COMPUTERS

Electronic Fundamentals

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FOREWORD

COMPUTERS: Electronic Fundamentals was written to provide the student technician with an understanding of the basic techniques used in complex computer systems. It is assumed that he already possesses a knowledge of elementary electricity and electronics.

After an introduction in Section I, those principles of circuit theory most useful in computer work are reviewed in Section II. In a similar manner, the fundamentals of electron tubes are covered in Section III.

Sections IV, V, and VI consider respectively, vacuum tube amplifiers, some of the special circuits used in computers, and power supply circuits. An introduction to the use of the oscilloscope in test procedures is contained in Section VII. Finally, the types and characteristics of relays are considered in Section VIII.

The material contained in this book is introductory to the classified book COMPUTERS: Basic Units. BuShips publication Navships 900,016 provided source material for parts of this book. A bibliography of additional reference material will be found following Section VIII.

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SECTION I

INTRODUCTION

I. DEFINITIONS AND USES. A. COMPUTERS. (1) A computer is a mechanical or electrical system--or a combination of mechanical and electrical components into a system--that is capable of performing operations with numbers or mathematical concepts at very high speeds. All of the fields of applied science, engineering, and statistical analysis face problems the solution of which is practical only if complex computers are available. These problems can be solved by ordinary means, but their solution would require batteries of desk calculators with operators working long periods of time--months, or even years. A computer provides the same solution in a matter of hours. Furthermore, it is not subject to human error or fatigue. Its advantages, then, are those of speed and accuracy.

B. CLASSIFICATIONS. (1) A computer operates on numbers or numerical concepts. Mathematical values can be represented in two ways: first, by numbers themselves, ordinarily called digits; and second, by numerical concepts that are analogous to numbers. We therefore need two types of computers--one to handle numbers and another to handle number analogies. These two types are known as digital and analog computers respectively.

(2) A digital computer uses discrete numerical values (numbers) and arithmetic-type calculations--that is, addition, subtraction, multiplication, and division--to solve the problems submitted to it. It is fundamentally a counter since the operations on numbers can all be reduced to addition which in turn can be reduced to counting. A large-scale digital computer is a machine capable not only of digital computation but also of long sequences of computations in accordance with a pre-established program of operation. It can solve complex problems involving numerous arithmetic operations without the intervention of a human operator. Digital computers of this type are known as sequence-controlled calculators.

(3) In an analog computer the numerical concepts of the problem are converted for purposes of computation into physically measurable quantities such as lengths and rotations of shafts, linear displacements, voltages, and angles of displacement. Computed results are obtained by the interaction of moving parts or electrical signals related in such a manner as to solve an equation or perform a given set of arithmetical or mathematical operations. Analog computers--although not, in general, so accurate as

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digital computers--are advantageous in the solution of certain types of problems that are not amenable to digital expression: when the numerical quantities to be manipulated are continuously variable rather than discrete values. A desk calculator is a digital (or discrete-variable) computer; a slide-rule is a continuous-variable computer. In addition to the four basic arithmetic operations, analog computers can perform directly the operations of differentiation, integration, and translation.

(4) Computing machines can be divided into two additional classes according to the type of problems for which they are used: synthesizers and analyzers. Synthesizers are designed to perform large numbers of calculations on relatively few input data and to yield relatively few output data. Analyzers are just the opposite: they are statistical machines which are designed to perform a few--even one--calculation on a mass of input data and to yield various amounts of output data. The Mark I and Mark II, ENIAC and EDVAC, and all general purpose computers are normally used as synthesizers; IBM card sorters and tabulators are examples of analytical type computers. The former are true arithmetic-type problem-solvers; the latter are statistical analyzers.

C. USES. (1) In general, computers are used to solve problems of a mathematical nature whose solution is impractical by other means. The classes of computers is an indication of their broad fields of application; analog computers in problems where the values to be handled are continuously variable, digital computers where the values are or can be made discrete numerical quantities. Digital computer applications can be further divided into the solution of problems involving synthesis or analysis.

(2) The advent of the computer opens up fields of applied mathematical research that were formerly considered impossible. There existed in these fields certain well-known problems whose solutions were never attempted simply because there was not enough time. The method of solution was known. These problems are now being solved on the new high-speed calculators.

(3) Specific examples of computer applications hardly need be listed; technical periodicals are full of both general and special purpose machines. It is sufficient to say that computers have become almost indispensable in the fields of pure mathematics, hydrodynamics, aerodynamics, ballistics, electrical theory, structural stress and vibrational analysis, servomechanisms, automatic control systems, and statistical analysis.

(4) The solution of the known problems does not exhaust the need for computers. New tools always have the effect of broadening the field of their application and of opening up new fields. So with computers. One of the merits of the field of computing devices is that it should contribute ultimately to replenishment of pure theory from which further technological and engineering advances can be made.

2. PRINCIPLES OF OPERATION. A. COMPUTER ELEMENTS. (1) Figure 1 is

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the block diagram of a digital computer. The physical connections of such a system are permanent and not altered for the problem to be solved.

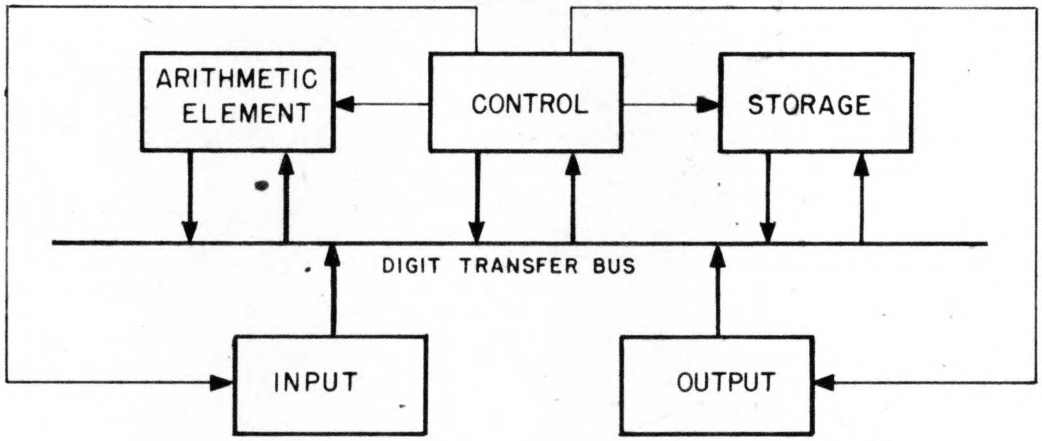

Figure 1. Block Diagram of a Digital Computer

Quantities are handled in the computer as numerical values and can be carried to any required number of decimal places by building the machine large enough. A digital computer requires the five principal functioning elements or units illustrated. The computer solves mathematical, scientific, and engineering problems by carrying out a series of arithmetic steps, one at a time.

(2) The arithmetic element can carry out the basic operations of arithmetic and other essential functions. Storage provides the required "memory" for retaining the program which controls the series of numerical steps to be executed; it likewise provides storage for problem data and intermediate partial numerical results during the process of a computation. The control element provides the timing signals for the entire computer. In operation it extracts a control order from storage and in response to the coded information therein accomplishes the next required numerical step in the computation.

(3) The input mechanism provides a communication means between the human operator and the computer. Problems in the form of initial data and controlling program are prepared in coded form external to the computer on photographic film, punched tape, punched cards, etc., and read into the storage element of the computer by the input mechanism.

(4) The output from the computer may be in several forms: typewritten or printed for isolated results, graphical for engineering data lending itself to this method (usually the output of analog computers), and digital or numerical as coded information on tape, cards, or film. This coded numerical information can later be used by the computer itself (or by another computer) through its input device, or it can be decoded and typed by a transcribing unit.

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B. LOGICAL DESIGN. (1) The above paragraphs name the basic physical elements of a digital computer and briefly describe their functions and methods of interaction. There yet remains to be described the ways in which a machine sees a number (or an order, since they are the same), and how it performs the basic arithmetical processes of addition, subtraction, multiplication, and division. The machine sees any number merely as an electrical pulse, or as a series of pulses. It operates on these pulses according to the laws built into its circuits. Its output is a series of pulses that are "translated" back into numbers. In other words, the computing machine is built around the logic of numbers and the laws controlling their operation.

(2) A computing machine, therefore, must be built around a definite number system--decimal, binary, octal, or other; it must provide for means to represent in a discrete way all the digits of the system chosen; it must have built in it an electronic system that is an exact counterpart of the laws of addition and multiplication of the chosen system; it must be able to represent place value. To repeat, a computer is simply a mechanical or electrical model of a number system, together with input and output systems to permit communication with its human operator.

3. SCOPE OF BOOK. A. GENERAL. (1) Computers of all types are rather complex machines. They consist of thousands of individual parts, intricately interconnected and delicately balanced to achieve a desired result. The malfunction of a single tube can introduce error or stop the machine. Proper operation and maintenance require special training and special knowledge.

(2) Since the field of computational equipment is relatively new and is rapidly expanding, there exists immediately a shortage of properly informed operating and maintenance personnel. For the same reasons there is a like shortage of the proper means of training operators and maintenance crews. The prime purpose, therefore, motivating the preparation of this book is to furnish computer personnel with sufficient information about the circuitry and theory of computing machines to enable them to operate and maintain the equipment efficiently.

B. COMPUTERS: BASIC UNITS. (1) The second book on computer techniques ties the basic circuits discussed in this book into various larger functional units as incorporated in certain special equipments.

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SECTION II

REVIEW OF CIRCUIT THEORY

4. INTRODUCTION. A. GENERAL. (1) In its simplest form a circuit is a single complete electrical path over which conventional current can flow through wires and circuit elements from the positive terminal of a voltage source to the negative terminal of the same voltage source. As commonly used in electronics, however, the term is not restricted to a single electrical path; it is used, instead, to describe a group of interconnected circuit elements, arranged in whatever configuration functionally required, which performs a discrete operation on an electrical signal. There is always, no matter how complex the circuit, the restriction that a complete electrical path be formed between the positive and negative terminals of the voltage source.

(2) The circuit elements most commonly used in electrical circuits are: resistors (R), inductors (L), capacitors (C), and electron tubes (V or T). Detailed discussion will be limited to these four circuit elements.

(3) In this review of circuit theory and the operation of electron tubes emphasis will be given to conditions of operation in which alternating currents and voltages are used. It must be assumed, however, that the basic concepts of direct current theory are understood since much of the material presented here represents an expansion of direct-current principles and definitions. In addition, the laws of direct current hold in the analysis of varying currents and voltages when they are understood to represent relationships between instantaneous values. A brief summary of some of the principles and definitions of direct-current theory are therefore in order.

(4) The following will serve as definitions of basic practical units:

Charge (Q)	A coulomb is equivalent to the charge contained on 6.3×10^{18} electrons.
Current (I)	A current of one ampere is said to flow when one coulomb of charge passes across any cross section of a conductor in one second.

$$I_{amps} = \frac{Q_{coulombs}}{T_{seconds}} \qquad (1)$$

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Potential (E) — A volt is the difference in potential energy existing between two points when one joule of work is done in transporting one coulomb of charge between them.

$$E_{volts} = \frac{W_{joules}}{Q_{coulombs}} \qquad (2)$$

Resistance (R) — An ohm is defined as the resistance of a conductor which requires one volt difference of potential across it to produce a current of one ampere. From this statement follows Ohm's Law which, when applied to a single resistance, may be stated

$$R_{ohms} = \frac{E_{volts}}{I_{amps}} \quad \text{or} \quad I = \frac{E}{R} \quad \text{or} \quad E = IR \qquad (3)$$

B. OHM'S LAW. (1) The use of Ohm's Law may be illustrated by an analysis of a simple circuit. Let us assume that we have a device capable of maintaining a difference of potential energy across its terminals when it is furnishing no current. The difference of potential energy per coulomb of charge is commonly called potential difference, or more simply potential. Its unit is the volt as defined in the preceding paragraph. It should be noticed that the definition of potential requires that a reference point be established; unless otherwise specified, ground is assumed to be the reference point. The device that has just been described is commonly called a generator or voltage source. All practical voltage sources have a certain amount of resistance, and this "internal resistance" must be considered when accurate circuit analysis is to be done. An actual voltage source is, therefore, represented by an ideal voltage source (that is, a source whose output voltage is independent of the current drawn from it) in series with a resistance R_g. If a load resistor, R_L, is connected across a practical voltage source, the resulting circuit is shown in Figure 2 (a).

(2) Figure 2 (b) shows the potential variations around the circuit. The circuit is the same as that of Figure 2 (a) redrawn slightly to illustrate the concept of voltage drop. The negative terminal of the voltage source has been grounded so that we may refer to its potential as zero by definition. As the charge passes through the generator its potential is increased until it reaches E, the electromotive force of the generator. This potential is realized before the charge reaches the internal resistance R_g which is lumped separately from the generator. The voltage E represents the work necessary to raise the charge from ground (zero) potential. Work is also necessary to move the charge through the internal resistance R_g since the action of a resistance is to resist the movement of the charge. The energy to perform this work is supplied by E, the potential of the charge as it leaves the generator. Energy is lost in moving the charge through the resistance. The energy lost per coulomb of charge is equal by Equation (2) to the voltage drop across the resistor and thus is also equal (by Ohm's Law) to

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the product of resistance in ohms and current in amperes. Thus a voltage drop or loss of potential equal to IR_g is experienced by the charge in moving through the internal resistance of the generator. The potential of the charge at point A then is $E - IR_g$ volts above point B or ground potential. As the charge moves through the load resistance R_L it experiences a

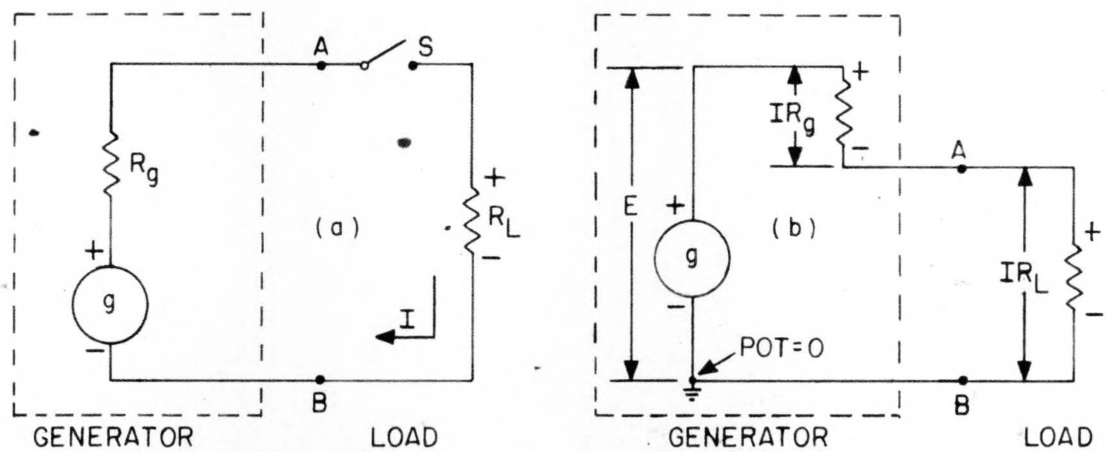

Figure 2. Diagram of Simple Generator Circuit

further loss of potential equal to IR_L volts. As the charge passes through point B and returns to its starting point it returns to zero potential. It can be seen that the total change in potential experienced by the charge is zero, and we can state the following circuit equations:

$$E - IR_g - IR_L = 0 \text{ or} \tag{4}$$

$$E = I(R_g + R_L). \tag{5}$$

C. KIRCHOFF'S LAWS. (1) In writing Equations (4) and (5) we have assumed that the currents through R_g and R_L of Figure 2 (b) are the same. The first of Kirchoff's Laws of Electric Networks, based on the theory of the conservation of charge, bears out this assumption. It states that:

I. The algebraic sum of all currents flowing to and away from a junction is zero.

If we investigate the currents at point A of Figure 2 (b) we see that there are only two currents involved: the current through R_g is flowing toward the junction; the current through R_L is flowing away from it. Since the algebraic sum of these currents must be zero by Kirchoff's Current Law, the currents must be equal in magnitude. If the current through R_g were larger than that through R_L, a charge would build up at point A, an impossible condition.

(2) Either Equation (4) or (5) may be taken as an example of Kirchoff's Voltage Law, based on the theory of conservation of energy, which states that:

II. The algebraic sum of the electromotive forces in any closed

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circuit is equal to the algebraic sum of the voltage drops in the circuit.

We have shown this to be true since the sum of the voltage drops across R_g and R_L in Figure 2 (b) was demonstrated to be equal to the electromotive force E of the generator.

D. SERIES CIRCUIT. (1) A group of circuit elements are said to be connected in <u>series</u> if they are so arranged that all the current flowing must pass in <u>succession</u> through each of them. Such a circuit is shown in Figure 3. It follows from Kirchoff's Laws that the current through each element is the same and that the algebraic sum of the voltage drops across

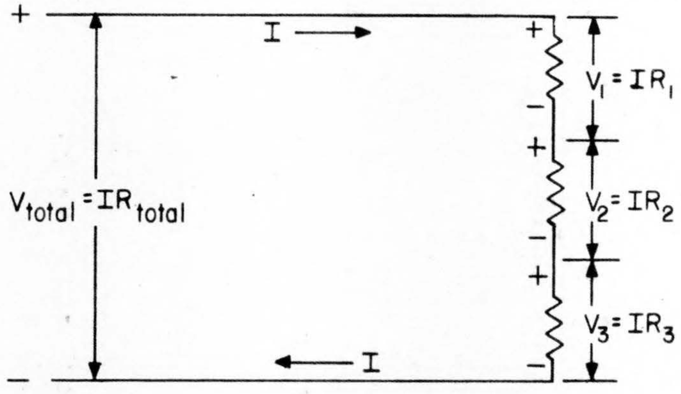

Figure 3. Series Circuit

each element is the same as the potential difference across the group.

(2) It will be noted in Figure 3 that the voltage drops across resistances R_1, R_2, and R_3 are all of the same sign. We know that the applied voltage V_{total} must equal the algebraic sum of the IR drops through the resistances. We can therefore state

$$V_{total} = IR_{total} = IR_1 + IR_2 + IR_3 \tag{6}$$

Dividing by the common factor I, we have

$$R_{total} = R_1 + R_2 + R_3 \tag{7}$$

Thus we can state that the total resistance in a series circuit is the sum of the individual resistances, or that resistances add in series.

E. PARALLEL CIRCUIT. (1) A group of circuit elements are said to be connected in parallel if they are so arranged that the current flowing in the circuit divides, with part of it passing through each element, and then again unites. A parallel resistance circuit is shown in Figure 4. In this circuit the voltage across each element is the same and equal to the voltage across

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the group. By Kirchoff's Current Law the current through the group will be the algebraic sum of the currents through each element.

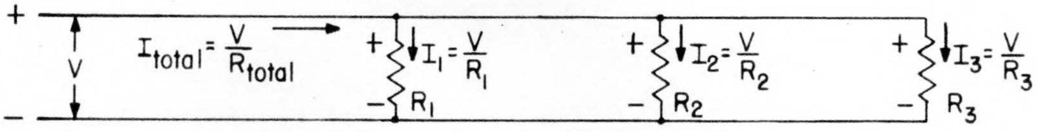

Figure 4. Parallel Circuit

(2) If the elements are resistances R_1, R_2, and R_3 as shown in Figure 4, and the combined resistance of the group is R_{total}, it follows that

$$I_{total} = \frac{V}{R_{total}} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \quad (8)$$

Dividing by the common factor V, we have

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad (9)$$

When the circuit consists of two resistances in parallel the expression for R_{total} may be simplified to

$$R_{total} = \frac{R_1 R_2}{R_1 + R_2} \quad \left[\frac{\text{product}}{\text{sum}}\right] \quad (10)$$

a relationship which is frequently used.

(3) In analyzing parallel circuits it is frequently easier to use the concept of conductance, the reciprocal expression of resistance. Conductance is expressed in mhos (ohms spelled backwards), and its value is given by

$$G_{mhos} = \frac{1}{R_{ohms}} \quad (11)$$

It will be noted that by substituting Equation (11) in Equation (9) an expression for total conductance can be formed:

$$G_{total} = G_1 + G_2 + G_3 \quad (12)$$

Thus we can state that the total conductance in a parallel circuit is the sum of the conductances or that conductances add in parallel.

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5. VARYING CURRENTS AND VOLTAGES. A. GENERAL. (1) It was stated in Paragraph 4A of this section that the laws of direct current held in the analysis of varying currents and voltages when they are understood to represent relationships between instantaneous values. In order to make

instantaneous values easily recognizable it is common practice to represent them by small or lower case letters. Thus the instantaneous value of a varying voltage which has a maximum value of E_{max} is represented by e, and the instantaneous value of a varying current which has a maximum value of I_{max} is represented by i.

(2) Direct currents and voltages do not vary with time so their instantaneous values as a function of time are constant:

$$e(t) = E \tag{13}$$

Alternating currents and voltages, however, vary with respect to a maximum during any selected time interval and must be represented by a function including time:

$$e(t) = E_{max}\, f(t) \tag{14}$$

(3) We shall concern ourselves at present only with currents and voltages which vary periodically and whose variations are assumed to be endless in time. An especially important variation of this kind is one which is sinusoidal.

B. SINUSOIDAL VARIATIONS. (1) A study of sinusoidal variations is important because it can be shown that any periodic variation can be approximated as closely as desired by the sum of a number of sinusoidal terms. Thus an understanding of sinusoidal variations will aid immensely in attacking problems involving more complicated periodic patterns.

(2) A sinusoidal variation is one expressed by a sine or cosine function of the following general form:

$$\underset{\text{Instantaneous voltage}}{e} = \underset{\text{Maximum amplitude}}{E_{max}} \begin{matrix}\sin\\ \text{or}\\ \cos\end{matrix} (\underset{\text{Angular velocity}}{\omega t} + \underset{\text{Phase angle}}{\theta}) \tag{15}$$

The varying voltage e is given here as a function of time with E_{max}, ω, and θ as parameters fixed for a given sinusoid. E_{max} is the absolute maximum amplitude the voltage may reach, since the sine or cosine function may vary only between the limits $\pm$ 1. For reasons to be given presently, ω is called the angular velocity and is measured in radians per second. The phase angle θ is determined by the arbitrary choice of a particular time as zero reference. This initial time is frequently chosen to make $\theta = 0$.

