# Fundamentals of

# ELECTRON DEVICES and CIRCUITS

by

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# PREFACE

The inclusion of electron devices and electric circuits in the study, application, and practice of all major branches of engineering science has presented a problem for suitable text material. It is the aim of this book to provide an integrated and teachable text at a level compatible with present mathematics and physics preparation in the engineering curricula. It is a specific attempt to write a single text covering the essential concepts of a-c circuit theory and electron devices that is equally useful to the electrical and the nonelectrical engineer. Each subject is developed in its logical sequence with a completeness assuring understanding without unnecessary complexity.

A working knowledge of calculus and a conventional background in electrical physics are assumed as prerequisites. All other necessary mathematical concepts are developed as they are used.

Although written as an integrated sequence, the text may be started at any point for which the reader has adequate preparation. Also, each chapter, although definitely a part of the overall development, represents an area of interest and may be selected for specific study.

Throughout the book an attempt has been made to present the fundamental concepts for complete understanding and to develop the basic methods of analysis applicable to all engineering problems. The specific applications have been described only to the extent necessary to provide a means for illustrating principles.

We are indebted to many people in the preparation of this book and take this opportunity to express our gratitude, although it is impossible to mention them all here by name. We are particularly indebted to Professor E. E. Dreese of the Ohio State University for his encouragement in the preparation of the manuscript, to many students and teachers, whose constructive criticism has enabled us to clarify points of question, and to our wives and children, whose patient cooperation has made such a work possible.

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## Chapter 1

# ELECTRIC CIRCUITS

Certain fundamental relationships are always true for passive electric circuit components such as resistance, inductance, and capacitance regardless of the additional circuit elements that may be associated with them. It is necessary that the reader become familiar with certain basic concepts of electric circuit theory and with some of the fundamental laws related to the components. Succeeding chapters make use of certain assumed background knowledge, and the complete understanding of electronic circuits would be seriously hindered without a complete familiarity with these basic principles. To provide for a review of the pertinent facts and to point out the fundamental relations considered most important, the next few pages will be devoted to a summary of electric circuit theory.

### 1.1. Resistance

The concept of electrical resistance is usually associated with the phenomenon of energy dissipation. Resistance in its simplest form would be a measure of the opposition of a piece of material such as copper to the flow of electric current. As such, energy must be dissipated to move current along a wire of this material, and as a result the wire may become hot. If the resistance of the material is small, it is considered to be a good conductor and the energy dissipated is small. Poorer conductors have higher resistance and dissipate more heat.

The concept of resistance is much more general than this simple example of power loss. Electrically, the dissipation of energy often appears as an equivalent resistance in the electrical circuit. The energy may ultimately appear as heat in the core of a transformer due to hystersis loss or as mechanical power delivered by a motor. If the supplying circuit is traced back far enough, this energy loss will appear as a fictitious or equivalent resistance. From this concept the idea of effective resistance has meaning in that a circuit between a pair of terminals may appear to be a resistance of a certain value as far as their circuit performance is concerned whether or not a wire of this ohmic resistance exists between them. The term *ohmic resistance* is usually used to refer to the simple conductor type of resistance discussed in the first paragraph.

With this broader idea of resistance it is of interest to the engineer to know the laws governing the relations between voltage and current at the terminals of such a device. The fundamental law is stated in any elementary physics text and is referred to as Ohm's law. The law states that the ratio of applied voltage to the resultant current is a constant at every instant and that this ratio is defined to be the resistance. If the voltage is expressed in volts and the current in amperes, the resistance is expressed in ohms. Using conventional symbols, the relation may be concisely stated in equation form:

$$\frac{e}{i} = R \text{ ohms,} \tag{1.1}$$

where $e$ is the instantaneous voltage in volts, $i$ is the instantaneous current in amperes, and $R$ is the resistance in ohms.

