \sin \alpha \text{ (volts)}$$
$$\text{or } i = I_{max} \sin \alpha \text{ (amperes)}$$

The table, Figure 13, gives instantaneous values for various angles, measured from the position of minimum induced voltage.

Angle α	*e*
0°	0
30°	0.50 E_{max}
60°	0.866 E_{max}
90°	1.00 E_{max}
120°	0.866 E_{max}
150°	0.50 E_{max}
180°	0
210°	−0.50 E_{max}
240°	−0.866 E_{max}
270°	−1.00 E_{max}
300°	−0.866 E_{max}
330°	−0.50 E_{max}
360°	0

FIG. 13. Table showing instantaneous values of induced electromotive force for various positions of the coil measured from the position of minimum induced voltage.

Since the operation of electrical devices may involve no rotation, it is necessary to express the equation above as a function of time or frequency of the alternating current. If the coil is rotating with a uniform angular velocity w,

$$\alpha = wt$$

If f is the frequency,

$$w = 2\pi f, \text{ since one complete revolution is } 2\pi \text{ radians.}$$

Then,

$$\varepsilon = E_{max} \sin(2\pi ft)$$

The average value of the ordinate of a wave is the area of a half-cycle divided by the length of its base, in suitable units. For a sine wave, this is

$$E_{av} = \frac{2}{\pi} E_{max} = 0.636\ E_{max}$$

Of great importance also is the effective value of an alternating current, or its comparison to a direct current with reference to energy content. This figure is obtained by determining the square root of the average of the squares of the instantaneous values for a complete cycle. This is called the root-mean-square value and for a sine wave is

$$E_{r.m.s.} = \frac{1}{\sqrt{2}} E_{max} = 0.707\ E_{max}$$

Since, for power calculations, the effective values are always used instead of average or maximum values, ammeters and voltmeters for alternating current are calibrated to read these values, and the subscript root-mean-square is understood.

The alternating current of sine wave form is the basis for electrical design and calculation and may, in most cases, be assumed to represent current and voltage waves in electrical circuits. It must be recognized, however. that any departures from the theoretical conditions assumed or the presence of distortions in the magnetic field, or of losses in the circuit itself may modify the wave shape to a considerable extent necessitating special methods of approach.

The Alternating Current Transformer

In the previous discussion of electricity and magnetism, two conclusions were established:

1. An electric current produces a magnetic

field in the vicinity of the circuit in which it flows.

2. An electromotive force is induced in a conductor when the magnetic field enclosed by the conductor is changing in intensity, the magnitude of the induced electromotive force being proportional to the rate of change of magnetic flux.

It was shown on page 5 that an electromotive force is induced in a conductor when the magnetic field enclosed by the conductor is changing in intensity, the magnitude of the induced electromotive force being proportional to the rate of change of magnetic flux. These principles can be combined in a manner shown in Figure 14. An iron core has wound on it two coils insulated from the core and from each other.

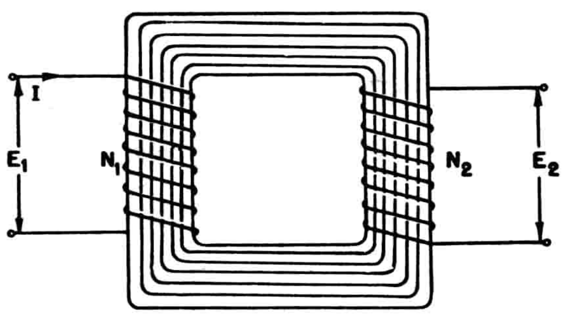

FIG. 14. The basic principle of the transformer—electromotive force produced in one coil as a result of current flowing through another.

One of these coils carries an electric current produced by an external electromotive force. The current I flowing through the coil No. 1 establishes a magnetic flux in the iron core which is proportional to the intensity of the current, the number of turns N_1 in the coil, the cross-sectional area of the core, its permeability and the inverse of its mean length. The flux so produced passes through the magnetic circuit and is linked by coil No. 2. A change in any of the factors affecting φ will produce a change in flux which will according to the law of magnetic induction, establish an electromotive force across the coil given by

$$E_2 = N_2 \frac{d\varphi}{dt} 10^{-8} \text{ (volts)}$$

in which E_2 = induced electromotive force across coil No. 2 (volts)

N_2 = number of turns in coil No. 2

$\frac{d\varphi}{dt}$ = rate of change of flux with time

E_2 is an electromotive force produced in the second coil as a result of mutual induction by the magnetic field, linking the first and second and established by the current flowing in the first coil. If the coil is connected to an external circuit, a current will flow which is proportional to the magnitude of the potential difference across the terminals. Neglecting losses due to heating of the windings and stray magnetic leakage, the power delivered by the second coil (secondary winding) will be equal to that delivered to the first coil (primary).

Since the magnetic flux is common to both coils, the voltage per turn induced in each must be the same. The voltage applied to the primary coil can be considered equal to the voltage of self-induction of the primary, and the terminal voltage of the secondary can be considered equal to the secondary induced voltage. Then,

$$\frac{E_1}{N_1} = \frac{E_2}{N_2}$$

in which E_1 = primary voltage

N_1 = primary turns

E_2 = secondary voltage

N_2 = secondary turns

or

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

which indicates that the primary and secondary voltages are in proportion to the number of turns of each.

A device of this type is known as a transformer since with it electrical power at any given voltage can be converted into power at any desired voltage by proper selection of the turn ratio.

Assume that the transformer of Figure 14 is supplied with an alternating sine wave voltage