C. VECTOR REPRESENTATION OF A SINUSOID. (1) A vector quantity is one which has both magnitude and direction. The quantity in its entirety is represented by a letter with an arrow over it ($\vec{E}$). Its magnitude alone is written as the letter without the arrow (E), and the direction of the vector

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quantity referred to some reference direction is represented by the angle θ. These relations may be given mathematical representation as follows:

$$\vec{E} = E \angle\theta \quad (16)$$

Suppose we start a vector, whose length is proportional to E_{max}, rotating about a point with a constant angular velocity of ω ; the tip of the vector will obviously generate a circle of radius E_{max}. If we project the tip of the vector on the vertical diameter, the projection will travel up and down with a motion which is a sinusoidal function of time. Such a rotating vector is shown in Figure 5 (a). By transferring the motion to a time base,

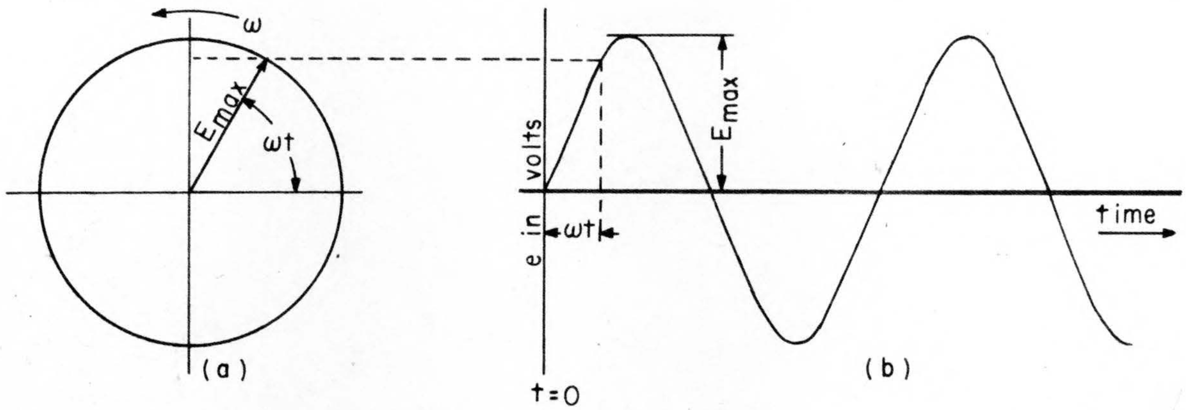

Figure 5. Vector Representation of a Sinusoidal Voltage

Figure 5 (b), we are able to determine the instantaneous value of the voltage at any time t. In this illustration we have chosen a phase angle equal to zero ($\theta = 0$) for simplicity; however, any phase angle may be represented merely by shifting the line for $t = 0$ to the left or right. The distance between $t = 0$ and the start of the sine wave is the phase angle θ. The starting point of a sine wave is considered that point where the function equals zero and is increasing.

(2) The frequency f of a periodic variation is the number of cycles or periods executed per second. Since the rotating vector must complete one revolution or go through 2π radians to generate one complete cycle, the frequency of the variation in cycles per second and the angular velocity in radians per second of the rotating vector may be related as follows:

$$f = \frac{\omega}{2\pi}, \text{ or } \omega = 2\pi f \quad (17)$$

The period T, the number of seconds required to complete one cycle, is related to the frequency and angular velocity as follows:

$$f = \frac{1}{T} \text{ or } T = \frac{2\pi}{\omega} \quad (18)$$

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D. ADDITION OF SINUSOIDS. (1) Sinusoids may be added in a number of different ways; perhaps the easiest, however, is by use of the rotating vector concept. Suppose we have a sinusoidal voltage, $E_{1max} \sin(\omega t + \theta_1)$, to which we wish to add another sinusoidal voltage, $E_{2max} \sin(\omega t + \theta_2)$. The addition may be carried out graphically as shown in Figure 6 (a). It can be seen that the sum of the two vectors representing the two sinusoidal

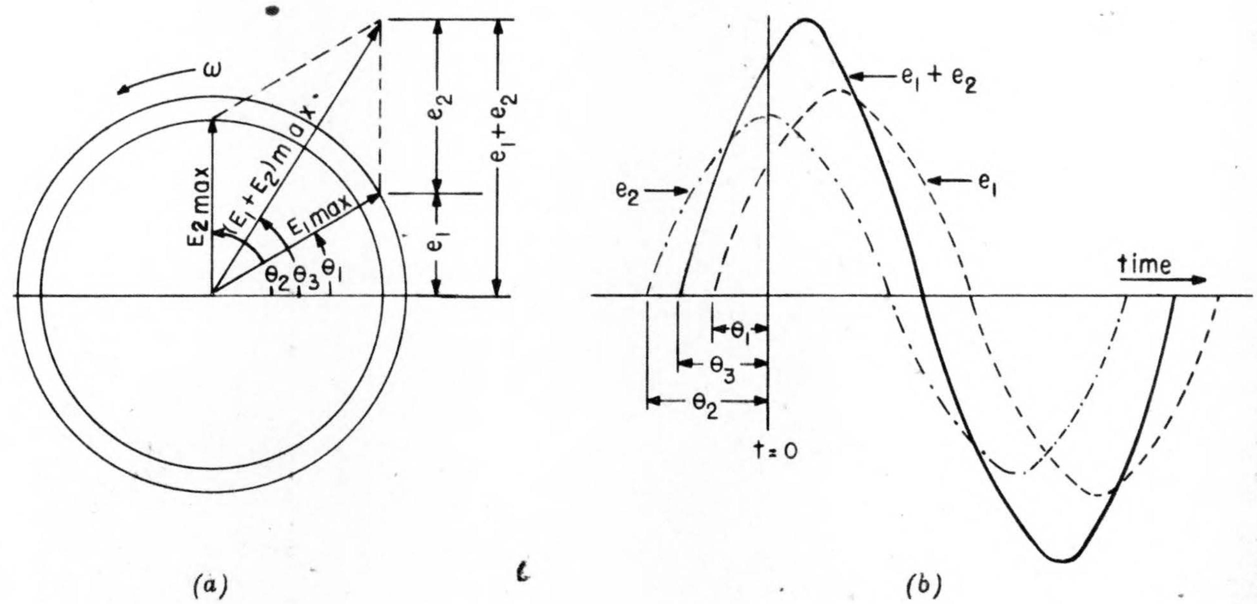

Figure 6. Vector Addition of Sinusoids

voltages is a third vector, rotating at the same angular velocity ω. Figure 6 (b) shows the waveform generated by the rotating vector $(E_1 + E_2)_{max}$. It also shows clearly that the algebraic sum of the instantaneous voltages e_1 and e_2 at any time gives the instantaneous value of the resultant voltage at that time. Phase relationships between the two original voltages and their resultant vector sum are also shown. If the vector diagram is made with care, voltage and phase values may be read directly. The student is warned that the phase relationships of Figure 6 are constant only because the two sine waves which were added were of the same frequency. The rotating vector concept may be used for adding sine waves of different frequency, but it must be remembered in this case that the phase relationships are continuously varying and that instantaneous values must be used.

(2) Where more accurate values are desired, they may be calculated with the aid of the Law of Cosines as illustrated in Figure 7. This method does not require the selection of a zero time. The expression for the maximum value of E, the resultant voltage is

$$E_{max} = \sqrt{(E_{1max})^2 + (E_{2max})^2 + 2E_{1max}E_{2max} \cos \theta} \qquad (19)$$

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and the phase angle is given by

$$\alpha = \tan^{-1}\left[\frac{E_2 \max \sin \theta}{E_{1max} + E_{2max} \cos \theta}\right] \tag{20}$$

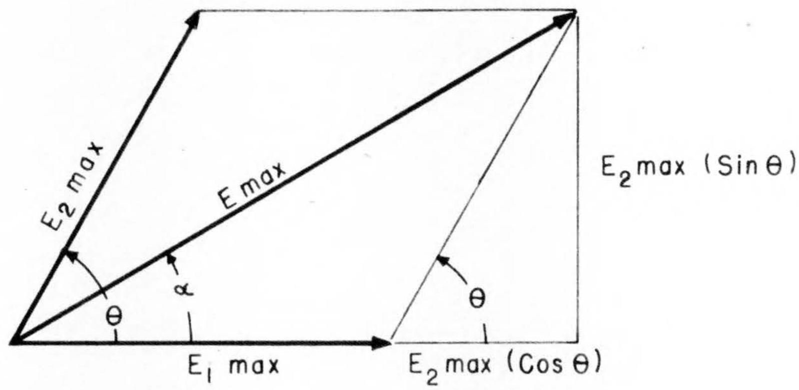

Figure 7. Trigonometric Relations in a Vector Diagram

(3) It can be seen from the above illustration of the addition of sinusoids that any number of sinusoids of equal frequencies when added together produce another sinusoid of the same frequency. Conversely, any sinusoid may be described as the sum of other sinusoids of the same frequency. A case of particular interest is one where a sinusoid of arbitrary phase and amplitude is represented as the sum of two other sinusoids whose phases differ by 90 degrees or $\frac{\pi}{2}$ radians. Thus we may write

$$C \sin (\omega t + \alpha) = A \sin \omega t + B \sin\left[\omega t + \frac{\pi}{2}\right] \tag{21}$$

or $$C \sin (\omega t + \alpha) = A \sin \omega t + B \cos \omega t \tag{22}$$

(4) The above paragraphs have shown several different ways of representing sinusoids: mathematical expressions, vector diagrams, and trigonometric expressions. These various methods have been given to illustrate the choice we have in describing a sinusoidal variation, either a voltage or a current, or in fact any quantity which varies sinusoidally. The student may expect to find any of these representations in his technical reading; he should therefore understand all of the methods with the realization that they are merely different ways of representing the same thing.

(5) There is yet another way, to be described in detail in later paragraphs, of representing sinusoidal variations. This method involves the use of complex algebra and is particularly useful in the addition of sinusoidal voltages and currents. Here again the addition of sinusoids whose phases differ by 90 degrees, that is, one quarter period, is of interest. In order not to

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confuse the student, however, the discussion of complex representation of sinusoids and its use in circuit analysis will be postponed until the student is given a clear graphical analysis of the basic circuit elements and a few simple circuits.

E. DERIVATIVE OF A SINUSOID. (1) If we consider the solid curve in Figure 8 to represent a sinusoidal variation with respect to time we may study the nature of its time derivative without specifically identifying the function. Remembering that the slope of a function represents the rate of change of that function, and that the derivative of a function gives its slope,

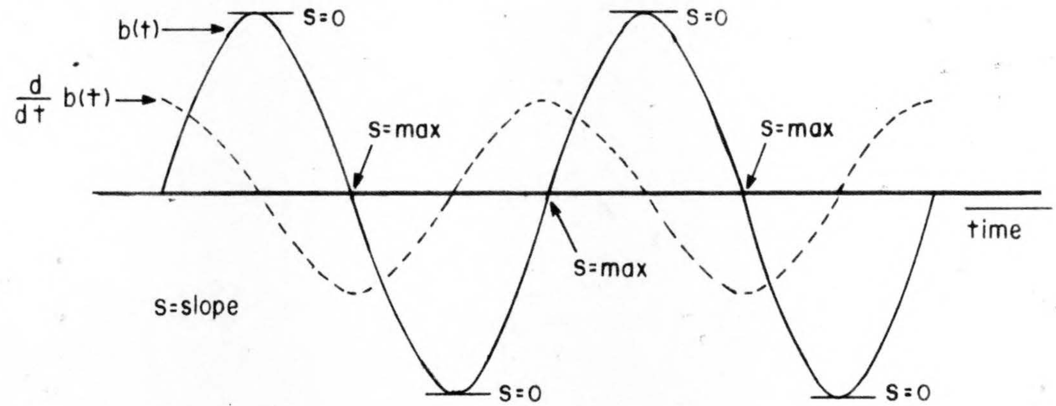

Figure 8. Sinusoidal Curve and Curve of Its Derivative

we may easily see that the dotted line in Figure 8 represents the time derivative of the original sinusoidal variation. It is another sinusoid with its maxima and minima displaced to the left by a quarter period. That is the same as saying that the derivative leads the original sinusoid by a quarter period (90 degrees or $\frac{\pi}{2}$ radians). This is in agreement with the following special case of the general formula for the derivative of the sine of a function:

$$\frac{d}{dt} \sin \omega t = \omega \cos \omega t = \omega \sin (\omega t + \frac{\pi}{2}) \tag{23}$$

Each successive differentiation advances the phase by one quarter period. Changes in amplitude also occur, dependent on the value of ω in this special case, but these do not affect the phase relationships.

F. MAGNITUDES AND UNITS OF VARYING ELECTRICAL QUANTITIES. (1) If we were to deal exclusively with sinusoidal variations, the maximum amplitude value would serve as a suitable measure. For more complicated waveforms it becomes necessary to define certain average and effective values. Current has been defined as a flow of charge; it may now be more specifically defined as the time rate of change of charge and the instantaneous value is given by

$$i = \frac{dq}{dt} \tag{24}$$

the derivative of charge with respect to time. We may then calculate the net transport of charge by evaluating the integral of the instantaneous current in the time interval t_1 to t_2.

$$\text{net transport of charge} = \int_{t_1}^{t_2} i\,dt \tag{25}$$

We might then define as the average value (I_{avg}) of a varying electrical current that d-c current which would transport an equal charge during the same time interval. Figure 9 shows three current waveforms and their average values I_{avg}.

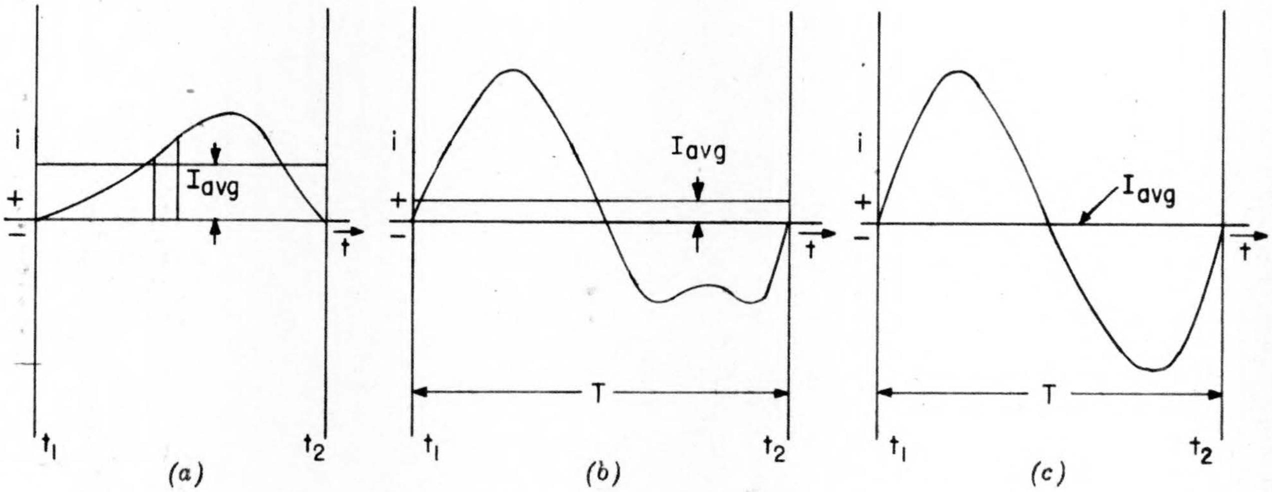

Figure 9. Current Waveforms and Their Average Values

(2) Evaluation of the integral is equivalent to finding an ordinate I_{avg} which completes a rectangle whose area is equal to the area under the curve. Since a negative current transports a charge in the opposite direction from that of a positive current, it can be seen, as in Figure 9 (b), the area cut off by the average current ordinate must be equivalent to the algebraic sum of the areas above and below the axis cut off by the curve. If this reasoning is applied to the sinusoidal curve of Figure 9 (c), the average current is zero. This leads to the statement that over any integral number of periods the average value of any sinusoid which varies symmetrically about zero is zero.

(3) The value found by evaluating the time integral of the instantaneous current is known as the d-c component or average value of the varying current. It is the value which would be read on a d-c meter whose mechanical

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period is much greater than the period of the current. It should not be assumed, however, that this d-c current would be equivalent to the varying current for purposes other than transport of charge. Their heating effects in a given resistor, for instance, would be quite different.

(4) If we are interested in the rate of energy dissipation in a resistor due to a sinusoidal current, we might desire to find a d-c current which would have the same effective value in producing heat. This effective value of current may be derived as follows: I_{eff} is defined as equal to that value of d-c current which dissipates the same average power in a given resistor as does the a-c current. Power considerations will be discussed more thoroughly in the next paragraph, but for purposes of this derivation we may state:

Instantaneous power $$p = i^2 R \tag{26}$$

and average power over a time interval T $$P_{avg} = \frac{\int_0^T i^2 R\, dt}{T} \tag{27}$$

Therefore, by the definition $$I_{eff}^2 R = \frac{\int_0^T i^2 R\, dt}{T} \tag{28}$$

and since R is not a function of time $$I_{eff} = \sqrt{\frac{1}{T}\int_0^T i^2\, dt} \tag{29}$$

Substituting $i^2 = I_{max}^2 \sin^2\omega t = I_{max}^2(1/2)(1-\cos 2\omega t)$ and integrating gives:

$$I_{eff} = \frac{I_{max}}{\sqrt{2}} = \frac{I_{max}}{1.4} = 0.707\, I_{max} \tag{30}$$

Because it represents the square root of the average squared current the effective value is also referred to as the root-mean-square or rms value. It is this value which is usually meant in referring to a-c electrical quantities. It is ordinarily written without subscript.

(5) We may now define a-c units and extend their application to define magnitudes of periodic variations which are not sinusoidal. One a-c ampere (effective or rms value) has been defined as that current producing the same heating effect in a given resistor as a current of one d-c ampere. At low frequencies the resistance a conductor offers to an alternating current is the same as that offered to a direct current. Therefore we may define an a-c volt in the following manner. An a-c volt (effective or rms value) is

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defined as that periodic voltage which will maintain an effective a-c current of one ampere through one ohm of resistance. This definition insures that Ohm's Law can be applied to calculate a-c current-voltage relations in a purely resistive circuit exactly as in a corresponding d-c circuit.

(6) The same relations exist between maximum and effective values when the voltages are sinusoidal; that is

$$E_{eff} = \frac{E_{max}}{\sqrt{2}} = \frac{E_{max}}{1.41} = 0.707\ E_{max} \tag{31}$$

Since the maximum and effective values for either currents or voltages differ by a constant, Ohm's Law may be used equally well with either value, but not of course with a mixture. Thus

$$E_{eff} = I_{eff}R \quad \text{or} \quad E_{max} = I_{max}R \tag{32}$$

G. POWER. (1) The student should remember from direct current theory the following formulas which give power in watts:

$$P = I^2R = IE = \frac{E^2}{R} \tag{33}$$

If we again use instantaneous values we may apply these formulas to the calculation of power in circuits using varying currents and voltages. The power so calculated is called the instantaneous power and is a function of time.

(2) If an impressed voltage $e = E_{max}\sin\omega t$ sends a current of $i = I_{max} \sin(\omega t - \phi)$ through a circuit element, then

$$p = ie = I_{max}E_{max}\sin\omega t \sin(\omega t - \phi) \tag{34}$$

where ϕ represents the phase angle by which (in this case) the current lags the voltage. By use of a trigonometric identity for the product of two sinusoids we may express this as

$$p = \frac{I_{max}E_{max}}{2}\left[\cos\phi - \cos(2\omega t - \phi)\right] \tag{35}$$

Since ϕ is a constant, the power developed consists of a constant term $\frac{I_{max}E_{max}}{2}\cos\phi$ and a sinusoidally varying term. The varying term has twice the frequency of the voltage or current, and refers to the rate of storage in or release of energy from the circuit element. It has been stated that the average value of a sinusoid which varies about zero is zero; therefore the steady or average power dissipated by the element is merely the constant term:

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$$P_{avg} = \frac{I_{max}E_{max}}{2} \cos \phi = \frac{I_{max}}{\sqrt{2}} \frac{E_{max}}{\sqrt{2}} \cos \phi = IE \cos \phi \qquad (36)$$

where I and E are effective values.

(3) These relations are illustrated in Figure 10. The current and voltage variations with respect to time are shown in solid lines; the corresponding variations of instantaneous power are shown in dotted lines. The power curve is obtained by multiplying the ordinates of the i and e curves. In Figure 10 (a) the phase difference between the current and voltage is 90 degrees. It can be seen that the average of the instantaneous power curve is zero -- that is, the circuit does not dissipate power; instead it stores power during the positive half of the power cycle and then releases it to the circuit during the negative half. This storing and releasing of power will occur whether the current leads or lags the voltage so long as the phase difference is 90 degrees. In Figure 10 (b) the phase difference has been reduced to 60 degrees. The curve of the instantaneous power remains the same in form but is shifted upward by an amount P_{avg} which is the steady component of power given by Equation (36). It can be seen from an examination of Figure 10 and Equation (36) that maximum average power will be developed when the phase difference ϕ becomes zero -- that is, when the current and voltage are in phase, and $\cos \phi$ becomes unity.

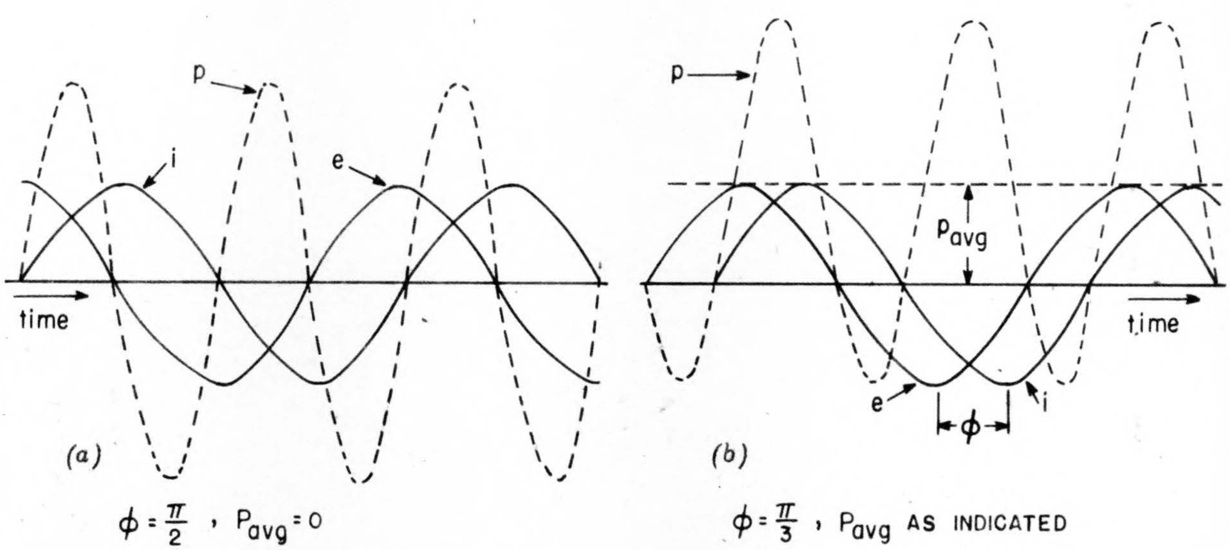

Figure 10. Instantaneous and Average Power Relationships

(4) The phase difference ϕ provides us with a handy measure of the ability of a circuit to deliver power. Its cosine, in fact, is equivalent to the ratio of delivered power (IE $\cos \phi$) to the apparent power (IE) which in power engineering is defined as <u>power factor</u>. The power factor ($\cos \phi$) varies

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from unity to zero as the phase difference between the current and the voltage varies from 0 degrees to 90 degrees. As can be seen from Equation (36) the average power also varies, from a maximum to zero, during this same period.

(5) That the expression $P_{avg} = I^2_{eff}R$ is correct can be demonstrated by assuming a current $i = I_{max} \sin \omega t$ and plotting the result. This is done in Figure 11. The solid line represents the current and the dotted line the current squared.

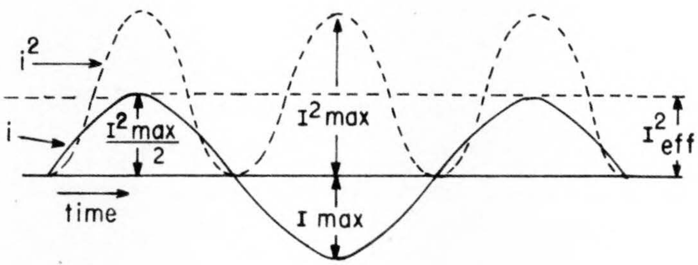

Figure 11. Sinusoidal Current and Its Square

Substitution gives the double frequency power curve we expect.

6. IDEAL CIRCUIT ELEMENTS IN A-C THEORY. A. GENERAL. (1) Now that we have a basic understanding of sinusoidal variations, let us investigate the application of sinusoidal voltages and currents to the basic circuit elements. For simplicity of explanation we will use ideal circuit elements -- that is, pure resistances, capacitances, and inductances. Even the best capacitors have some leakage resistance, and inductors, wound with wire, of course have the resistance of the wire. Circuit analysis may be carried out on the basis of ideal circuit elements, however, since the miscellaneous resistances can be lumped into one equivalent pure resistance.