Equation 1.1 may be conveniently rearranged into the familiar forms of

$$e = iR, \tag{1.2}$$

or

$$i = \frac{e}{R}. \tag{1.3}$$

It should be noted that the fundamental relation as stated by Eq. 1.1 is for instantaneous values and therefore is true at every instant. If such a relation is true at every instant it must likewise be true on the average. Thus, the ratio of average voltage to average current is also the constant $R$. Expressed in equation form,

$$\frac{E_{\text{d-c}}}{I_{\text{d-c}}} = R. \tag{1.4}$$

The symbols $E_{\text{d-c}}$ and $I_{\text{d-c}}$ are used in Eq. 1.4 to express average voltage and current, respectively, and will continue to have this meaning throughout the text. As a general rule the average value of any time-dependent variable such as voltage or current may be found from the instantaneous value by means of integration. Thus,

$$E_{\text{d-c}} = \frac{1}{T}\int_0^T e\,dt, \tag{1.5}$$

and

$$I_{\text{d-c}} = \frac{1}{T}\int_0^T i\,dt. \tag{1.6}$$

The average values are determined for the particular period of time $t$ from $t = 0$ to $t = T$. Whether or not this represents the average value for other periods of time or for longer or shorter intervals of time depends upon the form of the instantaneous wave. Frequently $T$ is the period of a repetitive function such as a sinusoid or a square wave.

It is convenient for circuit analysis purposes to have a symbol to represent resistance. The common symbols and the conventional indications of positive direction of voltage and current are shown in Fig. 1-1. It should be noted that the instantaneous voltage and current associated with this element are indicated by arrows. These arrows represent an arbitrary choice of positive sense. Although they may be chosen in either direction at the discretion of the analyst, they are conventionally chosen as shown.


**Fig. 1-1.** Resistance.

The meaning of a positive sense indication is that this is the direction of current flow or voltage rise that will be considered positive. It is not suggested that this is necessarily the actual direction in a certain application, but that it is the direction with respect to which the answer is expressed. As an example, if a conventional current of 2.0 amp actually flows in the resistance of Fig. 1-1 from top to bottom, it is flowing in the positive sense direction indicated and would be referred to as a positive current of +2.0 amp. If, on the other hand, a current of 2.0 amp actually flows from bottom to top in Fig. 1-1, it is flowing opposite to the assumed positive sense direction and would be considered a negative current of −2.0 amp. It is not correct in the second case to feel that the answer is wrong or that the current is flowing in the wrong direction. The answer of −2.0 amp is perfectly correct with respect to the assumed positive sense.

To continue the example, if the resistance $R$ is 50 ohms, a voltage of 100 v will appear across the resistance as a result of the 2.0 amp of current, according to Eq. 1.2. If the direction of current is assumed from top to bottom, the polarity of the resulting voltage will be such as to make the top of the resistance positive with respect to the bottom. Since this result agrees with the chosen positive sense, the voltage is +100 v. Thus, with the conventional assumptions of Fig. 1-1, if $i$ is positive, the resulting voltage rise $e$ is also positive. If one of the assumed positive senses is reversed, the relation between $e$ and $iR$ must include a negative sign to satisfy actual conditions. (See Fig. 1-2.) The actual polarity of voltage resulting from a particular flow of current is determined by the conservation of energy and is not an arbitrary choice of the analyst. Since the resistance represents an energy sink, the actual flow of current must be opposed by the resultant voltage of the element. Otherwise, the resistance would supply energy to the circuit rather than dissipating it. It is well to keep in mind that all circuit terminology and figures are only symbols representing a physical phenomenon. No arbitrary change of symbols or directions by the analyst will change the actual conditions in the circuit. The symbols must always be arranged to be consistent with the actual physical situation. These positive senses are often shown with plus and minus signs replacing the arrows.