B. APPLY A SINUSOID TO A PURE RESISTANCE. (1) Assume that we have a generator applying a sinusoidal voltage to a pure resistance R as shown in Figure 12 (a). Plus and minus signs have been indicated in Figure 12 (a). It should be noted that these are in relation to conventional current which flows from plus to minus during a voltage drop and from minus to plus during a voltage rise.

We wish to solve for the current through the resistor.

Given:	$e = E_{max} \cos (\omega t + \theta)$	(37)
By Ohm's Law	$i = \dfrac{v}{R}$	(38)
and by Kirchoff's Voltage Law	$v = e$	(39)

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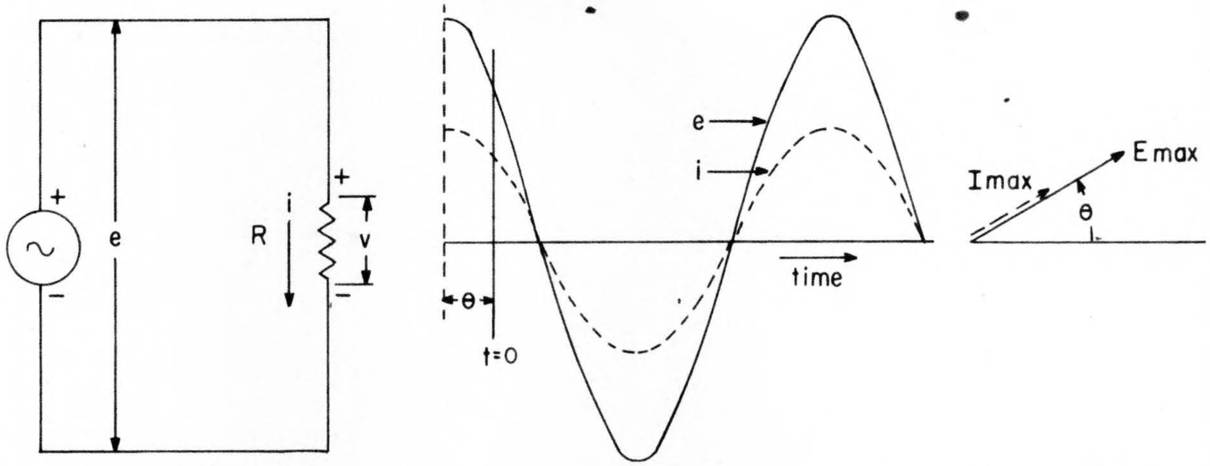
therefore
$$i = \frac{E_{max} \cos(\omega t + \theta)}{R} \tag{40}$$



(a) (b) (c)

Figure 12. Sinusoid Applied to a Pure Resistance

The instantaneous current is in phase with the applied emf. If we set

$$i = I_{max} \cos(\omega t + \theta') = \frac{E_{max} \cos(\omega t + \theta)}{R} \tag{41}$$

and remember that $\theta = \theta'$ since the current and voltage are in phase, we may reduce Equation (40) to the familiar form

$$I_{max} = \frac{E_{max}}{R} \quad \text{or } I_{eff} = \frac{E_{eff}}{R} \tag{42}$$

(2) Since the current and voltage are in phase, the phase difference is zero, $\cos \phi$ is unity, and the average power developed is

$$P_{avg} = IE \tag{43}$$

where I and E are effective values. Thus a pure resistance may be called a dissipative element since it does not conserve energy.

(3) Figure 12 (b) shows the waveforms and relationships of the instantaneous voltage and current with respect to a time base. Figure 12 (c) presents a vector diagram which clearly shows the phase relationship and gives the maximum values of the current and voltage.

c. APPLY A SINUSOID TO A PURE INDUCTANCE. (1) Assume that we have a generator applying a sinusoidal voltage to a pure inductance L as shown

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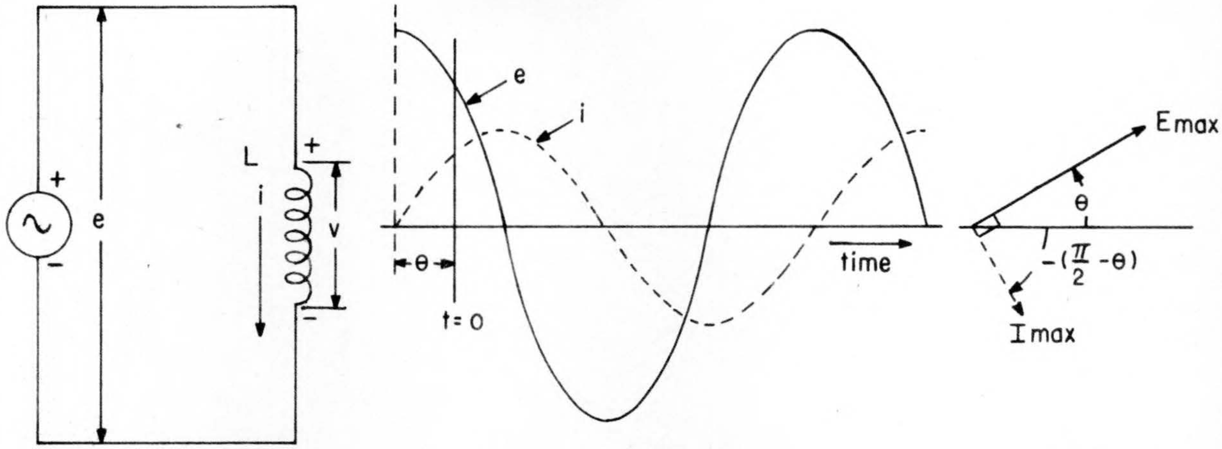
in Figure 13 (a).



(a) (b) (c)

Figure 13. Sinusoid Applied to a Pure Inductance

Again we wish to solve for the current. It can be shown that a current flowing through an inductance creates a back emf (e_B) which is equal and opposite to the impressed voltage which creates the current and to the voltage drop across the inductance. It can also be shown that the back emf is proportional to the time rate of change of current through the inductance -- that is, to the derivative of the current with respect to time.

Given: $$e = E_{max} \cos(\omega t + \theta) \quad (44)$$

$$e = -e_B = v = L\frac{di}{dt} \quad (45)$$

Combining (44) and (45) $$E_{max} \cos(\omega t + \theta) = L\frac{di}{dt} \quad (46)$$

Integrating both sides $$\frac{E_{max}}{\omega} \sin(\omega t + \theta) = Li \quad (47)$$

and $$i = \frac{E_{max}}{\omega L} \cos\left(\omega t + \theta - \frac{\pi}{2}\right) \quad (48)$$

The instantaneous current lags 90 degrees behind the applied emf. If we set

$$i = I_{max} \cos\left(\omega t + \theta - \frac{\pi}{2}\right) \quad (49)$$

we may reduce Equation (48) to

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$$I_{max} = \frac{E_{max}}{\omega L} \text{ or } I_{eff} = \frac{E_{eff}}{\omega L} \tag{50}$$

(2) Since the current and voltage are 90 degrees out of phase, the cosine of the phase difference is zero and the average power developed is

$$P_{avg} = 0 \tag{51}$$

However, the instantaneous power, which is the product of the instantaneous current and voltage, may be negative since i and e may be of opposite sign. This means that the magnetic field of the inductance is collapsing, and the element is delivering power to the circuit. Since the average power is zero, a pure inductance may be called a <u>conservative element</u> -- that is, an element which does not dissipate power.

(3) Figures 13 (b) and (c) show the waveforms and phase relationships of the instantaneous voltage and current, and also give their maximum values. Notice particularly that the current through an inductance <u>lags</u> 90 degrees behind the voltage drop across the inductance.

(4) It should be noted that there is a similarity between Equations (42) and (50) which equate the current to the voltage divided by a term dependent on the circuit element. In Equation (42) the term was a constant, the resistance in ohms of a resistor. In Equation (50) we find a variable term which is the product of the angular velocity and the inductance in henrys of an inductor. This term is called the <u>reactance</u> of the inductance and is denoted by X_L. Thus

$$X_L = \omega L \tag{52}$$

In order to be consistent in our use of units -- amps equal volts per ohm, -- we give the unit ohms to inductive reactance.

D. APPLY A SINUSOID TO A PURE CAPACITANCE. (1) Assume that we have a generator applying a sinusoidal voltage to a pure capacitance C as shown in Figure 14 (a). Once again we wish to solve for the current. It can be shown that the voltage built up across a capacitor is proportional to the charge stored on its plates. We have stated that current is equal to the time derivative of charge; conversely, charge is equal to the time integral of current.

Given:

$$e = E_{max} \cos(\omega t + \theta) \tag{53}$$

$$e = v = \frac{1}{C}\int i\,dt \tag{54}$$

Combining (53) and (54)

$$E_{max} \cos(\omega t + \theta) = \frac{1}{C}\int i\,dt \tag{55}$$

Differentiating both sides $$-E_{max}\,\omega \sin(\omega t + \theta) = \frac{i}{C} \qquad (56)$$

and $$i = -\omega C E_{max} \cos(\omega t + \theta - \frac{\pi}{2}) \qquad (57)$$

or $$i = \omega\, C\, E_{max} \cos(\omega t + \theta + \frac{\pi}{2}) \qquad (58)$$

The instantaneous current leads the applied emf by 90 degrees. If we set

$$i = I_{max} \cos(\omega t + \theta + \frac{\pi}{2}) \qquad (59)$$

we may reduce Equation (57) to

$$I_{max} = E_{max}\,\omega C \text{ or } I_{eff} = E_{eff}\,\omega C \qquad (60)$$

(2) Since the current and voltage are 90 degrees out of phase, the cosine of the phase difference ψ is zero and the average power developed is

$$P_{avg} = 0 \qquad (61)$$

The instantaneous power, however, may be negative since i and e may be of opposite sign. This means that the capacitor is discharging and is delivering power to the circuit. Since the average power is zero, a pure capacitance like a pure inductance may be called a conservative element -- that is, an element which does not dissipate power.

(3) Figures 14 (b) and (c) show the waveforms and phase relationships

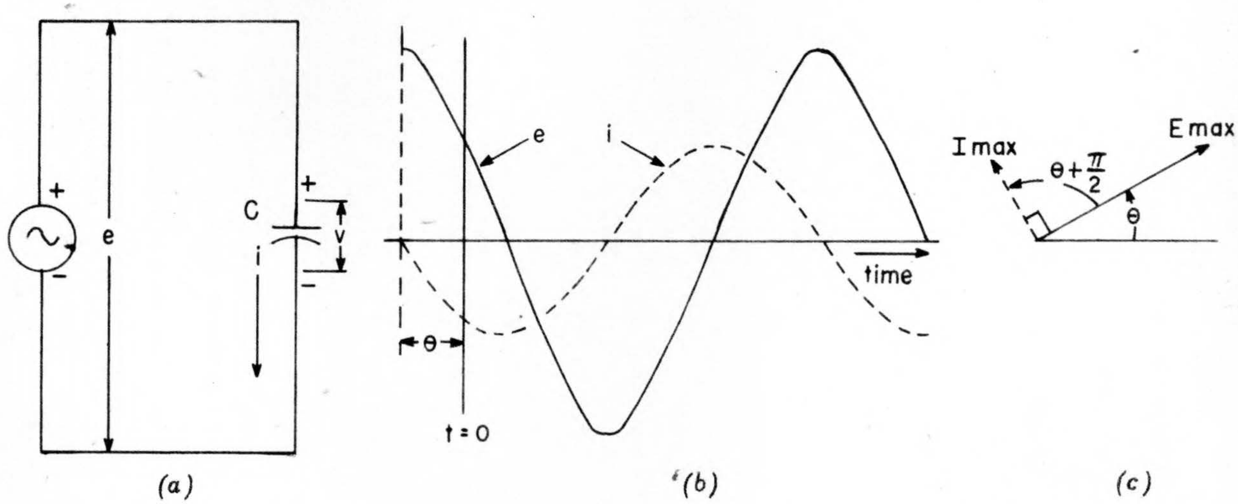

Figure 14. Sinusoid Applied to a Pure Capacitance

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of the instantaneous voltage and current, and also give their maximum values. Notice particularly that in the case of a capacitor the current leads the voltage by 90 degrees.

(4) Again a similarity may be noticed between Equation (60) and the statement of Ohm's Law given in Equation (42). This time the variable term is the product of the angular velocity and the capacitance in farads of the capacitor. We define a term called the reactance of the capacitor X_C as follows:

$$X_C = \frac{1}{\omega C} \tag{62}$$

Again, in order to be consistent in our use of units, we use ohms as the unit of capacitive reactance.

E. APPLY A SINUSOID TO A SERIES RLC CIRCUIT. (1) Assume that we have a generator applying a sinusoidal voltage to a pure resistance, inductance, and capacitance connected in series as shown in Figure 15 (a). Voltage and current relations derived from preceding paragraphs are shown in Figure 15 (b).

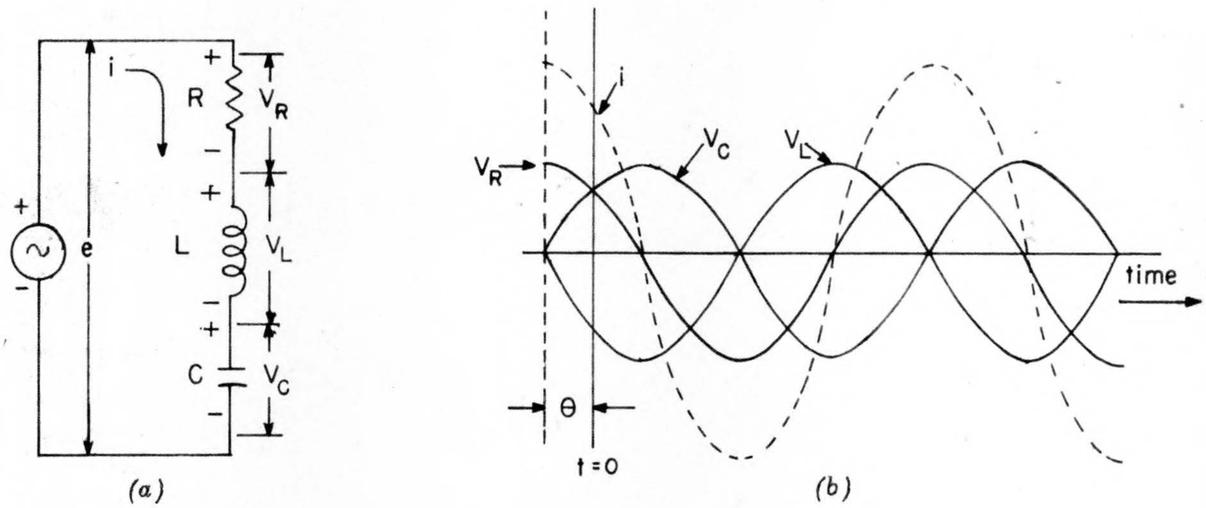

Figure 15. Sinusoid Applied to a Series RLC Circuit

(2) The current through the entire circuit is the same as that through any element and is of the same form as the applied voltage, e. Remembering this and using Kirchoff's Voltage Law, we may equate the applied voltage to the sum of the voltage drops across the three elements.

Given $$e = E_{max} \cos(\omega t + \theta) \tag{63}$$

$$e = Ri + L\frac{di}{dt} + \frac{1}{C}\int i\,dt \tag{64}$$

Assume $$i = I_{max} \cos(\omega t + \theta') \tag{65}$$

then differentiating both sides of (65): $$\frac{di}{dt} = -I_{max}\omega \sin(\omega t + \theta') \qquad (66)$$

and integrating both sides of (65): $$\int i dt = \frac{I_{max}}{\omega} \sin(\omega t + \theta') \qquad (67)$$

Substituting (63), (65), (66), and (67) into (64):

$$E_{max} \cos(\omega t + \theta) = I_{max}\left[R \cos(\omega t + \theta') - (\omega L - \frac{1}{\omega C}) \sin(\omega t + \theta')\right] \qquad (68)$$

(3) We recognize the coefficient of the sine term in Equation (68) as the difference of inductive and capacitative reactances. Let us then define an over-all reactance X as follows:

$$X = X_L - X_C = \omega L - \frac{1}{\omega C} \qquad (69)$$

Substituting in (68)

$$E_{max} \cos(\omega t + \theta) = I_{max} \left[R \cos(\omega t + \theta') - X \sin(\omega t + \theta')\right] \qquad (70)$$

Now let us define two new functions, Z and ϕ, such that

$$Z = \sqrt{R^2 + X^2} \qquad (71)$$

$$\phi = \tan^{-1} \frac{X}{R} \qquad (72)$$

Then Z, ϕ, X, and R must be related as shown in Figure 16. From this we may write

$$R = Z \cos \phi \qquad (73)$$

$$X = Z \sin \phi \qquad (74)$$

→ $\int$ Substituting in Equation (70)

$$E_{max} \cos(\omega t + \theta) = I_{max} Z \left[\cos \phi \cos(\omega t + \theta') - \sin \phi \sin(\omega t + \theta')\right] \qquad (75)$$

which may be reduced by trigonometric identity to

$$E_{max} \cos(\omega t + \theta) = I_{max} Z \cos(\omega t + \theta' + \phi) \qquad (76)$$

Here again we have an expression which reminds us of Ohm's Law. Let us call Z the impedance of the circuit. Figure 16 then becomes an impedance diagram. If we use ohms as the unit for the impedance $\vec{Z}$ (vector quantity)

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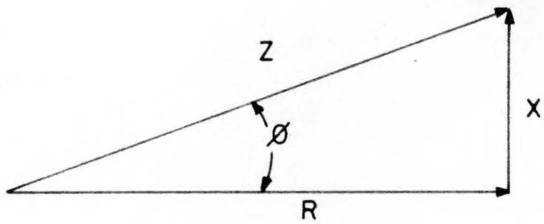

Figure 16. Impedance Diagram

we may write

$$E_{max} = I_{max}\ Z \quad (77)$$

and $\quad \theta' = \theta - \phi \quad (78)$

Thus giving us a general expression of Ohm's Law, the direct current application of which is merely a special case in which the reactance is zero.

(3) Figure 17 is a vector diagram of a general RLC circuit. It can be seen that the impedance is effectively an operator which multiplies the max-

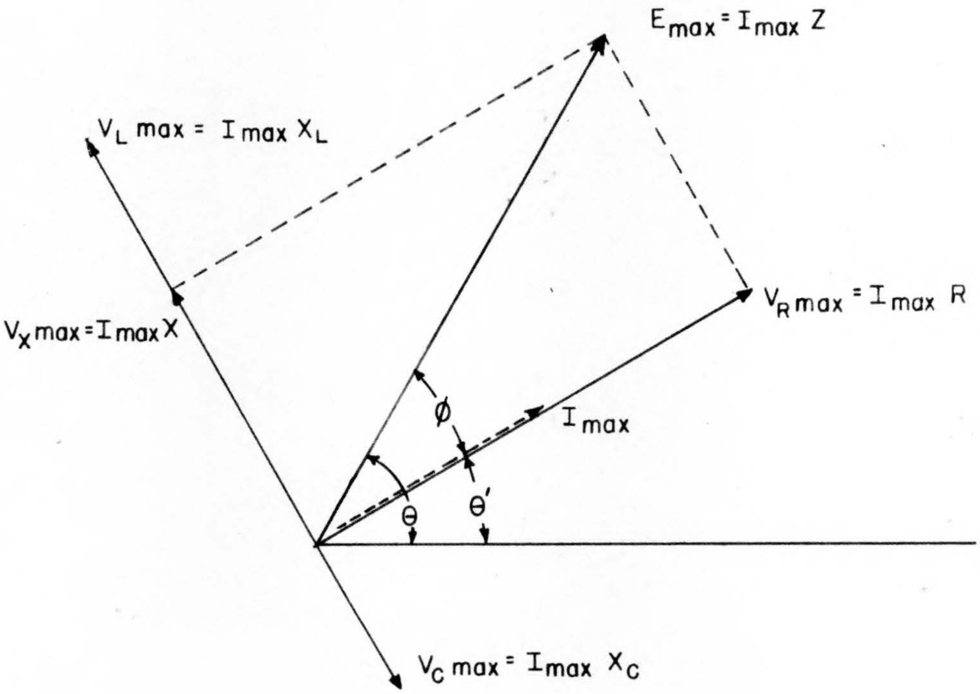

Figure 17. Vector Diagram of a Series RLC Circuit

imum current by $\sqrt{R^2 + X^2}$ and rotates it through an angle ϕ. The angle ϕ is the same phase difference we found in discussing average power, and cos ϕ is the power factor of the circuit. Notice that in order to describe E_{max} completely both its magnitude and phase angle must be given.

F. APPLY A SINUSOID TO A PARALLEL GCL CIRCUIT. (1) Assume that we have a generator applying a sinusoidal current to a pure conductance,

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capacitance, and inductance connected in parallel as shown in Figure 18 (a). Voltage and current relations derived from preceding paragraphs

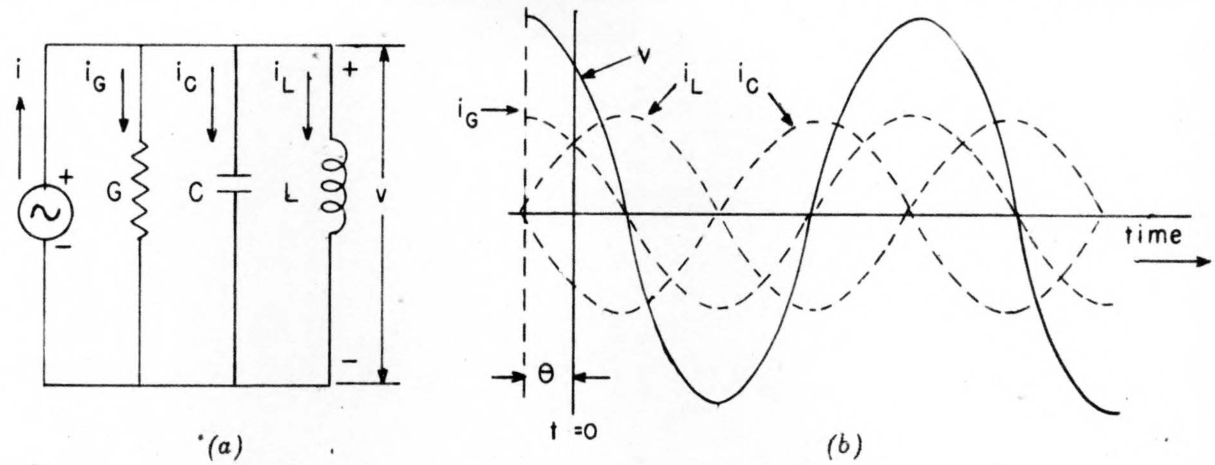

Figure 18. Sinusoid Applied to a Parallel GCL Circuit

are shown in Figure 18 (b).

(2) The voltage across the entire circuit is the same as that across any element and is of the same form. Remembering this and using Kirchoff's Current Law we may equate the applied current to the sum of the currents in the three elements derived from Equations (38), (45), and (54).

Given: $$i = I_{max} \cos(\omega t + \theta) \tag{79}$$

$$i = Gv + C\frac{dv}{dt} + \frac{1}{L}\int v\,dt \tag{80}$$

Assume $$v = V_{max} \cos(\omega t + \theta') \tag{81}$$

from which $$\frac{dv}{dt} = -V_{max}\,\omega \sin(\omega t + \theta') \tag{82}$$

and $$\int v\,dt = \frac{V_{max}}{\omega} \sin(\omega t + \theta') \tag{83}$$

Substituting in (80)

$$I_{max} \cos(\omega t + \theta) = V_{max} \left[G \cos(\omega t + \theta') - \left(C\omega - \frac{1}{L\omega}\right) \sin(\omega t + \theta') \right] \tag{84}$$

(3) We recognize the coefficient of the sine term in Equation (84) as the difference between the reciprocals of capacitative and inductive reactances. Let us then define an over-all term B, called susceptance, as follows:

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$$B = B_C - B_L = \frac{1}{X_C} - \frac{1}{X_L} = C\omega - \frac{1}{L\omega} \tag{85}$$

Substituting in (84)

$$I_{max} \cos(\omega t + \theta) = V_{max}\left[G \cos(\omega t + \theta') - B \sin(\omega t + \theta')\right] \tag{86}$$

Now let us define two new functions, Y and ψ , such that

$$Y = \sqrt{G^2 + B^2} \tag{87}$$

$$\psi = \tan^{-1} \frac{B}{G}$$

Then Y, ψ, B, and G must be related as shown in Figure 19. From this we may write

$$G = Y \cos \psi \tag{88}$$

$$B = Y \sin \psi \tag{89}$$

Substituting in Equation (86) and reducing by trigonometric identity as we did with Equation (75) we arrive at an expression describing the circuit as follows:

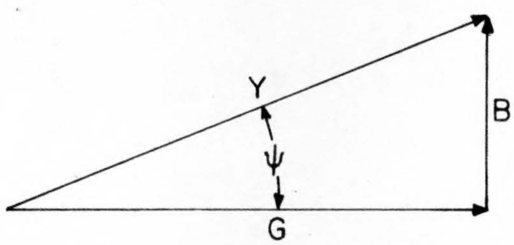

Figure 19. Admittance Diagram

$$I_{max} \cos(\omega t + \theta) = V_{max} Y \cos(\omega t + \theta' - \psi) \tag{90}$$

The vector quantity $\vec{Y}$ is called <u>admittance</u>. Figure 19 then becomes an admittance diagram. If we use mhos as the unit for the admittance $\vec{Y}$ we may write

$$I_{max} = E_{max} Y \tag{91}$$

and $$\theta' = \theta - \psi \tag{92}$$

thus giving us a general expression of Ohm's Law rewritten to apply to parallel circuits. By comparing Equations (77) and (91) it can be seen that the impedance $\vec{Z}$ and the admittance $\vec{Y}$ of a circuit are reciprocal to each other, that is

$$\vec{Z} = \frac{1}{\vec{Y}} \tag{93}$$

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(3) Figure 20 is an admittance diagram of a general GCL circuit. As with impedance it can be seen that admittance is effectively an operator which multiplies the maximum voltage by $\sqrt{G^2 + B^2}$ and rotates it through an angle ψ, which is equal to $-\phi$ because of the reciprocity between $\vec{Y}$ and $\vec{Z}$. The cosine of either angle then gives the power factor of the circuit.

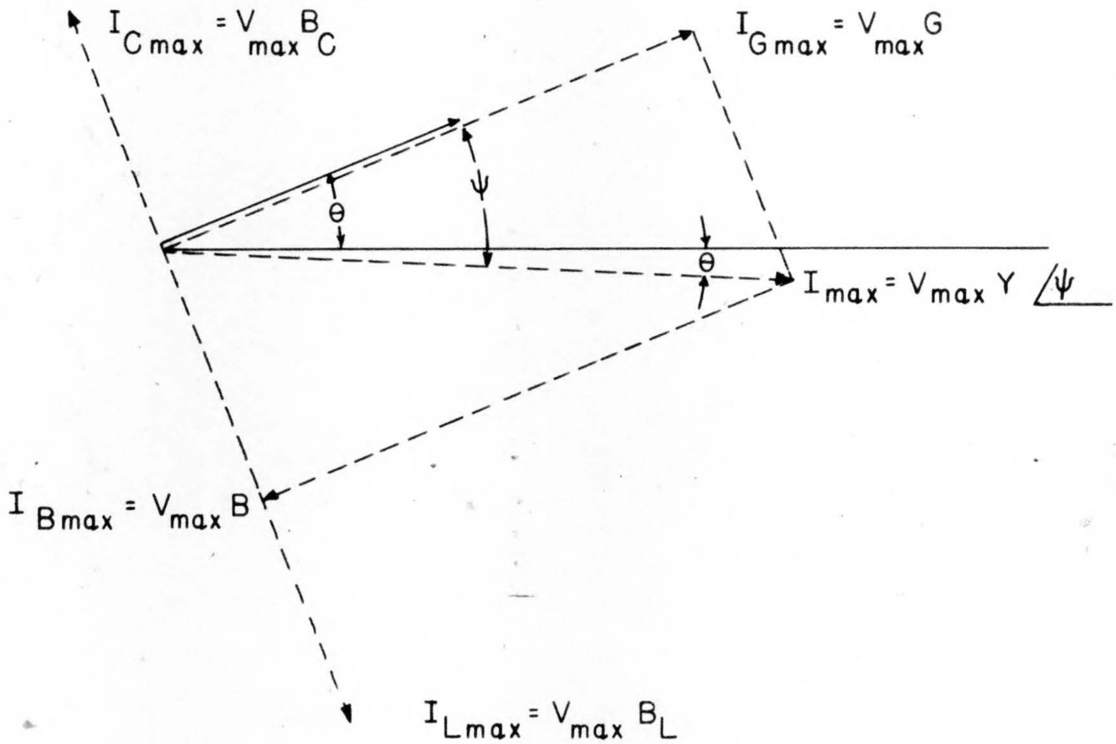

Figure 20. Vector Diagram of a Parallel GCL Circuit

7. COMPLEX REPRESENTATION. A. GENERAL. (1) It is our intention to demonstrate the application of complex representation to circuit analysis and show its practicability and usefulness rather than to discuss the theory of complex algebra to any great extent. The student is referred to any standard textbook on the subject for a detailed exposition of the theory of complex algebra; in this discussion it will be assumed either that the theory is understood or that the principles given will be accepted without rigorous mathematical justification.

(2) Complex algebra is little more than a more convenient method of manipulating vector quantities; in general, the use of complex algebra in circuit analysis requires no new concepts. The point to be emphasized is that the prime concept is the vector and that complex algebra is just a system for using that concept with a minimum of effort.

B. THE OPERATOR. J. (1) Basic to complex representation is the complex

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operator (j) which is defined as follows:

$$j = \sqrt{-1} \tag{94}$$

It should be remembered from mathematics that this is an imaginary number. In order to plot vectors described with the help of the complex operator we must put our coordinates, either Cartesian or polar, into a complex plane wherein the axis ordinarily labeled "X" is called the "real axis" (abbreviated Re) and that normally labeled "Y" is instead called the "imaginary axis" (abbreviated Im). Such a coordinate system is shown in Figure 21, and the plane in which they lie is called the complex plane.

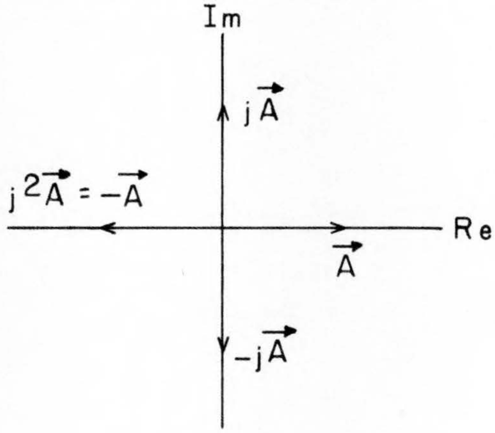

Figure 21. The Complex Plane

(2) We have said that j is a complex operator; specifically j produces a 90° counterclockwise rotation of any vector to which it is applied as a multiplying factor. Consider the vector $\vec{A}$ lying along the positive real axis of Figure 21; if we multiply it by the operator j, we get a new vector $j\vec{A}$ lying along the positive imaginary axis Similarly, multiplication of $j\vec{A}$ by j gives

$$jj\vec{A} = j^2\vec{A} = (\sqrt{-1})^2\vec{A} = -\vec{A} \tag{95}$$

which is a vector of length A lying along the negative real axis. The result of further applications of j may be determined in the same manner.

C. RECTANGULAR REPRESENTATION OF A VECTOR. (1) Any vector starting from the origin of the complex plane may be completely described by specifying its real and imaginary components. For example the vector $\vec{B}$ in Figure 22 may be represented by (a + jb) where a and b are scalar quantities. It is evident that

$$a = B \cos\theta \tag{96}$$

$$b = B \sin\theta. \tag{97}$$

Since $\vec{B} = a + jb$ (98)

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it is evident that

$$\vec{B} = B\ (\cos\theta + j\sin\theta) \tag{99}$$

$$= \sqrt{a^2 + b^2}\,(\cos\theta + j\sin\theta) \tag{100}$$

where

$$\theta = \tan^{-1}\frac{b}{a} \tag{101}$$

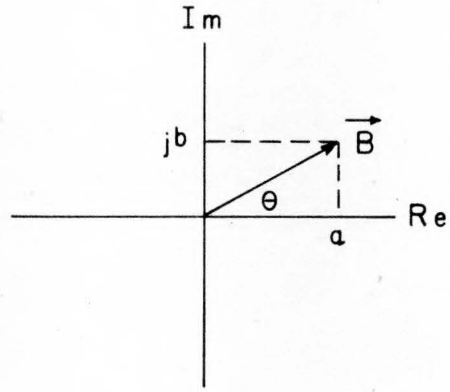

Figure 22. Vector Representation

D. POLAR REPRESENTATION OF A VECTOR. (1) Euler's equation in mathematics tells us that

$$\cos\theta \pm j\sin\theta = \epsilon^{\pm j\theta} \tag{102}$$

where ϵ is the base of the Napierian system of logarithms and the angle θ must be expressed in radians. In view of this we can rewrite Equation (99) as

$$\vec{B} = B\ \epsilon^{j\theta} \tag{103}$$

which is known as the polar representation of the vector B and is commonly written as

$$\vec{B} = B\ \underline{/\theta} \tag{104}$$

The right side of Equation (104) is read as "the magnitude of vector B at an angle θ". The various methods for writing a vector are summarized in Equation (105).

$$\vec{B} = a + jb = B\ (\cos\theta + j\sin\theta) = B\ \epsilon^{j\theta} = B\ \underline{/\theta} \tag{105}$$

E. MATHEMATICAL PROCESSES WITH VECTORS. (1) Addition and subtraction of complex numbers is done using the rectangular form:

$$(a + jb) \pm (c + jd) = a \pm c + j\,(b \pm d). \tag{106}$$

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(2) Multiplication of complex numbers may be performed in either rectangular or polar form:

$$(a + jb)(c + jd) = (ac - bd) + j\,(ad + bc) \tag{107}$$

$$(A\angle\theta)(B\angle\phi) = AB\angle\theta + \phi \tag{108}$$

(3) Complex numbers may be divided in rectangular form by rationalization:

$$\frac{a + jb}{c + jd} = \frac{(a + jb)(c - jd)}{(c + jd)(c - jd)} = \frac{(ac + bd) + j\,(bc - ad)}{c^2 + d^2} \tag{109}$$

It is generally easier, however, to perform division in the polar form, even if one must transform from rectangular to polar form and back again.

$$\frac{A\angle\theta}{B\angle\phi} = \frac{A}{B}\angle\theta - \phi \tag{110}$$

F. COMPLEX FORM OF IMPEDANCE. (1) In Paragraph 6E(3) we have defined impedance, Z, as having a magnitude

$$Z = \sqrt{R^2 + X^2} \tag{111}$$

and an angle

$$\phi = \tan^{-1}\frac{X}{R} \tag{112}$$

From the previous discussion of complex numbers it is evident that we may write

$$\vec{Z} = R + jX \tag{113}$$

or more generally

$$\vec{Z} = R + j\,(X_L - X_C) \tag{114}$$

C. CIRCUIT ANALYSIS USING COMPLEX REPRESENTATION. (1) It has been shown in Paragraph 6 of this section that currents and voltages in an a-c circuit may conveniently be represented as vectors. Complex numbers enable us to handle these vectors with a minimum of effort. In particular, the complex form of impedance properly relates vector voltages and currents to one another. If a vector current $\vec{I} = I\angle\theta$ flows through the complex impedance $\vec{Z} = Z\angle\phi$ the voltage across the impedance is

$$\vec{E} = \vec{I}\vec{Z} = IZ\angle\theta + \phi\,. \tag{115}$$

This is the most general form of Ohm's Law since $\vec{Z}$ represents both the

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magnitude and phase angle of any single circuit element or any combination of elements. Other forms in which Equation (115) may be written are

$$\vec{E} = \vec{I}\,(R + jX) = \vec{I}\left[R + j\left(\omega L - \frac{1}{\omega C}\right)\right] \tag{116}$$

(2) Unless otherwise mentioned, effective values of $\vec{E}$ and $\vec{I}$ are used in Equations (115) and (116), and it should be remembered that these do not vary with time.

(3) As an example of the use of complex notation in circuit analysis, let us find the current in the circuit of Figure 23 when a 60 cycle sinusoidal voltage of 100 effective volts is applied.

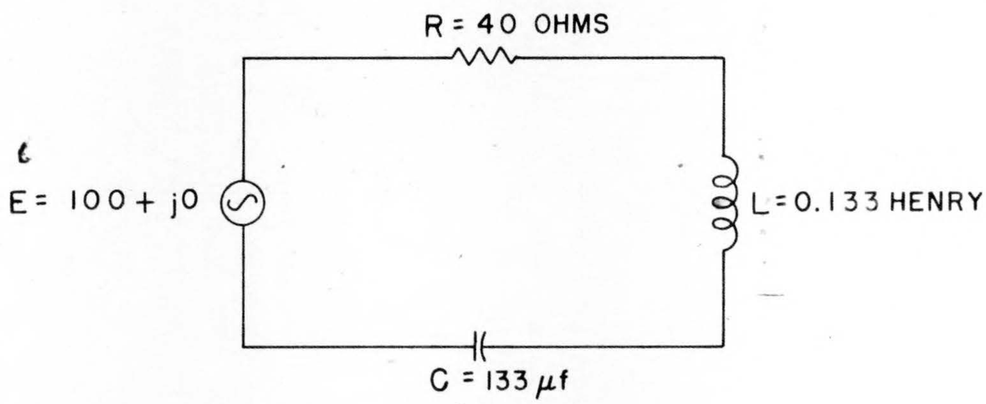

Figure 23. Series RLC Circuit

$$X_L = \omega L = 2\pi f L = 2\pi\,(60)(0.133) = 50 \text{ ohms}$$

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C} = \frac{1}{(2\pi)(60)(133 \times 10^{-6})} = 20 \text{ ohms}$$

Therefore

$$\vec{Z} = R + j\,(X_L - X_C) = 40 + j30 \text{ ohms}$$

$$\vec{I} = \frac{\vec{E}}{\vec{Z}} = \frac{100 + j0}{40 + j30} \quad \frac{100\,\angle 0^\circ}{50\,\angle 36.9^\circ}$$

$$= 2\,\angle{-36.9^\circ} \text{ amperes (effective)}$$

This indicates that the current waveform lags 36.9° behind the voltage waveform. With the current known, it is a simple matter to determine the voltage across each of the circuit elements.

$$\vec{E}_R = \vec{I}R = (2\,\angle{-36.9^\circ})(40\,\angle 0^\circ) = 80\,\angle{-36.9^\circ} \text{ volts}$$

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$$\vec{E}_L = \vec{I}jX_L = (2\ \angle{-36.9°})(50\ \angle{90°}) = 100\ \angle{54.1°} \text{ volts}$$

$$\vec{E}_C = \vec{I}jX_C = (2\ \angle{-36.9°})(20\ \angle{-90°}) = 40\ \angle{-126.9°} \text{ volts}$$

We can check our calculations by transforming the polar expression for $\vec{E}_R$, $\vec{E}_L$, and $\vec{E}_C$ to the rectangular form and adding them. The result should be 100 + j0, which is the generator voltage.

$$\begin{aligned} E_R &= 64.0 - j48.0 \\ E_L &= 60.0 + j80.0 \\ E &= \underline{-24.0 - j32.0} \\ &\ \ 100 \quad + j0 \end{aligned}$$

This result checks the preceding calculations.

(4) The vector diagram of the problem just solved is shown in Figure 24. It should be remembered that the angular relationship between the various circuit vectors and the axes depends in this case only on the choice of phase angle for the generator voltage E. If we had assumed that the generator

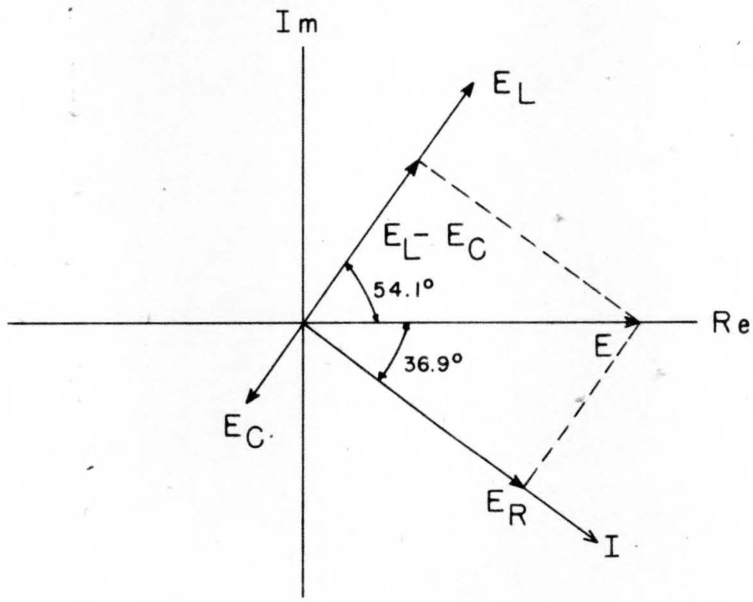

Figure 24. Vector Diagram of Circuit of Figure 23

voltage was E = 100 $\angle{36.9°}$, the entire vector diagram would have been rotated counterclockwise by 36.9°, but <u>the relationship among the various vectors would be unchanged.</u>

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8. TRANSIENTS. A. GENERAL. (1) The discussion of circuit theory given thus far in this section has been concerned with voltages and currents of two types: (a) constant (i.e. d-c), or (b) recurring, periodic functions of time. Both of these types exist in a network only under so-called steady-state conditions. Before a circuit can arrive at a steady state condition of operation it must pass through a transitional period during which the voltages and currents are changing to their new values and so are not periodic functions. These non-periodic and non-recurrent variations of voltage and current are called transients.

(2) Many practical circuits in electronic computers are operated continuously under transient conditions; their voltages and currents are constantly changing in an erratic manner. Some of the many specialized circuits whose operation is essentially transient in nature will be described in Section V, and the present paragraph will consider some of the more basic theory.

B. THE SERIES R-L CIRCUIT. (1) Figure 25 shows a resistance and inductance in series with a d-c voltage source and switch. The R-L branch is suddenly energized when the switch is closed. Kirchoff's Voltage Law tells us that

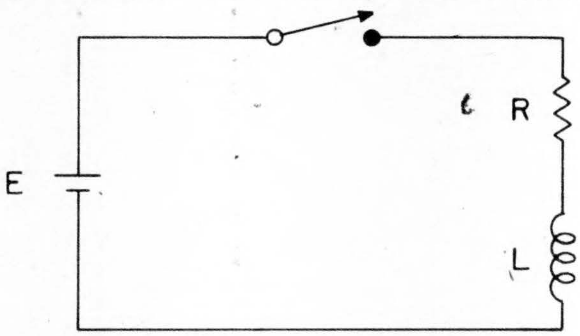

Figure 25. The R-L Circuit

$$E = Ri + L\frac{di}{dt} \tag{117}$$

which is a simple differential equation. If the switch was closed at time $t = 0$ and if the current was zero at that instant, then the solution of Equation (117) is

$$i = \frac{E}{R} - \frac{E}{R}\epsilon^{-(R/L)t} \tag{118}$$

(2) The right hand side of this equation is made up of two parts: the first, E/R, is the steady state term and the second is the transient term. When the switch is closed at $t = 0$, the transient term is equal to $\frac{E}{R}$ so $i = 0$. As the time, t, increases from zero, the transient term gets smaller and approaches zero; the current thus approaches the steady state value of E/R.

(3) A plot of the instantaneous current, i, as given by Equation (118) is

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shown in Figure 26. The time in which the current would reach its final

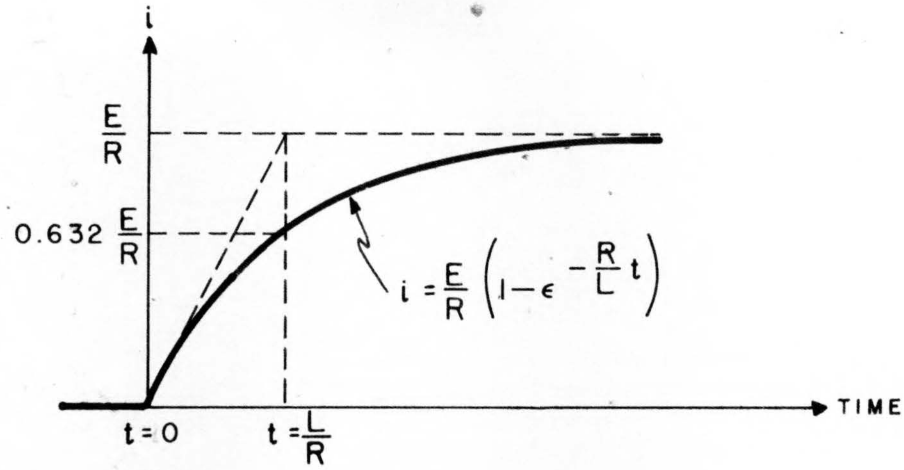

Figure 26. Rise of Current in The R-L Circuit

value, $\frac{E}{R}$, if it continued to build up at its initial rate is known as the <u>time constant</u> and is equal to L/R seconds. In this interval of time the current actually reaches 63.2 percent of its final value.

(4) Since the voltage across R in Figure 25 is equal to iR, its waveform will be the same as that of i. Also after the switch is closed at t = 0,

$$E_R + E_L = E = \text{constant} \tag{119}$$

which means that E_L must decrease as E_R increases. At the instant of switch closure, therefore, a voltage E exists across L, but this voltage decays and becomes zero under steady-state conditions.

C. THE SERIES R-C CIRCUIT. (1) Undoubtedly the most common circuit used to produce transients is the simple series resistor-capacitor combination shown in Figure 27. Its equation is

$$E = iR + \frac{1}{C}\int i\,dt \tag{120}$$

and the solution of this if the charge on C is zero and if t = 0 at the instant the switch is closed is

$$i = \frac{E}{R}\,\epsilon^{-(1/RC)t} \tag{121}$$

The solution in this case has a transient term but no steady state term.

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(2) The manner in which i varies with time is shown graphically in Figure 27. The current jumps from zero to $i = \frac{E}{R}$ at the instant the switch is closed, but immediately begins to decay as charge builds up on the capacitor.