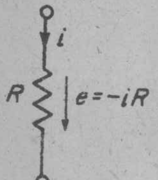


**Fig. 1-2.** Resistance.

It might be advantageous to plot the relation of Eq. 1.3. Then the current $i$ becomes a linear function of the voltage $e$ and passes through the coordinate origin. Such a plot as shown in Fig. 1-3 is referred to as the volt-ampere characteristic of the resistance. Since the general resistance is bilateral, that is, it will conduct current equally well in either direction, the slope of the curve is the same for positive or negative voltage or current. The slope of the curve is, of course, $\Delta i/\Delta e = 1/R$.

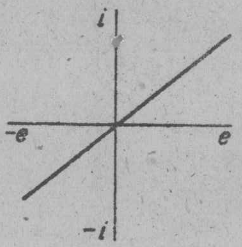


**Fig. 1–3.** Volt-ampere characteristic of a resistance.

There are many possible waveforms that the current through, or the voltage across, a resistance may take as a function of time. The instantaneous relation expressed in Eq. 1.1 must hold for all. Thus, if the voltage applied is a constant direct voltage as from a battery, the current in turn will also be constant. If the voltage is a square wave, so also will be the current. In fact, since Eq. 1.1 states that a constant ratio, independent of time, exists between the voltage and current, whatever waveform the one has as a function of time, the other must have the identical shape, differing only in magnitude. A few possible wave shapes are shown in Fig. 1-4. Some are more familiar than others. The one shown in Fig. 1-4(d) is probably the most common and the one most often referred to. It is the sine wave. It is apparent from what has already

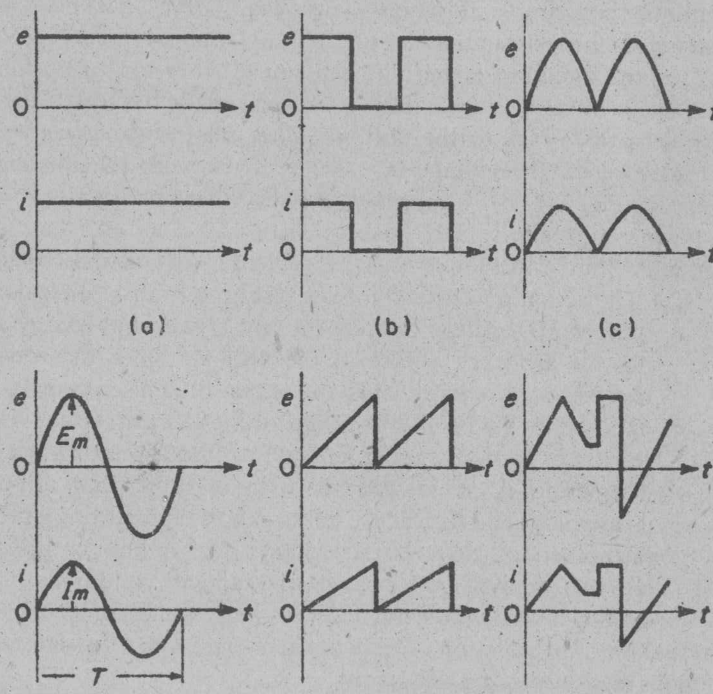


**Fig. 1–4.** Current and voltage relationships in a pure resistance.

been said that if the current passing through a resistance is in the form of a sine wave expressed as

$$i = I_m \sin \omega t, \tag{1.7}$$

the voltage must also be a sine wave and may be expressed as

$$e = iR = I_m R \sin \omega t = E_m \sin \omega t, \tag{1.8}$$

where $\omega = 2\pi f = 2\pi/T$. In Eq. 1.7, $I_m$ is the maximum value of the sinusoidally varying current, and it is called the amplitude of the sinusoid.

The product $\omega t$ is the radian measure of the angle measured from zero to the instant $t$ at which $i$ is to be evaluated. The time $t$ is in seconds and $\omega$ is the angular velocity in radians per second. Figure 1-4(d) is drawn for one complete cycle and represents $2\pi$ radians or 360 degrees.