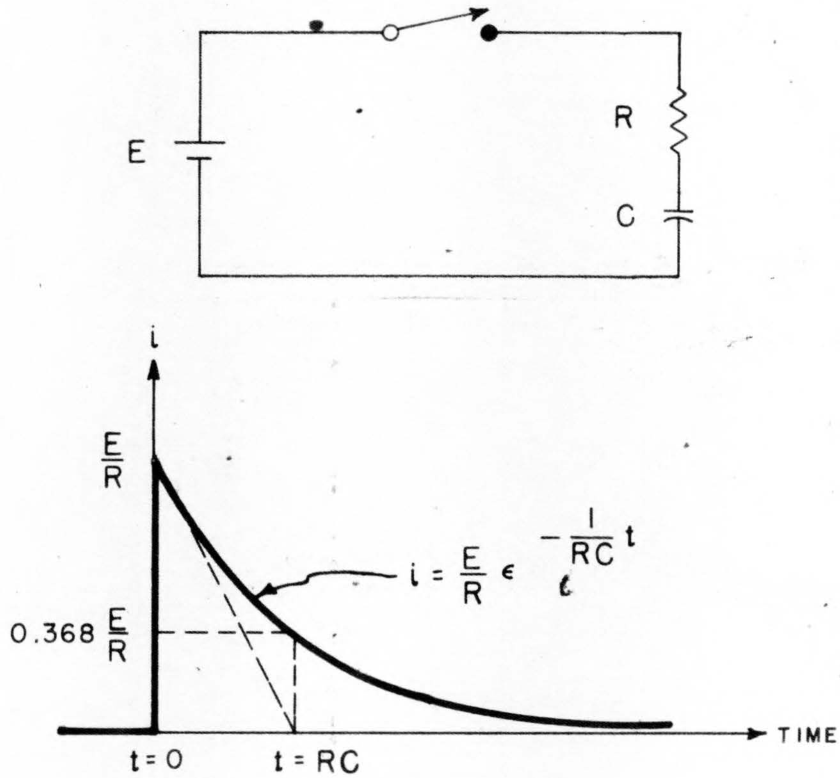

Figure 27. Decay of Current in the R-C Circuit

The time constant in this case is t = RC seconds at which time the current has dropped to 36.8 percent of its initial value.

D. UNIVERSAL TIME CONSTANT CHART. (1) The Universal Time Constant Chart shown in Figure 28 is an accurate graph of the voltage or current rise or fall in an R-L or R-C circuit. The time scale is graduated in terms of RC and L/R so that the curves may be applied to any practical case.

(2) Example of chart use: A circuit is required in which a capacitor must charge to one-fifth of the charging voltage in 100 microseconds. The resistance used is 20,000 ohms as dictated by other factors. What size of capacitor is needed? <u>Solution:</u> Curve A shows that it requires 0.22 RC seconds for a capacitor to charge to one-fifth (20 percent) of its final voltage. Since this must also happen in 100 microseconds, we have

$$0.22\ RC = 100 \times 10^{-6}$$

but $\qquad R = 20{,}000$ ohms

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so $$C = \frac{100 \times 10^{-6}}{(0.22)(20{,}000)}$$

$$= 0.0227 \text{ microfarads}$$

In an actual circuit, a 0.02 μf capacitor would be used unless special precision was required.

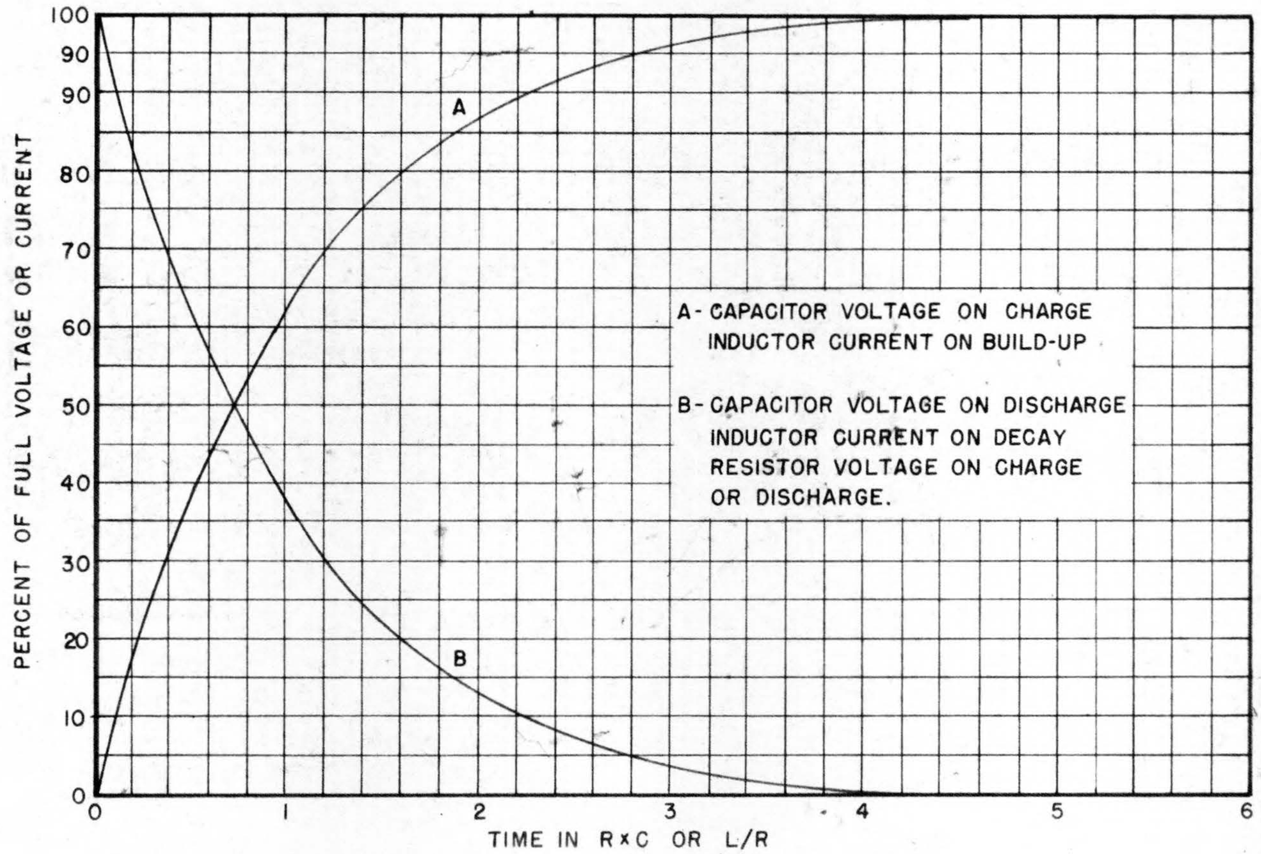

Figure 28. Universal Time Constant Chart for R-C and R-L Circuits

E. RESPONSE OF R-C CIRCUITS TO SQUARE WAVE VOLTAGES. (1) R-C circuits with various time constants are widely used in electronic applications. The capacitance may be either that of an actual component, or it may be distributed capacitance between wires, other component parts, the chassis, etc. R-L circuits find fewer practical applications than do R-C circuits because of the greater bulk and weight of inductances. The basic principles of R-C circuits have just been discussed, but further insight may be gained by examining their operation when excited by a square wave voltage.

(2) Figure 29(A) shows an R-C circuit excited by a square wave generator. In practice, this generator would be electronic (such generators will be discussed in Section V), but for the present discussion it might just as well be

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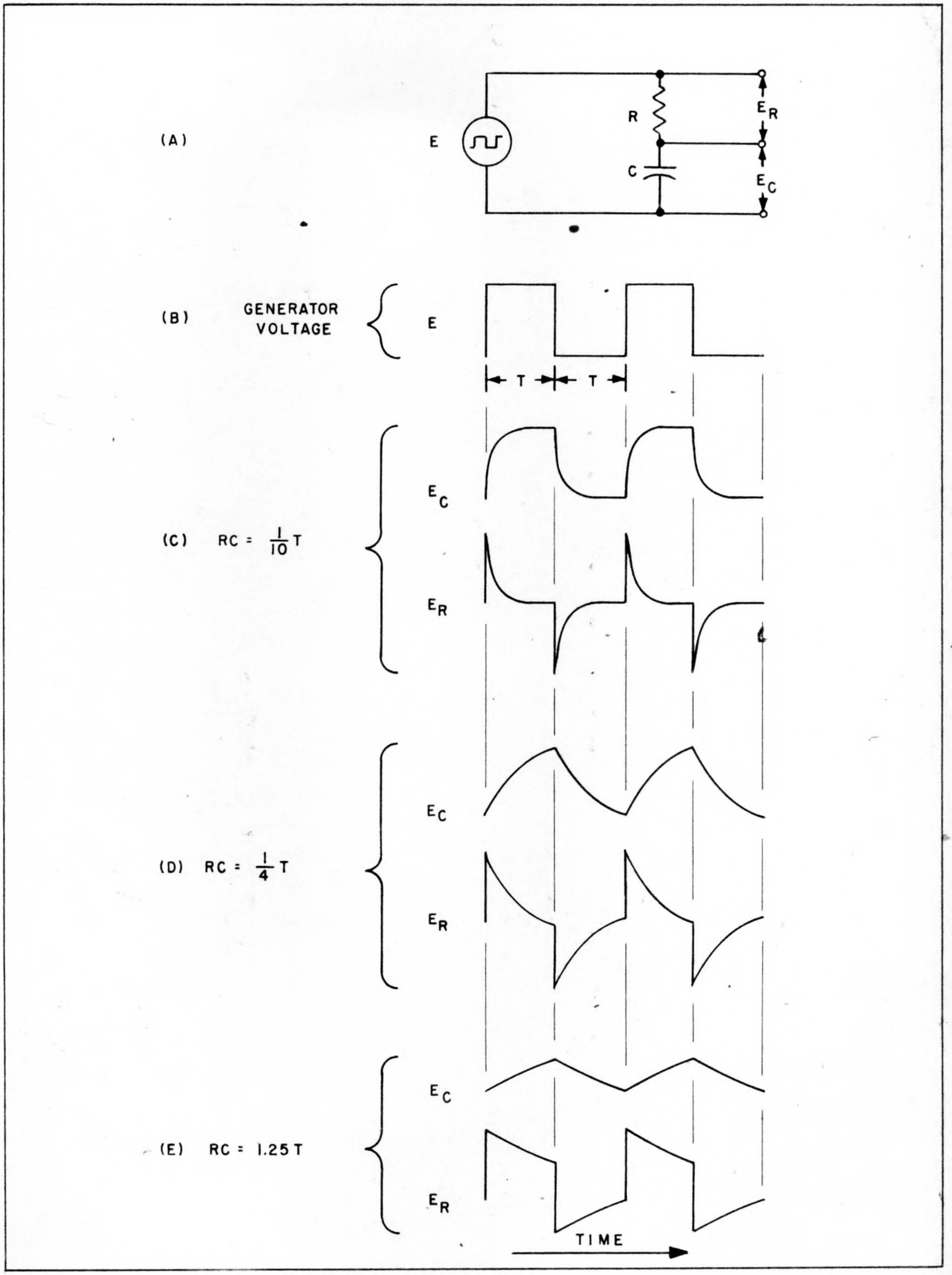

Figure 29. Waveforms in an R-C Circuit with Square Wave Excitation

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a battery which is alternately applied to and removed from the circuit after equal time intervals. The generator voltage waveform is shown in Figure 29 (B). In (C), (D), and (E) of Figure 29 the voltage waveforms across the capacitance and resistance are shown for various values of the RC time constant relative to the half-period, T, of the generator voltage.

(3) When RC is small relative to T (Figure 29(C)) and the output is taken from the resistor, we have what is known as a differentiating or peaking circuit which produces a sharp pulse of voltage each time the generator voltage changes. The E_C waveform of Figure 29(C) also shows the rounding of a pulse wavefront which in many circuits is unwanted but occurs because the capacity is of the stray interwiring type.

(4) When RC is equal to or greater than about unity and the output is taken from the capacitor, we have an integrating or smoothing circuit. The E_C waveform of Figure 29(E) shows this to a small extent. For much larger values of RC, E_C will remain practically constant. This form of network is much used for filtering and decoupling.

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SECTION III

ELECTRON TUBE FUNDAMENTALS

9. **INTRODUCTION. A. GENERAL.** (1) An electron tube may be defined as a device in which electronic conduction takes place in an evacuated enclosure. Two basic classifications may be drawn up. High vacuum tubes are those in which the gas pressure is reduced to the point where the remaining gas molecules have no appreciable effect on the tube operation. The second class, gaseous tubes, includes those tubes in which the gas molecules do have a definite effect upon the characteristics of the tube. The following paragraphs will review the fundamentals of electron tubes.

10. HIGH VACUUM TUBES. A. DIODES. (1) The diode is the simplest of vacuum tubes and contains two electrodes: a source of electrons which may be a filament or indirectly heated cathode, and an electron collector known as the anode or plate.

(2) Electrons emitted from a heated cathode do not pass instantaneously to the plate, and these electrons in transit cause the region between cathode and plate to have a net negative volume charge density called space charge. The space charge normally repels some of the electrons emitted by the cathode and causes them to return to the surface of the cathode. The diode current is then said to be space-charge limited. If the plate voltage of the diode is increased, the plate current increases until the plate collects the electrons as fast as they are emitted from the cathode. The diode has then become emission limited. In an ideal diode, further increases in plate voltage result in no increase in plate current unless the cathode temperature is raised. Although practical diodes do not behave precisely in this manner, the difference is usually small and the factors involved are beyond the scope of this review. Figure 30 shows the dependence of plate current upon plate voltage in an ideal diode. Diodes are normally operated in the space charge limited portion of the curve.

B. TRIODES. (1) The triode is made by inserting a wire mesh or grid between the cathode and anode of a diode. A connection to the grid is brought outside the tube. The cathode is ordinarily placed at the center of the tube with the grid and plate concentric around it.

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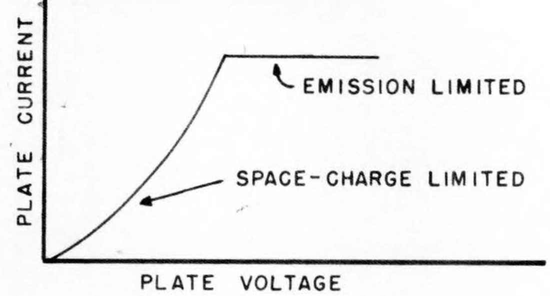

Figure 30. Diode Characteristic

(2) The primary purpose of the grid in a triode is to control the flow of current between plate and cathode. It is usually desirable to do this without either impeding the electron flow mechanically or having any electrons flow to or from the grid. The first condition is approached by making the grid of fine wire with relatively large openings. The condition of no grid current is advantageous since it means that no power is required to operate the grid. Electron flow from the cathode to the grid is prevented by giving the latter a negative potential with respect to the former, and electron flow from the grid is made negligible by keeping its temperature low.

(3) The presence of a grid with no applied voltage will cause negligible effect on the operation of a triode; it will operate as a diode. The application of a negative voltage to the grid with respect to the cathode will, however, cause the grid to repel electrons emitted from the cathode and thus reduce the plate current. If the grid is made sufficiently negative, no electrons emitted by the cathode will have velocity great enough to pass the potential barrier of the grid, and the plate current will fall to zero. The negative grid voltage of least magnitude which will cut off the plate current is called the <u>cut-off grid voltage</u>. Its value depends upon the plate voltage used.

(4) The characteristics of vacuum tubes with cathode, grid, and plate electrodes involve the relationships between grid voltage (e_c), plate voltage (e_b) and grid current (i_b). Although these relationships cannot be expressed in any exact mathematical form simple enough to be useful, it is a relatively easy matter to take experimental data on an actual tube and determine the way that plate current acts as a function of grid and plate voltages. Figure 31 shows the result of such an experiment: the plate characteristics of a typical triode.

(5) In connection with the characteristics of a triode, we may define three quantities called coefficients which are important both in the analysis of vacuum tube circuits and as rough figures of merit for the performance of a given tube. First is the amplification factor which is defined as

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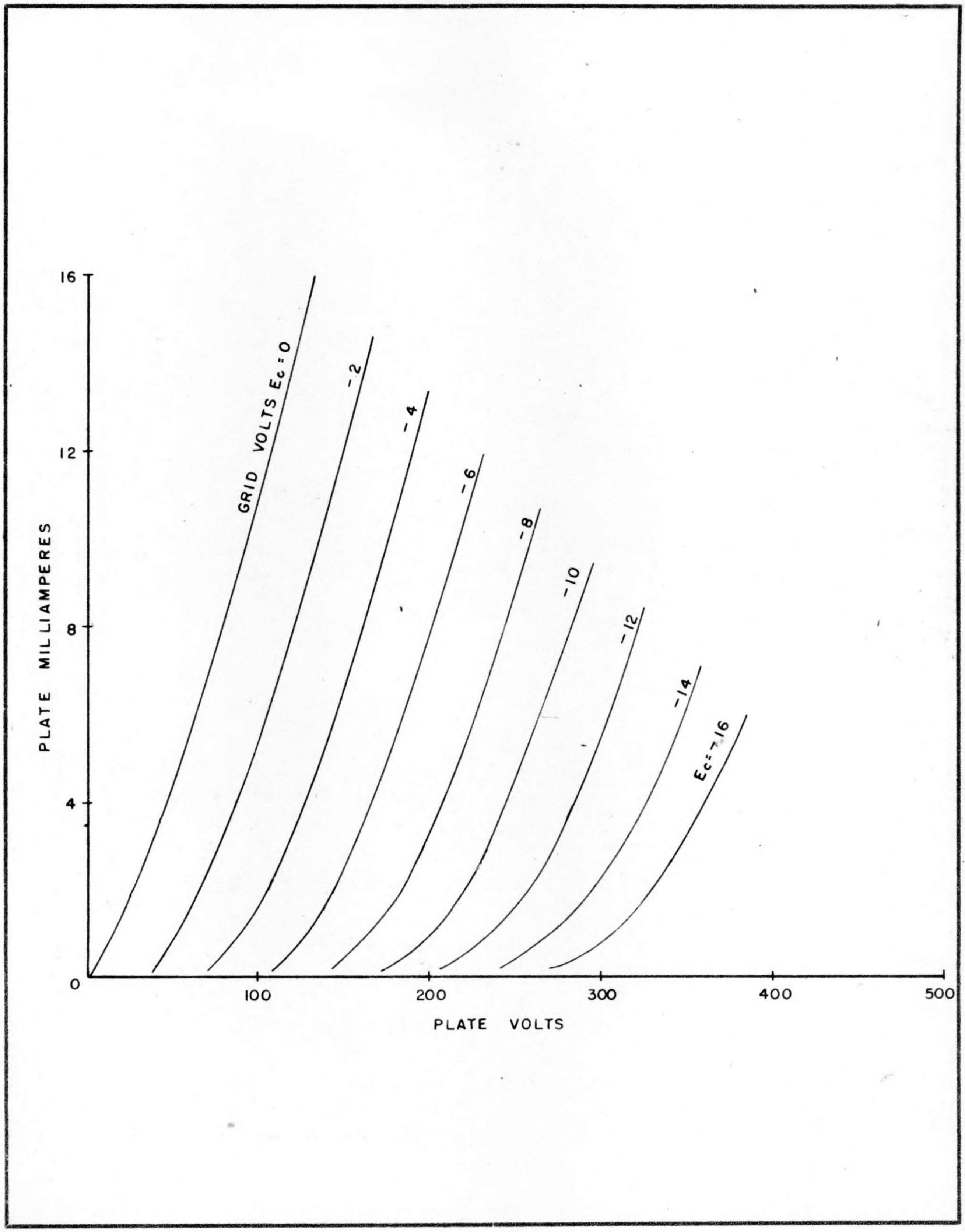

Figure 31. Plate Characteristics of a Triode

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$$\mu = - \frac{\Delta e_b}{\Delta e_c} \quad (i_b \text{ constant}) \tag{122}$$

It is the ratio of a small change in plate voltage to the corresponding change in grid voltage needed to keep the plate current constant. Second is the dynamic or a-c plate resistance:

$$r_p \text{(in ohms)} = \frac{\Delta e_b}{\Delta i_b} \quad (e_c \text{ constant}) \tag{123}$$

This is the resistance offered to a small change in plate current. Finally, the grid-plate or mutual transconductance is

$$g_m \text{(in mhos)} = \frac{\Delta i_b}{\Delta e_c} \quad (e_b \text{ constant}) \tag{124}$$

None of the coefficients, or "constants" as they are sometimes called, is really constant. Each of the coefficients may be obtained from the characteristic curves of a given tube, and since these are not linear and equidistant for equal increments of the parameter, the coefficients cannot be constant. Published values of the coefficients are the values that exist in that region of the characteristics where they are nearly linear.

(6) The coefficients depend fundamentally on the tube structure and are related by the following expression:

$$\mu = g_m r_p \tag{125}$$

Obviously, the values used in this equation must all be for the same point on the characteristic curves.

(7) The tube coefficients are applicable to tubes other than triodes if the voltages applied to additional electrodes are held constant.

C. TETRODES. (1) Tetrodes have a second grid called the <u>screen grid</u> which is inserted between the <u>control grid</u> and the plate.

(2) Triodes are at a disadvantage for amplification at the higher frequencies because the capacitance between grid and plate may lead to oscillation. The screen grid shields the grid from the plate and is generally given a positive potential somewhat lower than the plate. This results in some screen current which generally serves no useful purpose.

(3) Tetrodes have high plate resistance and amplification factors. By proper design the transconductance can also be made high. Plate voltages lower than the screen voltage produce secondary emission from the plate and a negative plate resistance. This is undesirable in normal operation.

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D. PENTODES. (1) Pentodes are similar to tetrodes with the addition of a suppressor grid between screen grid and plate.

(2) The suppressor grid is usually operated at cathode potential and thus tends to force secondary electrons back to the plate. This eliminates the negative resistance region of the tetrode.

(3) Pentodes have high values of amplification factor, plate resistance, and transconductances.

E. BEAM POWER TUBES. (1) A special type of tetrode which functions in the manner of a power pentode is called a beam-power tube. Instead of using a suppressor grid to control the secondary emission from the plate, this tube obtains the same effect because its electrodes are shaped in such a way as to control the space charge near the plate. A beam-forming plate, connected internally to the cathode, causes a concentration of electrons in the vicinity of the plate, thereby producing a region of minimum potential. As long as the plate potential is greater than this minimum potential, secondary electrons are returned to the plate. A beam-power tube operated at the same voltages as a normal tetrode provides more power output for a given signal voltage. This is accomplished without an increase in internal tube capacitances.

II. GASEOUS TUBES. A. GENERAL. (1) If a small amount of gas is present in a diode either because of insufficient evacuation or deliberate insertion, the characteristics of the tube are markedly altered from those discussed in Paragraph 10. The difference is due to ionization of the gas molecules.

(2) When electrons are emitted from the cathode in a gas-filled tube and are attracted to the plate, they encounter gas molecules. Depending upon the speed of the electrons (and therefore on the plate potential), they may have enough energy to ionize some of the gas molecules. The liberated electrons may then join the original electron stream and may ionize other gas molecules. The heavier positive ions drift toward the cathode. For any gas filled tube, the electrons need a certain minimum value of kinetic energy to produce ionization, and there is a corresponding minimum plate voltage which is called the ionization potential.

(3) After ionization has started, it will maintain itself at a voltage somewhat lower than the ionization potential. If the voltage from plate to cathode falls below a certain value, the gas de-ionizes and conduction ceases. This lower voltage is known as the deionizing or extinction potential.

(4) After ionization, the voltage drop across a gas-filled tube is almost independent of the current through the tube. This constant voltage is of great importance in the application of gas tubes and means that the current must be limited by resistance in the external circuit or the tube will be destroyed.

B. GAS-FILLED DIODES. (1) A large number of cold-cathode gaseous diodes are used as indicator lamps, voltage regulators, etc. Because the

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cathodes of these tubes are unheated, their ionization potentials are higher than those of tubes with thermionic cathodes. Ionization is started by corona discharge from the electrodes.

(2) Other types of gaseous diodes have thermionic cathodes and generally contain mercury vapor. Their most important application is as high-current rectifiers. It must be remembered when using mercury vapor rectifiers that these tubes are unable to carry their rated current until the mercury has completely vaporized. Application of plate voltage too soon will demand excessive emission from the cathode and will result in its destruction.