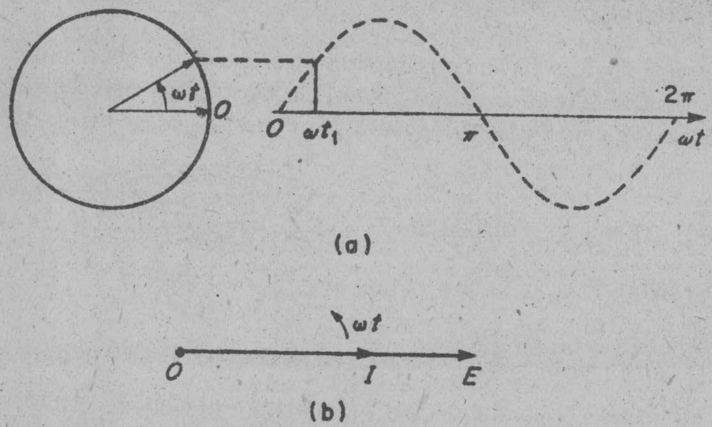


Fig. 1-5. Vector representation of sine waves.

The time in seconds for one cycle is the period $T$, and is the reciprocal of the number of complete cycles that would be swept out in one second. Thus, the frequency, $f$, is

$$f = 1/T \text{ cycles per second.} \tag{1.9}$$

The angular velocity, $\omega$, may be further defined as the radian measure of one cycle divided by the period of one cycle. Thus,

$$\omega = \frac{2\pi}{T} = 2\pi f. \tag{1.10}$$

When sinusoidal variations are being used it is common practice in electrical engineering to represent these time variations by rotating vectors or phasors. The basis of this representation is the fact that a rotating vector of constant amplitude has a vertical projection that varies as the sine of the rotation angle and a horizontal projection that varies as the cosine of the rotation angle if the positive horizontal axis of a right-handed coordinate system is taken as reference and rotation is counterclockwise. An illustration is shown in Fig. 1-5(a). It is convenient to permit the vector to represent the voltage or current quantity and to add or subtract by vector addition. With such a representation it is apparent that a vector representing the sinusoidal current in a resistance and a vector representing the sinusoidal voltage rise across the resistance would differ only in magnitude and could be spoken of as being in phase. This is shown in Fig. 1-5(b). It is sometimes convenient to allow the magnitude of the vector to be the instantaneous maximum value as the plots would indicate, and at other times it may prove useful to allow the vectors to be a certain fraction of this maximum value which is commonly known as the effective value. The exact meaning of this term will be discussed in Sec. 1.6.

## 1.2. Inductance

Inductance might well be considered a measure of the effect on a circuit of the magnetic field produced by a flow of electric charge commonly thought of as current. This magnetic field is a form of energy storage and in the ideal

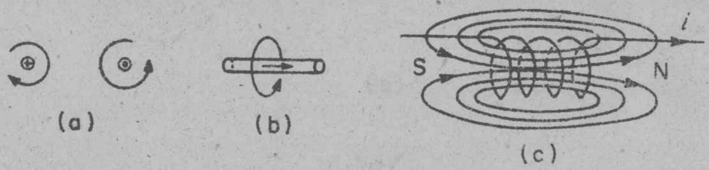


**Fig. 1–6.** Magnetic field around current-carrying conductor.

case has no losses. Thus, the perfect inductance will exhibit the property of energy storage but not the characteristic of power dissipation. Any energy stored in the magnetic field of a current may be, and in fact must be, eventually returned to the circuit.

It is perhaps best to start by assuming that a magnetic field, represented by lines of force, is set up around a conductor carrying a current. This fact can be shown by experiment. It is this direct relation between magnetic field and current in which we are interested. Although a single wire carrying current possesses this field, the effect may be increased by forming the wire into a coil or solenoid so that the magnetic field is concentrated in the area inside the loops. A sketch showing the field by the theoretical method of lines of flux is shown in Fig. 1-6(c). In Fig. 1-6(a), two single wires are shown, one carrying current into the paper as indicated by the tail of the arrow in the conductor, the other carrying current out of the paper as indicated by the point of the arrow in the conductor. By the right-hand rule the positive direction of the magnetic flux is clockwise for the first case and counter-clockwise for the second. Figure (b) shows a side view of a single conductor and the resulting field, and (c) shows a coil of conductor and the consequent concentration of the field. The conventional markings of N for north pole and S for south pole of the resulting field are also shown. Since the coil represents the concentration of the effect to be called inductance in a circuit, it is the usual symbol shown. We are interested in deriving the relationships between voltage, current, and time for such a circuit element.

It will be convenient to start with the concept of Faraday's law. This law states that whenever a conductor is linked by lines of flux and the number of these linkages is changed, a voltage will be induced in the conductor proportional to the rate of change of flux-linkages. Referring again to Fig. 1-6(c), the number of turns of the coil multiplied by the number of lines of flux interlacing all these turns would be the flux-linkages, $N\Phi$. Here $N$ is the number of turns, and $\Phi$ is the number of lines of magnetic flux linking all $N$ turns. Faraday's law may be conveniently stated in mathematical form as

$$e = \frac{d(N\Phi)}{dt} \times 10^{-8} \text{ v}, \tag{1.11}$$

where $\Phi$ is the number of flux lines, or the number of maxwells.

The statement of voltage being proportional to a time derivative emphasizes the fact that the voltage exists only during the time the actual change in flux-linkages is taking place and that it is proportional to the rate of change rather than the absolute change.

If the unit of flux called the weber is used, where

$$1 \text{ weber} = 10^8 \text{ lines}, \tag{1.12}$$

Eq. 1.11 may be written in mksc units as

$$e = \frac{d(N\Phi)}{dt} \text{ v}. \tag{1.13}$$

It should be further emphasized that it is the rate of change of the product $N\Phi$ which is important, and this change could be brought about by changing $N$, or $\Phi$, or both. Some texts give Eq. 1.11 or 1.13 preceded by a negative sign and then explain that this symbol indicates that the voltage so induced must obey the law of conservation of energy and oppose the source of energy that produced it. Although this is true, there is no real difference between this case and the case of the voltage produced across a resistance carrying current, in which no such signpost was felt necessary. In fact, the assignment of positive sense to the induced voltage is an arbitrary matter as before, and once assigned will determine the plus and minus signs required. Let us emphasize again that the signs used with a particular voltage or current cannot change the physical situation, but must be arranged to coincide with the arbitrary references established by the person wishing to solve the problem. As a result, the negative sign will not be used in Eq. 1.12.

If Faraday's law is now considered in its particular application to a coil in which a current is flowing and producing a magnetic field, it is possible to say that the field represented by $\Phi$ webers of flux is directly proportional to the current $i$, provided no magnetic material such as iron is present. This relation is usually given as

$$\Phi = \frac{Ni}{\mathcal{R}} \text{ webers.} \tag{1.14}$$

$\mathcal{R}$ is the magnetic circuit reluctance and is equal to $l/\mu\mu_o A$ for a simple solenoid, where $\mu$ is the relative permeability, $l$ is the length of the solenoid in meters, $A$ the cross-sectional area in square meters, and $\mu_o = 4\pi \times 10^{-7}$ henry/meter, the permeability of free space. The specific relation is not important for our consideration other than for the fact that the flux is proportional to $i$ and to the total permeability $\mu\mu_o$. It is well known that certain materials such as iron and ferrites exhibit large values of $\mu$ up to a point and then decrease or saturate in accordance with various nonlinear relationships. Let us consider the simple case of nonmagnetic material such as air where $\mu$ is a constant equal to unity. It is then possible to state that $\Phi$ is a linear function of $Ni$. Thus,

$$\Phi = Ni/\mathcal{R} \text{ webers.} \tag{1.15}$$

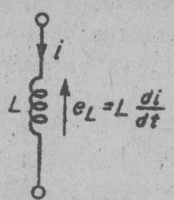


Fig. 1-7. Conventional notation for circuit inductance.