C. MULTI-ELEMENT GASEOUS TUBES (THYRATRONS). (1) A gas-filled triode or tetrode in which a grid is used to control the firing potential is called a thyratron. The function of the grid is to trigger the tube, that is, initiate conduction from cathode to plate. After conduction has started, the grid loses all control over the plate current, and conduction can be stopped only by lowering the plate voltage as in a gas diode. Both plate and grid currents must be limited by external impedances.

(2) A thyratron acts as a relay; it cannot be made to amplify any form of continuous function. As a relay, its action is extremely fast, but it must be "reset" for each new cycle of operation. As mentioned above, resetting is accomplished by lowering or removing the plate voltage. This may be done conveniently by using a-c voltage on the plate.

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SECTION IV

VACUUM TUBE AMPLIFIERS

12. BASIC AMPLIFIER THEORY. A. CLASSIFICATIONS. (1) The manner in which a vacuum tube is operated may be classified in a variety of ways. One of the most useful methods is based upon the magnitude of variation of voltages associated with the tube. There are three cases:

(a) Quiescent operation: only d-c voltages are applied to the tube.
(b) Linear operation: alternating voltages of small amplitude are added to the d-c voltages of quiescent operation so that voltage variations do not extend outside of a linear range of the tube characteristics.
(c) Non-linear operation: alternating voltages of such amplitude are added to the d-c voltages that the plate voltage is no longer a linear function of grid voltage.

(2) Another method of classifying tube operation is on the basis of the percentage of time that plate current flows in the tube. Thus

(a) Class A operation: plate current flows at all times.
(b) Class AB operation: plate current flows for appreciably more than half but less than the entire cycle of grid voltage.
(c) Class B operation: plate current flows for approximately one-half of each cycle of grid voltage.
(d) Class C operation: plate current flows for less than one-half of each cycle of grid voltage.

The subscript 1 or 2 following these classifications indicates that grid current does not or does flow respectively during part of the cycle of grid voltage.

B. VOLTAGE AND CURRENT NOMENCLATURE FOR AMPLIFIERS. (1) The symbols used in the discussion and analysis of amplifiers are necessarily involved. Figure 32 shows some of the most important quantities and their assigned positive directions. The following general rules should be memorized.

(a) The cathode is taken as the zero reference of potential for all tube voltages (but not necessarily for voltages in the external circuit).

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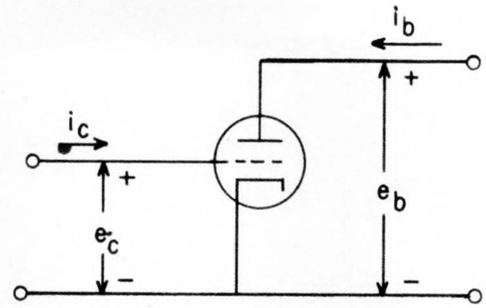

Figure 32. Assigned Positive Directions of Currents and Voltages

(b) All currents in the tube flow to the cathode.
(c) Lower case letters are used for varying voltages and currents.
(d) Upper case letters are used for non-varying voltage and currents.
(e) The subscripts c and b are used respectively to denote the total quantity involved for the grid and plate.
(f) The subscripts g and p are used respectively to denote the varying quantity involved for grid and plate.
(g) Supply voltages are given a double subscript: cc for grid and bb for plate.
(h) Quiescent voltages and currents are denoted by the subscript 0 following any other subscript.

These rules will be illustrated in the material that follows.

C. QUIESCENT OPERATION AND THE LOAD LINE. (1) Figure 33 shows a triode connected to a load, R_L, and supply batteries. A problem of basic importance is to find the plate voltage and current in the circuit of Figure 33.

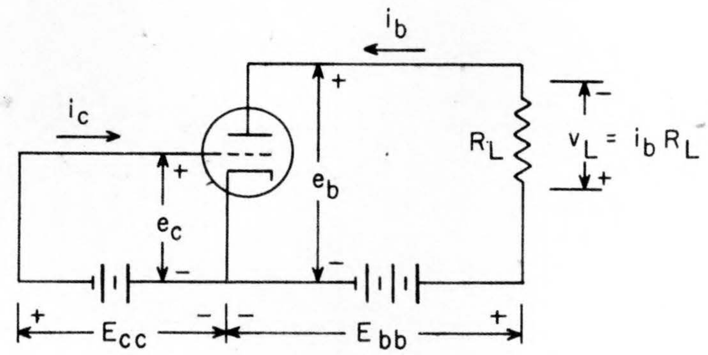

Figure 33. Schematic Diagram of a Triode with Resistance Load

This is done by means of the plate characteristics of the tube, a typical set

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being shown in Figure 34. First apply Kirchoff's Voltage Law to the plate

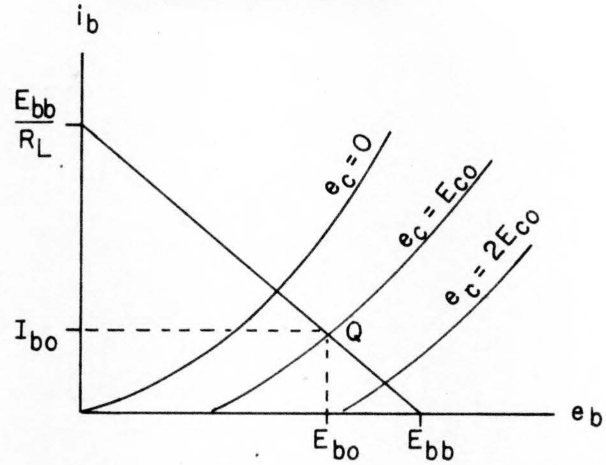

Figure 34. Triode Plate Characteristics with Load Line

circuit of the tube:

$$E_{bb} = i_b R_L + e_b \tag{126}$$

Solving for i_b:

$$i_b = \frac{E_{bb} - e_b}{R_L} \tag{127}$$

This equation represents a straight line function and when plotted on the tube characteristics is known as the load line. It is important to note that the load line is a function only of the external circuit and is independent of the type of tube used.

(2) The easiest way to plot the load line is to find its intercepts. These are

$$\text{for } e_b = 0,\ i_b = \frac{E_{bb}}{R_L} \tag{128}$$

$$\text{for } i_b = 0,\ e_b = E_{bb} \tag{129}$$

Figure 34 shows a typical load line and gives the locus of values over which the tube may operate with the given values of E_{bb} and R_L. For the circuit of Figure 35, $e_c = E_{cc}$ and the tube voltages and currents may be found from the intersection of the load line and the characteristic for $e_c = E_{cc}$. Since only d-c voltages are present in this case, the values obtained are quiescent ones:

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$$e_c = E_{co} \tag{130}$$

$$e_b = E_{bo} \tag{131}$$

$$i_b = I_{bo} \tag{132}$$

D. LINEAR OPERATION AND EQUIVALENT CIRCUITS. (1) The linear operation of vacuum tube amplifiers is important not only because of practical application but also because an understanding of this mode of operation is basic to the understanding of other types of operation. If a sinusoidal signal voltage is applied to the grid of a triode as shown in Figure 35 and if the magnitude of e_{in} and the location of the quiescent operating point are such as

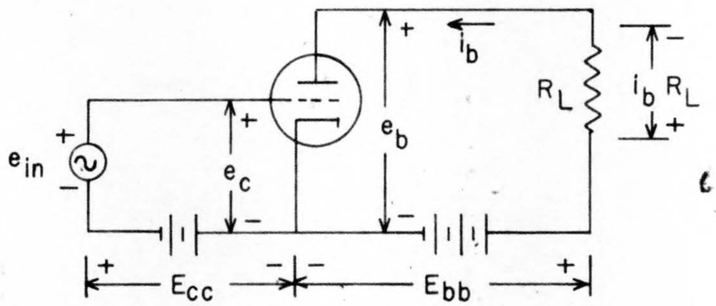

Figure 35. Triode Amplifier with Sinusoidal Input

to insure linear operation, then it can be shown that conditions produced in the plate circuit are the same as those existing in the <u>equivalent circuit</u> shown in Figure 36. μ and r_p are respectively the amplification factor and

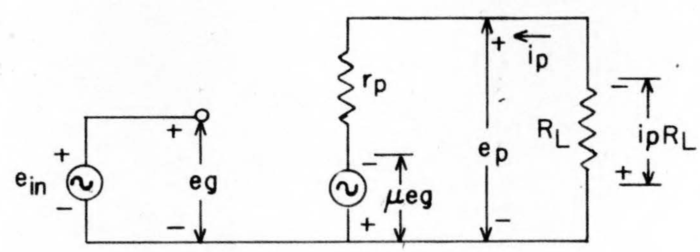

Figure 36. Equivalent Circuit of Triode Amplifier

the plate resistance of the triode being used. Note particularly that only varying voltages and currents appear in the equivalent circuit.

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(2) Any analysis of a linearly-operated vacuum tube circuit may be carried out on the basis of the equivalent circuit. Suppose that it is desired to know the output voltage of the circuit of Figure 35 (in this case equal to e_p). Applying Kirchoff's Voltage Law to the equivalent circuit:

$$\mu e_g = i_p R_L + i_p r_p \tag{133}$$

which may be rearranged:

$$i_p = \frac{\mu e_g}{R_L + r_p} . \tag{134}$$

But $$e_p = - i_p R_L \tag{135}$$

so $$e_p = - \mu e_g \frac{R_L}{R_L + r_p} \tag{136}$$

This indicates that the varying component of plate voltage is 180° out of phase with the grid voltage and is $\frac{\mu R_L}{R_L + r_p}$ times as large as the grid voltage.

(3) It is common to speak of the <u>voltage gain</u> of an amplifier. This may be defined as the ratio of plate voltage change to corresponding grid voltage change. From the previous paragraph:

$$\text{voltage gain} = K = \frac{e_p}{e_g} = - \mu \frac{R_L}{R_L + r_p} \tag{137}$$

(4) The manner in which a triode amplifies a grid signal may be clarified by Figure 37 which shows one-half of a 6SN7 triode operating in the circuit of Figure 35 under the following conditions:

$E_{cc} = - 4$ volts

$E_{bb} = 300$ volts

$R_L = 8000$ ohms

$e_{in} = 4$ volts peak

The load line has been drawn on the tube characteristics, and the quiescent operating point is labeled Q. The varying component (e_g) of grid voltage is equal to the input (e_{in}) and swings the grid $\pm$ 4 volts about the quiescent grid voltage $E_{co} = -4$. The operating point therefore slides up and down the load line from the characteristic $e_c = 0$ to that for $e_c = -8$. Figure 37 shows that when $e_c = 0$, $e_b = 154$, and $i_b = 18.25$; and that when $e_c = -8$, $e_b = 240$,

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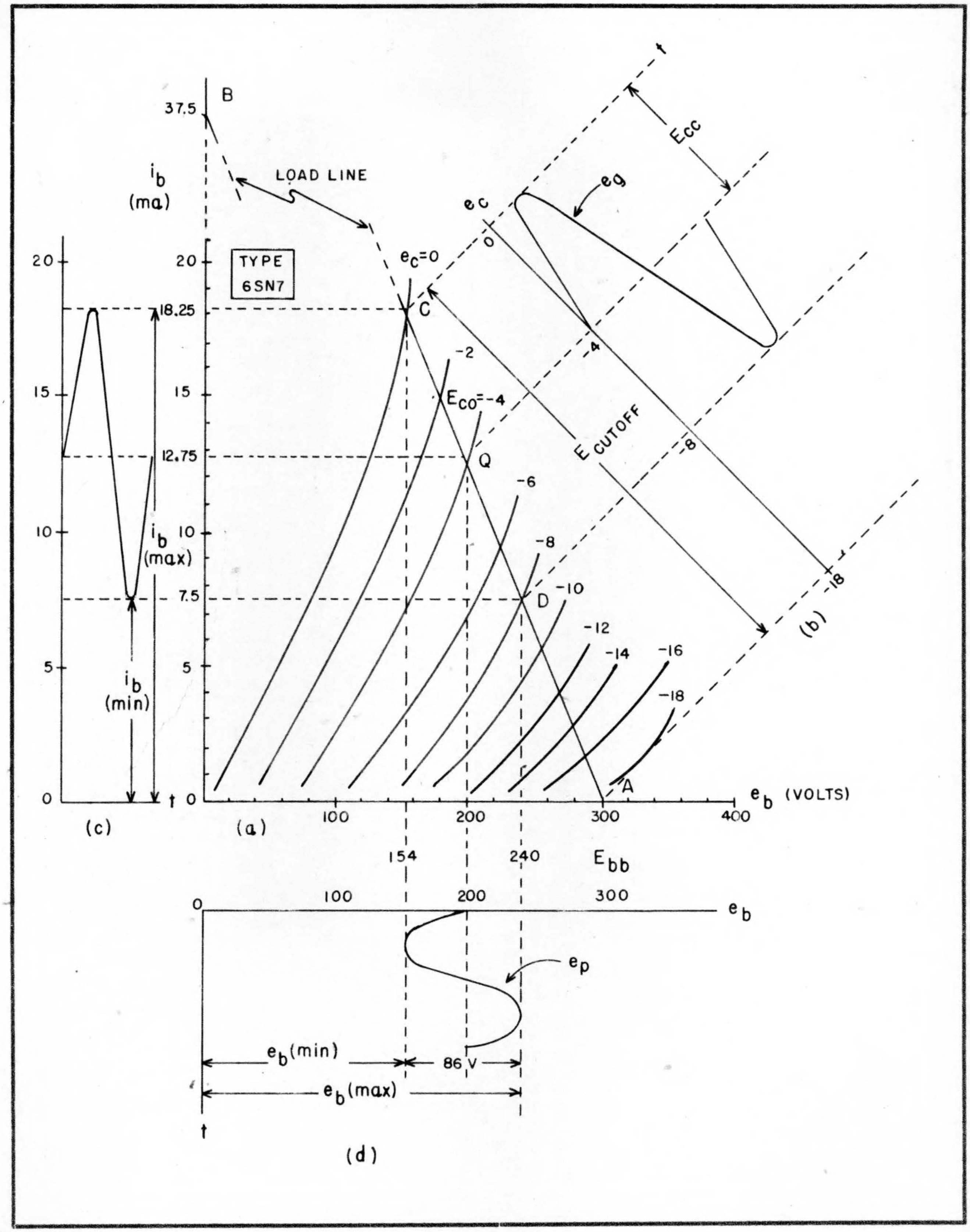

Figure 37. Application of i_p vs. e_p characteristic to a typical tube problem

and i_b = 7.5. Similarly if $e_{in} = e_g$ is sinusoidal with time as shown in (b) then the plate voltage and currents may be plotted point by point as shown in (d) and (c). Note the phase relationships between the grid and plate voltages and plate current.

(5) This graphical analysis illustrates the operation of an amplifier. A signal of 4 volts peak on the grid of the tube produces a signal of 43 volts peak at the plate and 180° out of phase with the grid voltage.

E. DISTORTION IN AMPLIFIERS. (1) A perfect amplifier produces an output whose waveshape duplicates the input and whose magnitude is proportional to the input. Most practical amplifiers suffer from one or more of three possible types of distortion. If the output waveform is not strictly proportional to the input, we have amplitude distortion; if the various frequency components in the input signal do not have the same transit time through the amplifier, we have phase distortion; and if different frequency components of an input signal are not amplified equally well, we have frequency distortion.

(2) Amplitude or nonlinear distortion may be caused by non-linearity of the characteristic curves of a tube or by driving the grid to cut-off or saturation. It results in the presence of frequency components in the output which were not present in the input. These distortion frequencies are principally harmonics of the input frequencies and may be reduced by restricting the amplitude of the grid signal. The design of power amplifiers usually involves a choice between increased power with greater amplitude distortion and lower power with greater fidelity.

(3) Figure 38 illustrates the result of phase distortion in an amplifier.

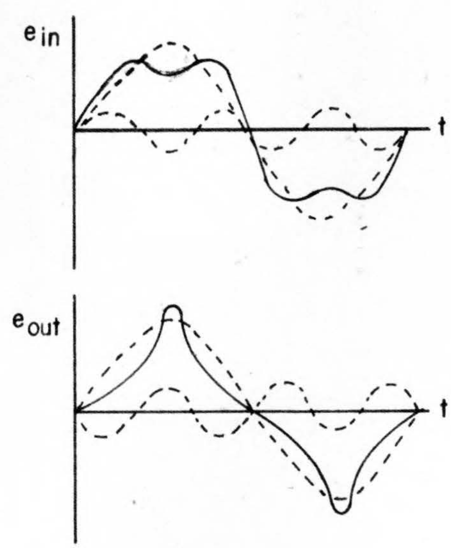

Figure 38. Phase Distortion

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The input signal is composed of a fundamental and third harmonic. Although the amplitudes of both components are increased by the same factor in the amplifier, the phase of the third harmonic component has been shifted with respect to the fundamental so that the output waveform is completely different from the input. Since the ear is unable to detect relative phase angles, phase distortion is unimportant in audio systems; but in systems using pulses, it is very important.

(4) Frequency distortion is caused by the inability of any one amplifier to amplify all frequencies equally well. More technically we say that the gain-frequency characteristic is not constant or "flat". Amplifiers may be designed to give essentially flat response over a portion of the frequency spectrum, but in view of the tremendous range of frequencies which have been found useful to date (from zero to thousands of megacycles per second) it is not unreasonable that different types of amplifiers are used in different parts of the frequency spectrum. More will be said about these matters in the following paragraphs.

F. POWER AMPLIFIERS. (1) Power amplifiers differ from voltage amplifiers principally in that the former are required to control relatively large amounts of power in the output circuit while the latter must supply large voltage swings into a high load impedance. Although the design of power amplifiers is beyond the scope of this book, the following paragraphs will point out a few of their features and applications.

(2) The design of a class A power amplifier usually includes consideration of the allowable distortion. Although the power output from a particular tube may be increased within limits by driving it harder, the distortion increases with greater voltage swings. Consequently the maximum power output is generally limited by the degree of waveform distortion that can be tolerated. The efficiency of class A amplifiers is low, varying from 20 to 40 percent.

(3) Class B power amplifiers are those in which plate current flows about 50 percent of the time. Because the grid is at cut-off during a portion of each cycle, such amplifiers are always operated with two tubes in push-pull. One tube then conducts while the other is cut off. This type of amplifier has a greater maximum efficiency (up to about 65 percent) than class A amplifiers and will deliver an unusually large output in proportion to tube size.

(4) In class C amplifiers, the plate current flows during only a small part of each grid voltage cycle. These amplifiers are extensively used with tuned load circuits to develop radio-frequency power. They are the most efficient of all power amplifiers.

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G. TUNED AMPLIFIERS. (1) In a tuned amplifier the load impedance is a parallel resonant circuit. Over a range of frequencies centered on the resonant frequency of the tuned circuit, the response of such an amplifier depends principally upon the selectivity or Q of the circuit. Both high Q (very selective) and low Q (broad band) tuned amplifiers find wide application in

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13. CASCADE AMPLIFIERS. A. GENERAL. (1) Since the voltage gain needed in practical applications often exceeds that which may be obtained with a single amplifier tube, cascade amplifiers are frequently used in which the first tube supplies the grid signal voltage for the second and so on. Coupling circuits are used to connect the plate circuit of one tube to the grid of the succeeding tube. Since the type of coupling network selected will determine in large measure the over-all characteristics of the amplifier, the next few paragraphs will point out some of the features of amplifiers coupled in various ways.

B. DIRECT-COUPLED AMPLIFIERS. (1) The cascade amplifier having the simplest coupling network is the so-called direct-coupled type. Essentially non-reactive resistors and constant voltage elements are used with the result that the voltage gain is nearly independent of frequency from zero frequency (d-c) up to the point where stray capacitance becomes appreciable.

(2) The basic circuit of the direct coupled amplifier is shown in Figure 39A. The battery used as the coupling means in this circuit is necessary to

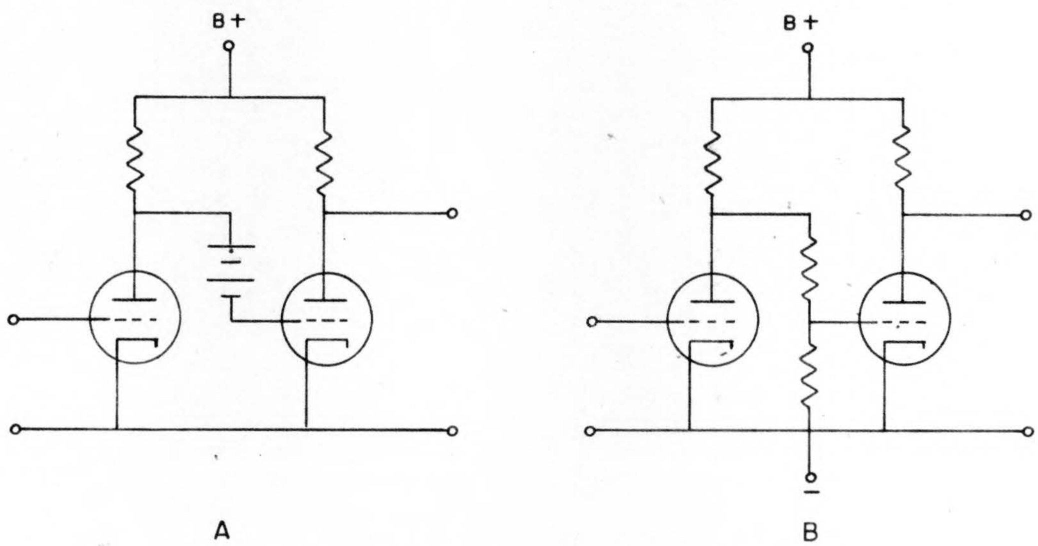

Figure 39. Direct-Coupled Amplifier

place the quiescent grid voltage of the second tube in the proper range. The gain of this circuit is equal to the product of the gains of the individual stages.

(3) The circuit of Figure 39B dispenses with the undesirable grid battery in the first circuit, but a negative power supply is required and some gain is lost by voltage divider action.

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(4) Direct-coupled amplifiers are inherently unstable because any drift in the d-c voltages of the first stage is amplified and may be sufficient to throw the operating paths of following stages out of the linear region. Balanced circuits and degenerative feedback will reduce these difficulties.

C. RESISTANCE-CAPACITANCE COUPLED AMPLIFIERS. (1) Figure 40 illustrates the circuit of what is perhaps the most widely used type of cascade

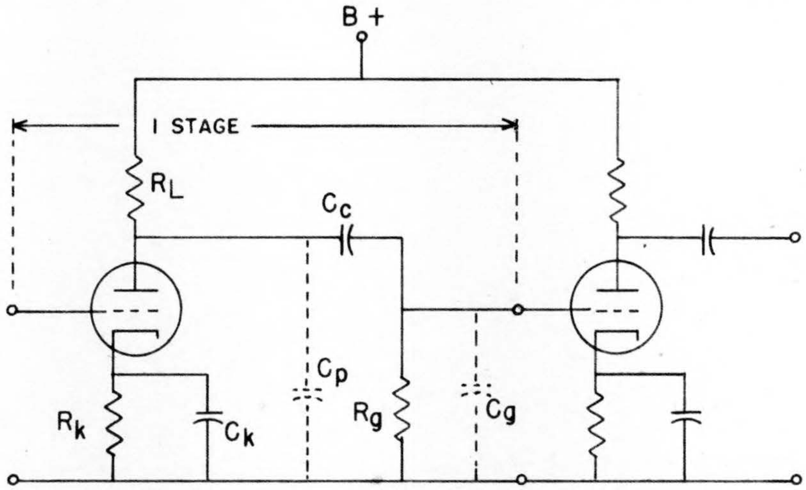

Figure 40. Resistance-Capacitance Coupled Amplifier

amplifier. Cathode bias is used, and the stray capacitances that affect the plate circuit have been shown dashed. Coupling capacitor C_c should be large enough to have a small reactance compared with the resistance of R_g over the desired frequency range. Therefore most of the output of the first stage is applied to the grid of the second. C_c blocks the d-c plate voltage of the first stage, however.

(2) The gain-frequency characteristic of a resistance-capacitance coupled amplifier is not constant as would be desirable for most purposes. It is usually relatively constant over the so-called mid-band range of frequencies. Below this, in the low frequency range, the reactance of C_c increases, and C_c and R_g form a voltage divider which reduces the output. Above the mid-band region, in the high frequency range, the gain drops off because the reactance of C_p and C_g decreases and their shunting effect becomes important. The characteristic for an audio amplifier is shown in Figure 41. The frequencies at which the gain drops to 70.7 percent of maximum are called the upper and lower half power frequencies and have been labeled f_1 and f_2 respectively. Typical values for f_1 and f_2 might be 100 and 5000 cycles.

(3) The frequency range of resistance-capacitance coupled amplifiers may be extended to the supersonic and low radio frequencies by suitable modification of their design. Circuits designed to amplify voltages with frequencies up to about one megacycle are called video amplifiers. The

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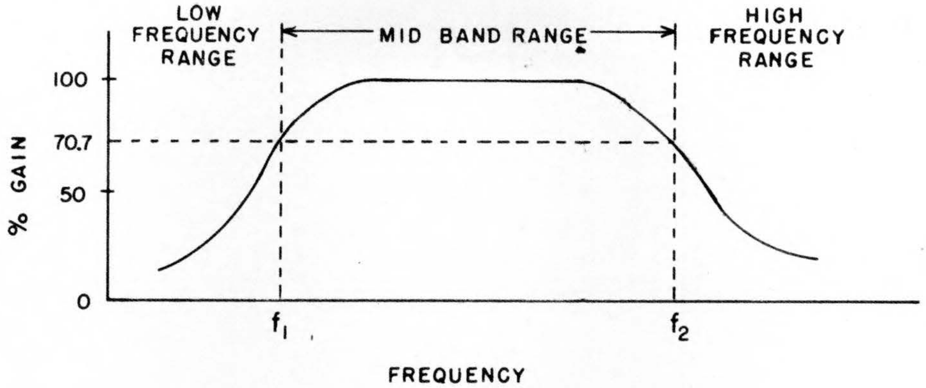

Figure 41. Gain Frequency Characteristic

equivalent circuit for one stage of the circuit in Figure 40 for the <u>high frequency range</u> is shown in Figure 42. The tube is symbolized as a constant current source ($g_m e_g$) in parallel with r_p; this is entirely equivalent

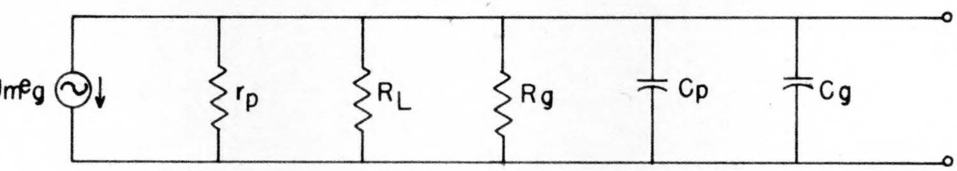

Figure 42. Equivalent Circuit of First Stage of the Circuit of Figure 11 for the High Frequency Range

to a constant voltage source μe_g in series with r_p. C_c is not shown in the equivalent circuit since its reactance is negligible at high frequencies. The equivalent circuit shows that the stray capacitances C_p and C_g shunt the output of the amplifier and reduce the gain as the frequency increases. If a small inductance is put in series with R_L it will have negligible effect over the low and middle frequencies, but at the higher frequencies it will tend to parallel-resonate with $C_p + C_g$ and keep the effective load impedance (and gain) from dropping off until a higher frequency is reached. The actual circuit for a single stage would be as shown in Figure 43 and is called a shunt peaked amplifier. More elaborate peaking systems have been devised but will not be considered in this review.

(4) Amplifiers which must operate at frequencies greater than about one megacycle and with a constant gain-frequency characteristic are usually built in the form of tuned rather than resistance-capacitance coupled

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amplifiers. Tuned amplifiers were discussed briefly in Paragraph 12G.

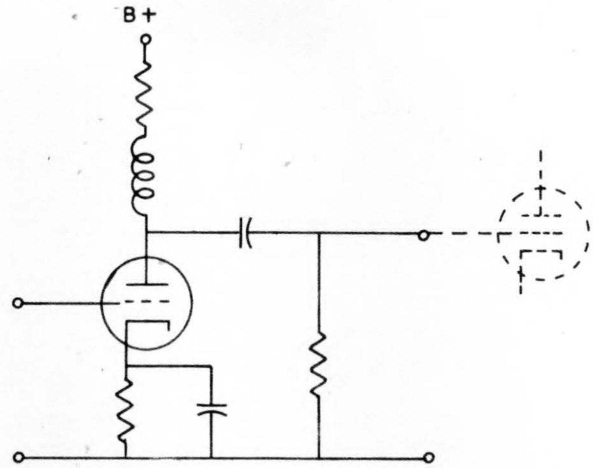

Figure 43. Shunt Peaked Amplifier

D. AMPLIFIERS WITH IRON-CORE TRANSFORMERS. (1) Iron core transformers may be used as the coupling means between the stages of an audio amplifier, and in such service they are called <u>interstage</u> transformers. They are used more extensively, however, as <u>input</u> or <u>output</u> transformers for audio amplifiers.

(2) The principal advantage of transformer coupling between amplifier stages lies in increased voltage gain with a given tube and plate supply voltage. Their disadvantages are mainly physical and economic; transformers are bulky, heavy, and expensive in comparison with resistance-capacitance coupling systems. Their frequency response can be extended to 15 or 20 kilocycles and even higher by special design, but such transformers are costly.

(3) Because their impedance ratio is equal to the square of their turns ratio, transformers are particularly adopted to impedance transforming functions. Furthermore, audio-frequency transmission lines and loud speakers have low impedances while vacuum tubes (except for the output of a cathode follower) have high input and output impedances. The most extensive use of iron-core transformers with audio amplifiers is, therefore, to match impedances at the input and output. Another important use for transformers lies in the fact that the secondary may be readily center-tapped to provide two outputs 180° out of phase for the excitation of a push-pull stage.

E. FEEDBACK AMPLIFIERS. (1) Feedback is the process of transferring part of the output signal of a device back to the input. There are two types of feedback: <u>regenerative</u> or positive feedback and <u>degenerative</u> or negative feedback. Regenerative feedback exists if the signal fed back increases the effective input signal; it results in an oscillator. If the signal fed back from output to input reduces the net input signal, we have degenerative feedback with accompanying desirable properties that compensate for the loss of gain.

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(2) The principles of feedback amplifiers are readily found from a consideration of Figure 44. A fraction β of the output is fed back from the output to the input of the amplifier so that the voltage fed back is βE_o. Writing

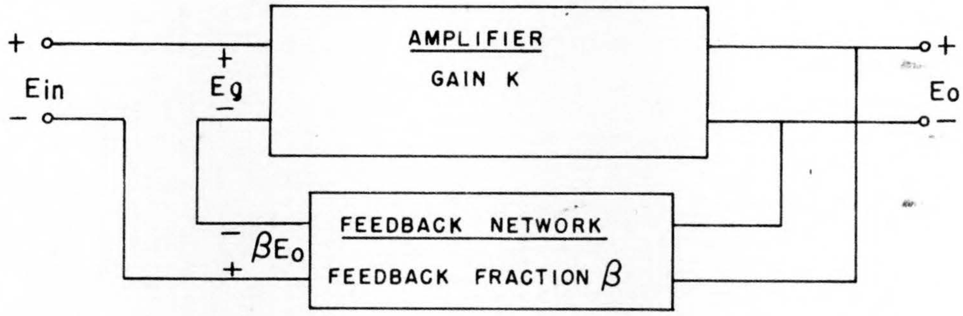

Figure 44. Principles of a Feedback Amplifier

Kirchoff's Voltage Law for the input circuit we have

$$E_g = \beta E_o + E_{in} \tag{138}$$

The gain of the amplifier without feedback is

$$K = \frac{E_o}{E_g} \tag{139}$$

and substituting the value of E_g from (139) into (138) gives

$$\frac{E_o}{K} = \beta E_o + E_{in} \tag{140}$$

The overall gain of the circuit with feedback is readily obtained from (140):

$$\text{Overall gain} = \frac{E_o}{E_{in}} = \frac{K}{1 - \beta K} \tag{141}$$

(3) Whenever the absolute value of $(1 - \beta K)$ in Equation (141) is greater than unity, the feedback is negative because the overall gain becomes less than K. In practical cases βK is usually much greater than unity and Equation (141) then becomes

$$\text{Overall gain} = \frac{E_o}{E_{in}} = -\frac{1}{\beta} \tag{142}$$

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This is an important expression because it shows that the overall gain of a feedback amplifier may be made independent of the gain of the same amplifier without feedback. In this way the overall gain is unaffected by instability, poor frequency response, noise, and other undesirable characteristics of the same amplifier but without feedback. Note, however, that a degenerative amplifier cannot reduce the effects of noise or distortion that are already present in the input signal E_{in}.

(4) Degenerative feedback may be obtained in many practical ways. The feedback voltage is commonly injected into either the grid or cathode circuit of a voltage amplifier. Because of the 180° phase shift from grid to plate in an amplifier tube, feedback over any odd number of stages from plate to grid will be degenerative, and feedback over any even number of stages from plate to cathode will also be degenerative.

SECTION V

SPECIAL CIRCUITS

14. INTRODUCTION. A. GENERAL. (1) A wide variety of special circuits are used in computers. In the present section, particular attention will be given to those circuits useful in digital computers. Many of these circuits are the same as, or are closely related to, circuits used in radar equipments.

15. SHAPING CIRCUITS. A. DIFFERENTIATORS AND INTEGRATORS. (1) These circuits are simply R-C and R-L circuits with proper choice of circuit constants. Refer to Section II, paragraph 8 for a complete discussion and particularly to paragraph 8E.

B. CLIPPERS AND LIMITERS. (1) The terms clipper and limiter are used more or less interchangeably to denote circuits which remove by electronic means a portion of either amplitude extremity of an input signal. They find wide application for such tasks as producing a nearly rectangular wave from a sine wave, for eliminating either positive or negative pulses from a series of both, etc.

(2) Figure 45 shows a variety of clipper circuits using a diode either in series or parallel with the signal path. The operation of the series diode shown in Figure 45A is precisely the same as that of a half wave rectifier which will be discussed in Section VI. On the positive peak of the input voltage, the diode plate is positive with respect to ground and so a current flows through the diode and resistor, R, to ground. The output voltage is developed across R and is equal to the input voltage less the drop, e_b, across the diode. On the negative half cycles of the input voltage, the diode does not conduct so the output voltage is zero.

(3) If the positive half cycles of a signal should be clipped, it may be done with a series diode by merely turning it around (see Figure 45B). The operation of this circuit is basically the same as the negative clipper.

(4) A diode may be connected in shunt across a circuit for clipping action. Figure 45C shows a shunt-diode positive clipper. The diode acts essentially like a switch which short-circuits the load when the plate becomes positive;

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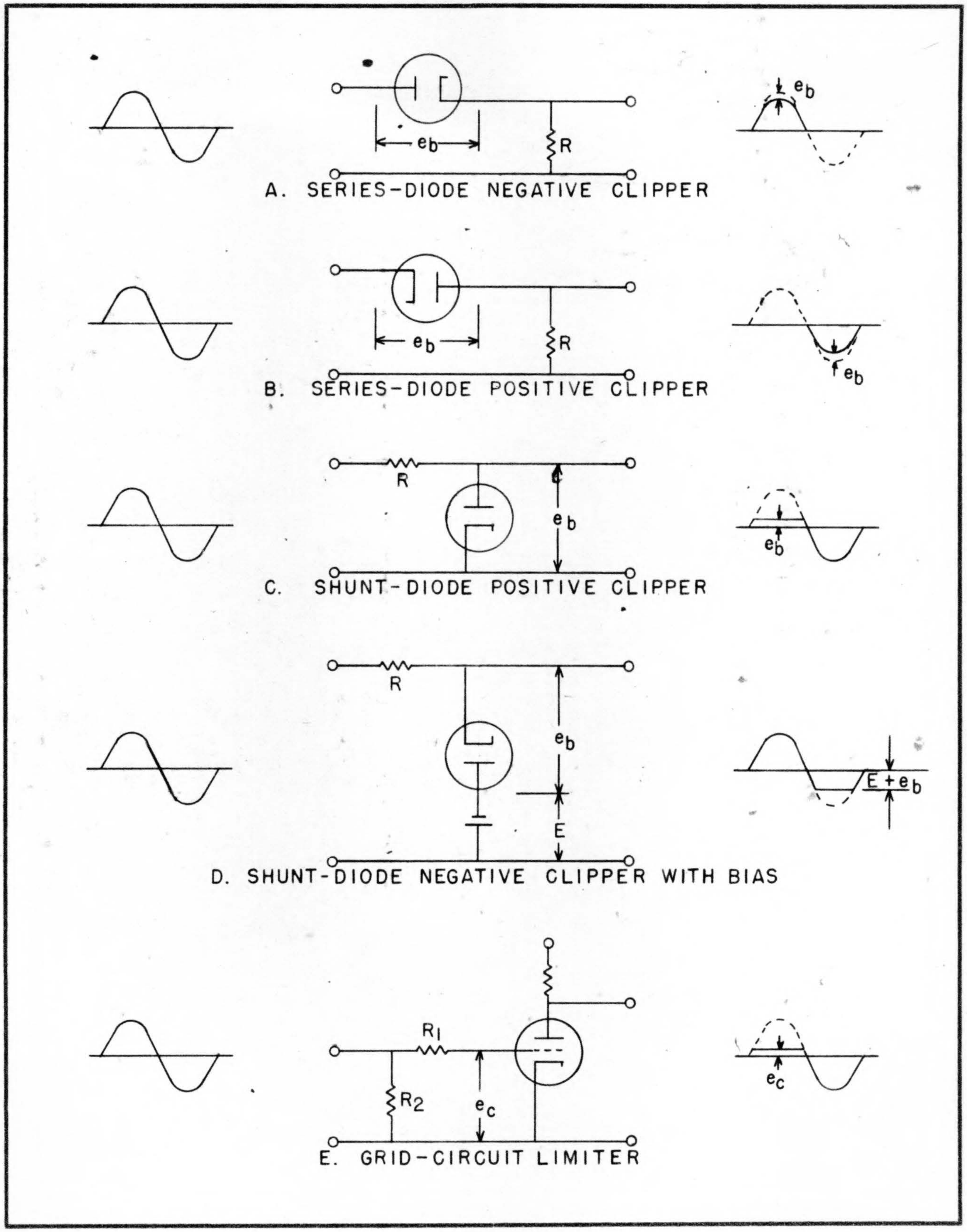

Figure 45. Clipper Circuits

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the output voltage then being equal to the tube drop, e_b. On negative swings of the input voltage, the diode acts as an open switch and has no effect on the circuit.

(5) There are two simple and useful variations of the circuit of Figure 45C. The shunt-diode can be made a negative clipper by merely reversing the diode. The other variation is the inclusion of a battery or other voltage source in series with the shunt-diode. A combination of these schemes is shown in Figure 45D where the input signal is clipped at a voltage E negative with respect to ground.

(6) Clipping, or limiting as it is usually called in this case, may be accomplished in the grid circuit of a voltage amplifier as shown in Figure 45E. The grid in this case acts precisely the same as did the plate of the diode in Figure 45C; that is, the grid draws current when it swings positive and a voltage drop appears across R_1. Clipping at different levels may be obtained with this circuit by returning R_2 to a voltage other than ground potential.

(7) Limiting may also be obtained in an amplifier by driving the grid beyond saturation, or cut-off, or both. This requires large amplitude input voltages, but may also be obtained by reducing the plate supply voltage (E_{bb}) of the tube. This shifts the load line (see Figure 34) to the left and permits saturation and cut-off to be reached with lower grid voltage swings.

C. CLAMPING CIRCUITS. (1) Because no conductive path exists whenever any assymetrical waveform is passed through a capacitor or a transformer, the average value of the waveform assumes a zero potential. This fact is a source of difficulty whenever the average value of the waveform must have some voltage other than zero. If the waveform is invariable in form and magnitude, a constant bias voltage can be applied to displace the average value from zero by the proper amount. This is known as <u>d-c restoration.</u> If, however, some dimension of the wave is changed, resort must be made to <u>clamping circuits</u> which are able to handle varying waveforms.

(2) Although several types of clamping circuits are sometimes used, only variations of the simple diode clamp shown in Figure 46 will be dis-

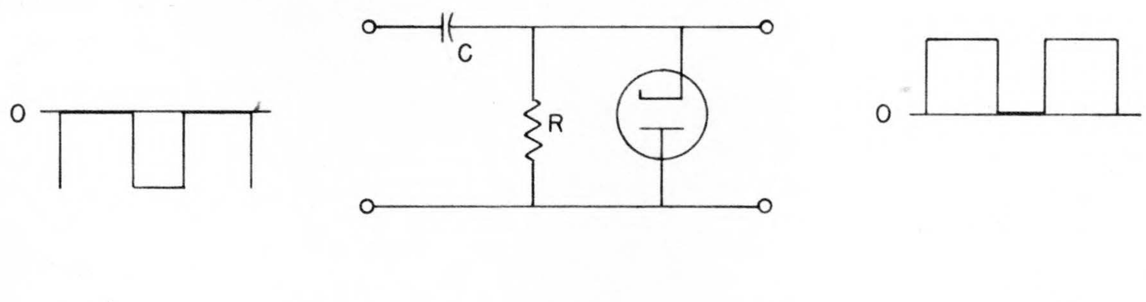

Figure 46. Positive Diode Clamping Circuit

cussed here. Figure 47 shows the input and output waveforms of a positive

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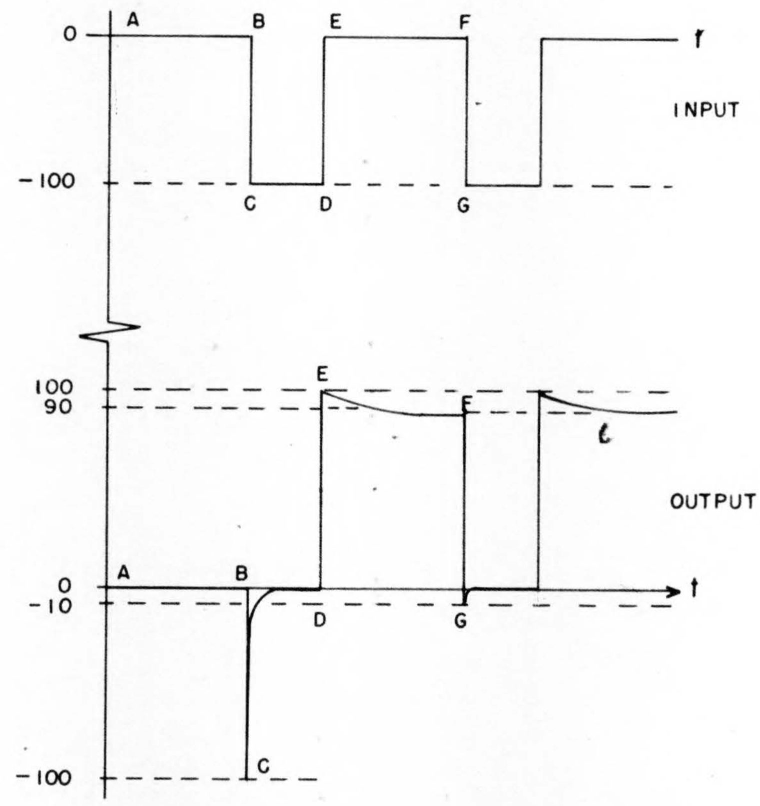

Figure 47. Waveforms in a Positive Diode Clamper

diode clamper in greater detail. During the time interval from A to B, the input voltage is zero, and the output is likewise zero. At the point B, the input voltage drops suddenly to -100 volts. Since the capacitor cannot change its charge instantaneously, the voltage across R also drops suddenly to -100 volts. The plate of the diode is now 100 volts positive with respect to its cathode and it conducts heavily. At point C the capacitor begins to charge very rapidly through the low forward resistance of the diode until the capacitor voltage equals the applied voltage and the output voltage is zero. At point D the input voltage changes back to zero, a 100 volt change in the positive direction. This change appears also in the output, and from points E to F the capacitor discharges slowly through resistor R with a long time constant; the diode does not conduct during this interval. By time F, the output has decayed only 10 volts, and therefore drops to -10 volts when the input waveform again goes 100 volts negative. The diode then conducts, quickly returning the output from -10 volts to zero; and the cycle repeats. Note that no portion of the waveform is lost after the first cycle.

(3) The clamping circuit of Figure 46 may be used to clamp the top of

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the input waveform to zero by merely reversing the diode connections. The result is a negative clamper, since the output waveform is always negative with respect to the reference voltage.

(4) It is not necessary that a clamping circuit tie one extremity of the input signal to zero potential. The resistor and diode may be returned to almost any voltage desired. Figure 48 illustrates a negative clamper with a +10 volt reference voltage.

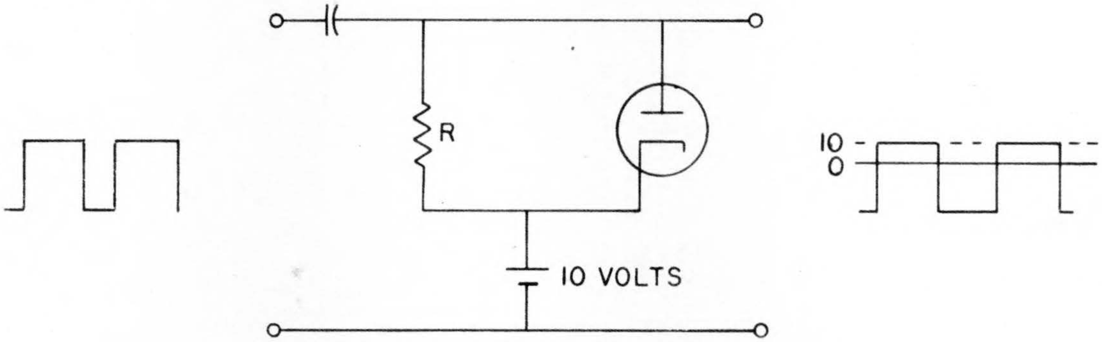

Figure 48. Negative Clamper with 10-volt Reference Level

16. MISCELLANEOUS CIRCUITS. A. CATHODE FOLLOWERS. (1) The cathode follower is a degenerative vacuum-tube circuit in which the inverse feedback is obtained by way of an unbypassed cathode resistor, across which the output is taken. This circuit is essentially an impedance-matching or impedance-lowering device having less than unity voltage gain but capable of producing power gain. Its high input impedance and very low output impedance render it particularly suitable for coupling between pulse-generating or pulse-transmitting stages and transmission lines or circuits with shunt capacitance which otherwise might cause objectionable effects. The cathode-follower output "follows" the grid-input voltage and hence is of the same polarity. The output voltage of a cathode follower has good regulation because of its low impedance while the input voltage to the cathode follower may have a high impedance and very poor regulation.

(2) The conventional cathode follower (Figure 49) is a single-stage inverse feedback circuit in which the output voltage is taken across the cathode resistor. The cathode bypass capacitor is absent and either the plate is tied directly to B+ or the plate load resistor, if present, is bypassed. Thus, if a positive signal is applied to the grid, the rise in plate current through R_k produces a greater i_bR_k drop, making the cathode more positive. Likewise, a negative signal applied to the grid causes a decrease in the i_bR_k drop, making the cathode less positive. Thus, the voltage across the cathode resistor "follows" the grid, which in effect tends to reduce the voltage difference between grid and cathode as established by the input signal.