It is now possible to substitute Eq. 1.15 into Eq. 1.13 and obtain

$$e = \frac{d(N^2 i/\mathcal{R})}{dt} \text{ v.} \tag{1.16}$$

For a particular coil where $\mathcal{R}$ and $N$ are constant,

$$e = \left(\frac{N^2}{\mathcal{R}}\right)\frac{di}{dt} = L\frac{di}{dt}. \tag{1.17}$$

The constant ratio between induced voltage and the rate of change of current is symbolized by $L$ and is called the self-inductance of the coil. It is very important to note that $L$ is dependent only on the coil construction and is in no way a function of the applied current or resultant voltage so long as Eq. 1.15 is valid. The term is called the self-inductance of the coil, and the induced voltage is called the voltage of self-induction since it is the voltage induced in the coil as a result of a change of current in the coil itself.

Equation 1.17 is often referred to as Lenz's law, and is the instantaneous relation between voltage, current, time, and inductance for a coil. In order to make use of this concept in circuit analysis, certain conventions relative to notation and positive sense are helpful. These are shown in Fig. 1-7. The positive sense of the current and the voltage rise are chosen in opposition to each other just as in the case of the resistance. This will satisfy the conservation of energy requirement mentioned earlier. Thus a positive rate of change of current in the assumed positive direction of $i$ will result in a positive voltage rise in the assumed positive direction of $e_L$, and $e_L$ will tend to oppose the increase in current.

Since Eq. 1.17 is an instantaneous relationship, the wave shape of the voltage as a function of time will vary as the derivative of the current waveform. A few possible examples are shown in Fig. 1-8. Only plot (d) results in current and voltage of the same wave shape. This is the special case of a

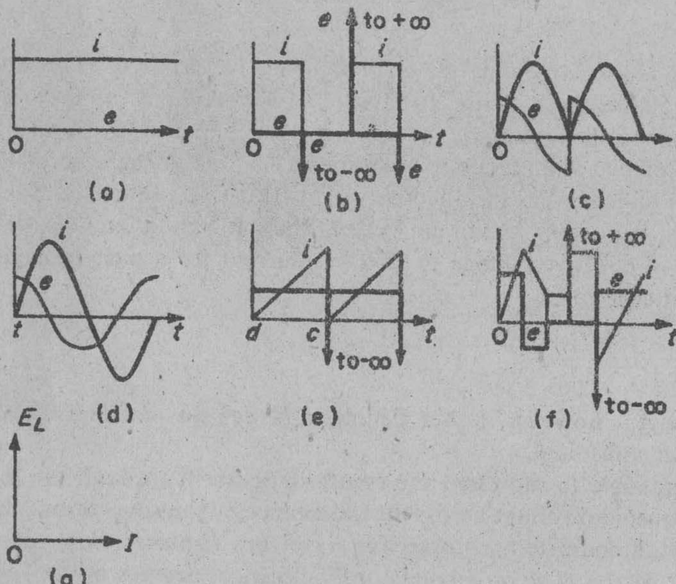


**Fig. 1-8.** Current and voltage relationships in a pure inductance.

sinusoidal variation of current. The derivative of a sine wave is also a sine wave, displaced in time by 90°. Thus, if

$$i = I_m \sin \omega t, \tag{1.18}$$

$$e_L = L\frac{di}{dt} = LI_m\omega \cos \omega t. \tag{1.19}$$

Equation 1.19 may be expressed as

$$e_L = E_m \sin (\omega t + 90^\circ), \tag{1.20}$$

where

$$E_m = I_m\omega L. \tag{1.21}$$

It is from this special case that the concept of a 90 degree phase difference between current and voltage is derived for a pure inductance. *It cannot be too strongly emphasized that the idea of the current lagging the voltage by 90° is not a fundamental relationship for all waveforms, but is the result of applying the fundamental law of Eq. 1.17 to the very special case of pure sinusoidal waves.* Naturally, the sine wave is encountered a great deal in electrical work, and the relation is useful in these instances.