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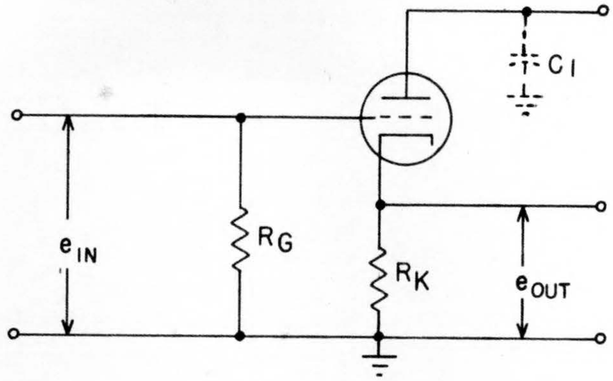

Figure 49. Conventional Cathode Follower

(3) If no signal is applied to the grid there is a certain amount of plate current flowing through R_k. The resulting $i_b R_k$ drop establishes the amount of no-signal bias developed across the resistance. Thus, the signal variation on the grid produces a plate-current variation through the cathode resistor which reduces the effectiveness of the input signal.

(4) The equivalent circuit of the cathode follower is shown in Figure 50.

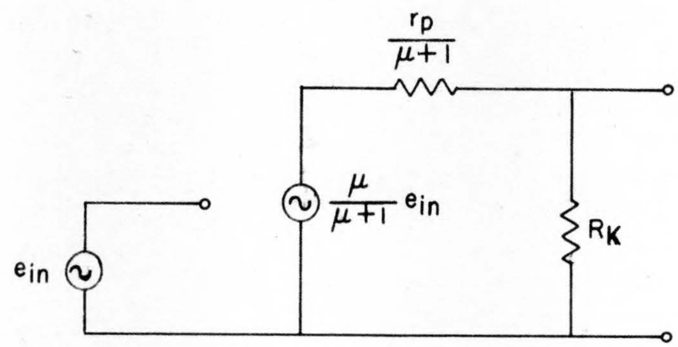

Figure 50. Equivalent Circuit of the Conventional Cathode Follower

Comparison with Figure 36 indicates that the stage acts as a conventional amplifier in which both amplification factor (μ) and plate resistances (r_p) have been divided by the factor ($\mu + 1$). As a result, the gain of the cathode follower is always less than unity.

(5) The output voltage of the cathode follower is essentially distortionless when operated within its normal range. However, if the input voltage is of sufficiently high amplitude, limiting action occurs and the output voltage is distorted with respect to the input.

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In order to accommodate negative signals of higher amplitude on the grid without the effects of cut-off limiting, the cathode follower may be modified as shown in Figure 51. The bias is reduced because the grid resistor

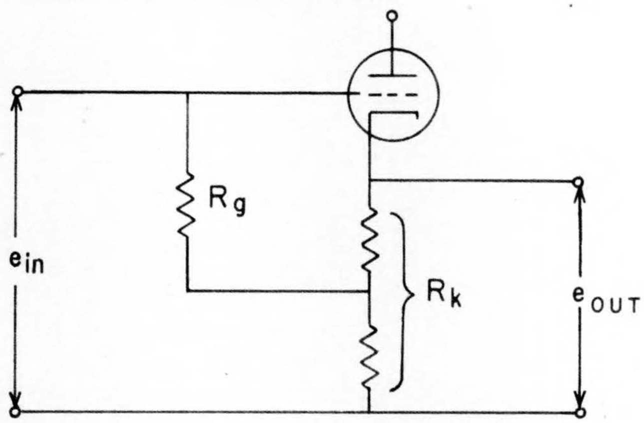

Figure 51. Cathode Follower with Reduced Grid Bias Voltage

R_g is terminated at a more positive point on R_k, therefore e_{in} can swing to a greater negative value without cutting off the tube. Otherwise the operation of the circuit is essentially the same as that of the cathode follower illustrated in Figure 49.

B. GATES. (1) The circuits in computers often handle long series of identical pulses some of which must be blocked and others allowed to pass through. Circuits which are designed to stop or pass pulses are appropriately called gates.

(2) A typical pentode gate circuit is shown in Figure 52 with the important waveforms. The suppressor grid is normally made sufficiently negative

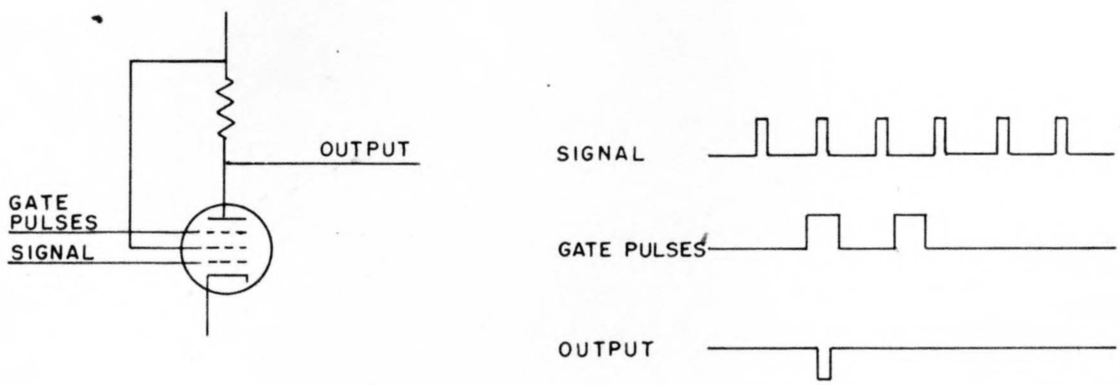

Figure 52. Pentode Gate Circuit

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with respect to the cathode to keep the plate current cut off in spite of signal pulses on the control grid. The circuit is "gated" at the desired time by applying a positive pulse to the suppressor; if a signal pulse is simultaneously present on the control grid, it will appear in the output; if no signal pulse is simultaneously present, the gating pulse will have no effect on the output.

(3) Two triodes may be used to form a gate circuit as shown in Figure 53.

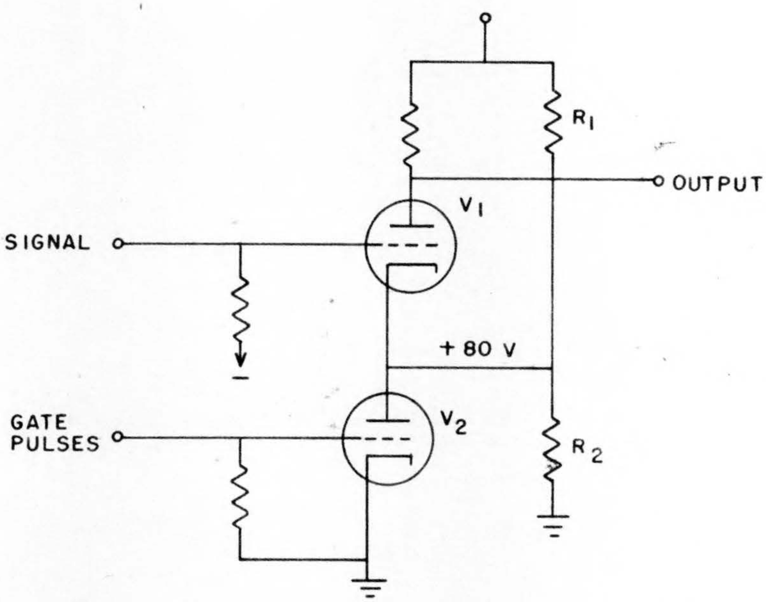

Figure 53. Triode Gating Circuit

V_1 is a triode voltage amplifier with the gate tube (V_2) in series with its cathode. R_1 and R_2 are so proportioned that the cathode of V_1 is highly positive with respect to its grid with no signal input to either tube. V_1 is thus normally cut off, and no signal pulses can pass through to the output. When V_2 is gated by a large positive pulse, it conducts heavily and lowers the voltage at its plate (and the cathode of V_1) to a low positive value. This permits V_1 to pass a signal pulse if one arrives during the gating interval. The waveforms shown in Figure 52 apply also to the circuit of Figure 53.

C. TRIGGER CIRCUITS AND MULTIVIBRATORS. (1) There are a large number of closely related circuits based upon the Eccles-Jordan trigger circuit and the Abraham-Bloch multivibrator. In general, they are made up of two voltage amplifiers that are coupled together in various ways. They may be designed to have one or two stable states or to be unstable (oscillatory).

(2) The Eccles-Jordan trigger circuit is shown in Figure 54. It employs direct coupling from the plate of one tube to the grid of the other. Trigger circuits of this type are often called flip-flops because they have two stable states: when V_1 is conducting and V_2 is cut off, and vice versa. Transfer

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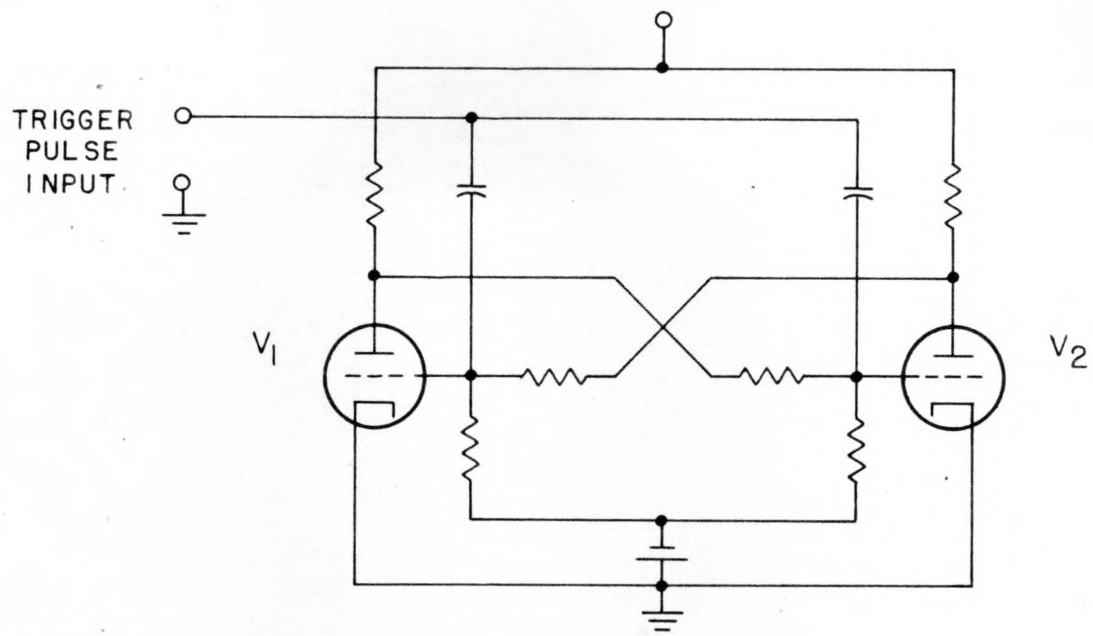

Figure 54. Eccles-Jordan Trigger Circuit

from one stable state to the other may be initiated by applying either a positive or negative pulse to both grids. Suppose that V_1 is conducting and V_2 is cut off. If a positive pulse is applied to both grids, it will have little effect on V_1 but will cause conduction to start in V_2. Conduction in V_2 causes its plate voltage to drop slightly and this drop is transmitted to the grid of V_1 which conducts less heavily as a result. The plate voltage of V_1 therefore rises slightly and this rise is transferred to the grid of V_2 causing a further increase in its plate current. The action is therefore cumulative and continues until V_2 is conducting and V_1 is cut off. It should be noted that the reversing action just described occurs so rapidly that it is almost instantaneous. Negative pulses may also be used to trigger the circuit in which case the action starts with a reduction of plate current in the conducting tube. The output may be taken from the plate of either tube.

(3) A practical refinement of the Eccles-Jordan circuit is shown in Figure 55; capacitors have been shunted across the resistors that couple between the plate of one tube and the grid of the other. These capacitors are often about 50 $\mu\mu$f and are used to increase the speed and reliability of triggering. The capacitors perform two important functions: (a) they overcome the effect of tube interelectrode capacitances which tend to resist any rapid change in tube voltages, and (b) they transfer the entire initial plate voltage change of one tube to the grid of the other tube and thus overcome the voltage divider action of the coupling and grid resistors.

(4) The circuit of the Abraham-Bloch multivibrator (Figure 56) is very similar to the trigger circuits just discussed. It is evident that this is simply a two stage resistance-capacitance coupled amplifier with the output of

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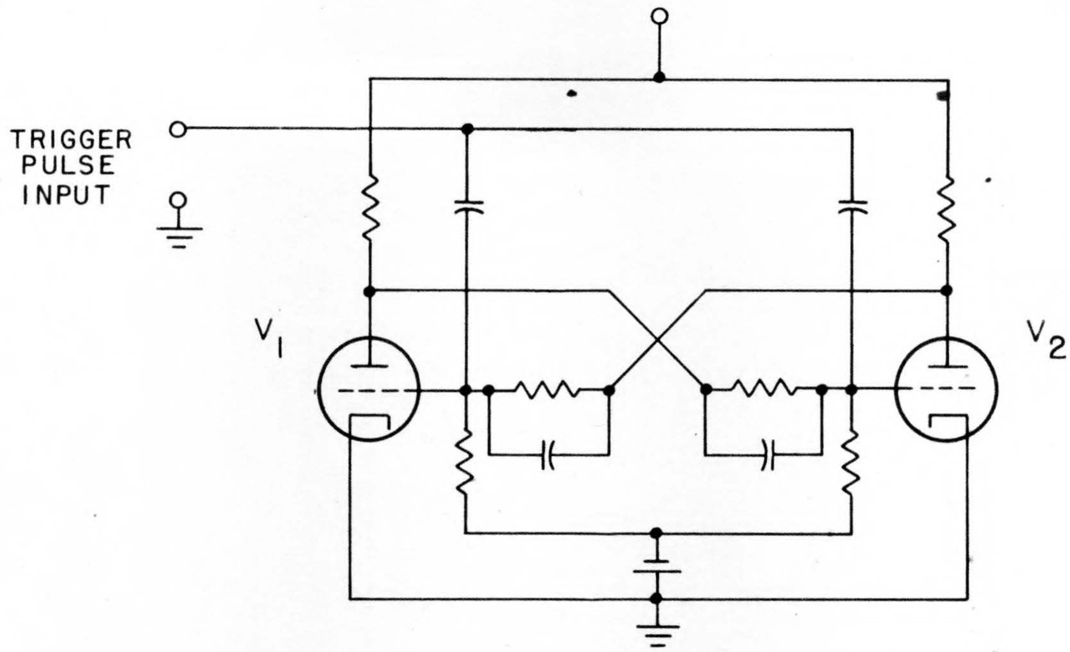

Figure 55. Practical Trigger Circuit

the second stage coupled back to the input of the first, and for this reason it is commonly called a plate-coupled multivibrator. Since the output of the

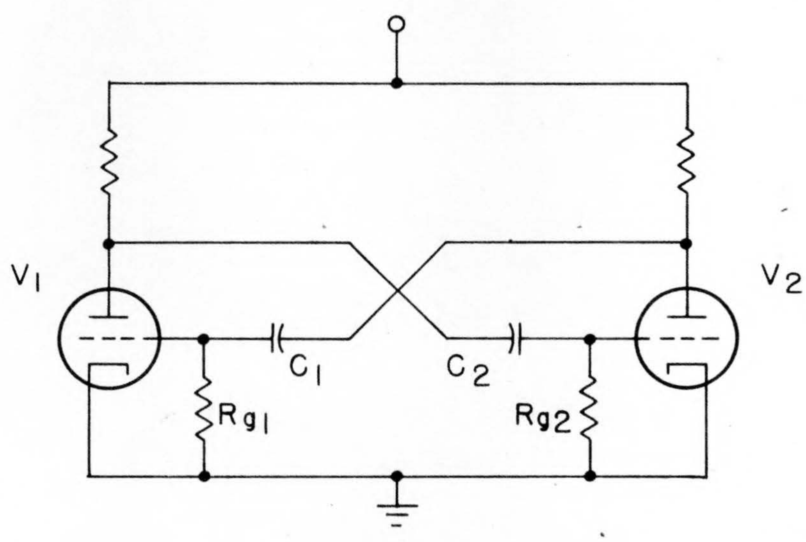

Figure 56. Free-Running Plate-Coupled Multtvibrator

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second stage has the same phase as the input to the first, oscillations can take place. The operation of the circuit is similar to that of the trigger circuits but no stable state exists. When the plate current in one of the tubes, say V_1, is increasing because of a positive-going signal on the grid, a negative signal is being applied to the grid of the second tube V_2. As a result, the current in V_2 is reduced, and the output signal is positive. This positive signal, which is coupled back to V_1, causes the grid of V_1 to become more positive, thus increasing the anode current of V_1 still further. This effect is cumulative - the current in V_1 reaches a maximum, while the potential of the grid of V_2 is driven so far negatively, almost instantaneously, that the current in V_2 is cut off. With V_2 still cut off, the charge on capacitor C_2 leaks away through the resistor R_{g2}, and at some point the potential of the grid of V_2 becomes such that the tube will again begin to conduct. This results in a negative output signal being applied to the grid of V_1. The current in V_1 decreases, and the start of a cumulative chain, which results in V_1 being cut off and V_2 reaching the state of maximum conduction, is initiated. Evidently there are two unstable limiting conditions that occur. In one of these V_1 is cut off and V_2 is fully conducting, and in the other the roles of V_1 and V_2 are interchanged. The waveform on one plate of a symmetrical free-running multivibrator is shown in Figure 57; the waveform on the other

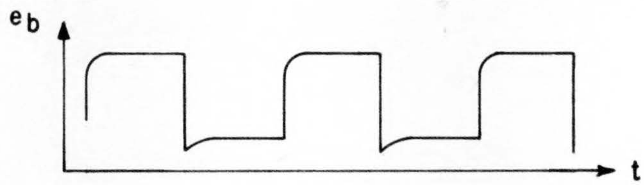

Figure 57. Plate Voltage in a Free-Running Multivibrator

plate is identical in shape but displaced in phase by 180°. The frequency of multivibrators is often controlled very accurately by applying trigger pulses to one of the grids in order to initiate the switching action.

(5) The circuit of a cathode-coupled delay multivibrator is shown in Figure 58. This type of circuit generates a single positive rectangular pulse for each trigger pulse applied to its input. V_2 is normally conducting and its plate current flowing through R_k biases V_1 to cut-off. When a positive trigger pulse is applied to the grid of V_1, it begins to conduct which drops both its plate voltage and the grid-to-cathode voltage of V_2 (because of capacitor C and the increased voltage drop across R_k). The output voltage then rises sharply. V_2 remains cut off while the capacitor discharges through R and permits the grid voltage of V_2 to approach cut-off bias. At the instant the

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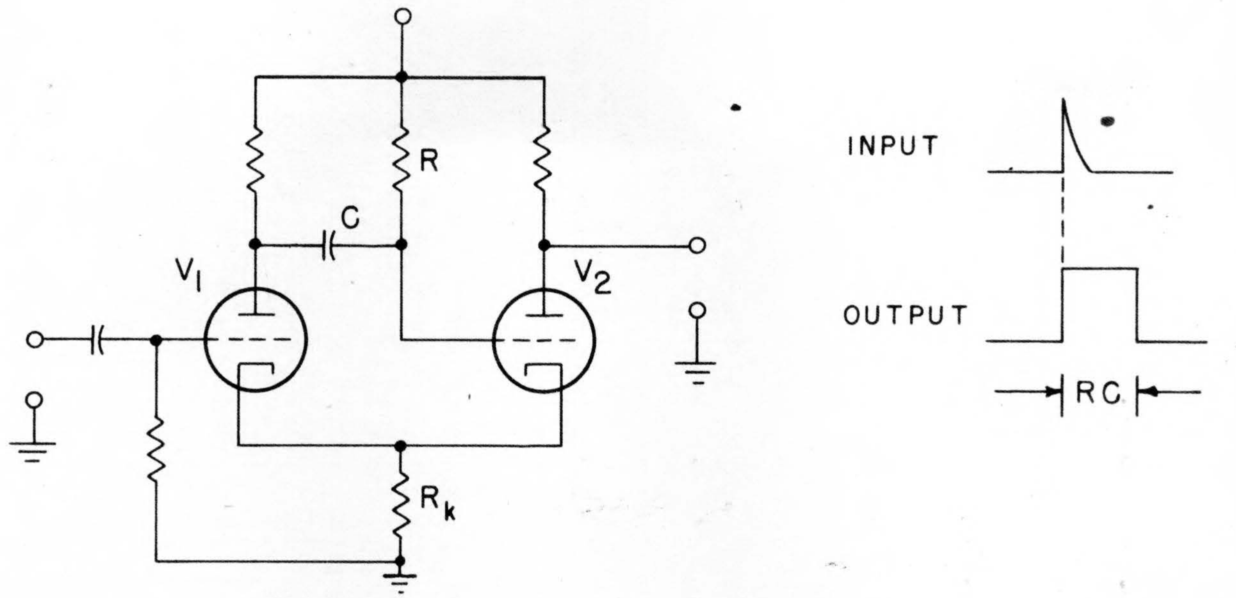

Figure 58. Cathode Coupled Delay Multivibrator

grid of V_2 reaches cut-off bias, conduction begins and the plate voltage of V_2 drops while the cathode voltage increases. The rise in voltage across R_k reduces the plate current in V_1 and raises the plate voltage of V_1 (and therefore the grid voltage of V_2). In practice, V_1 becomes cut off almost instantaneously after the grid of V_2 reaches cut-off. The time duration of the output pulse is governed by the discharge of capacitor C through resistor R, the pulse length being equal to about one-half the RC time constant. R is usually about one megohm and C is chosen as required.

D. COUNTERS. (1) A counting circuit is designed to receive uniform pulses, representing units to be counted, and to produce a voltage proportional to the number of pulses received. Over a given time, therefore, it will give a measure of the average pulse repetition rate.

(2) The pulses applied to a counting circuit must be of the same amplitude and time duration if the circuit is to function properly. Thus counting circuits are ordinarily preceded by shaping and limiting circuits to insure the necessary uniformity.

(3) Although other counting circuits exist, the step-by-step counter shown in Figure 59 is the only one that will be discussed here. When a positive pulse is applied to the input, V_2 conducts and charges both C_1 and C_2. C_1, which is much smaller than C_2, takes on a larger charge with each input pulse; but at the end of each pulse, the charge on C_1 is discharged through V_1. The charge on C_2 is increased slightly during the time of each input pulse, producing a step voltage across the output. These steps decrease in

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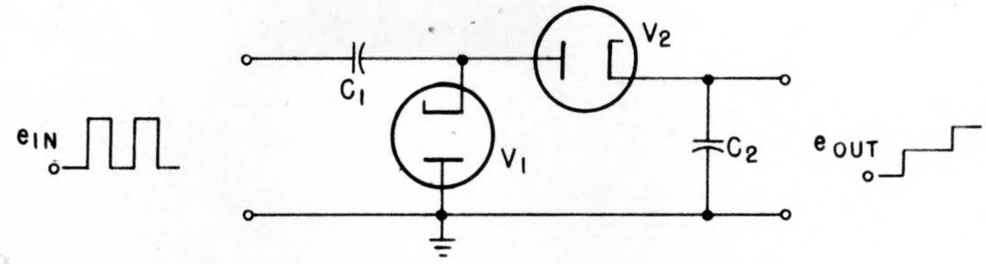

Figure 59. Step-by-step Counting Circuit

size exponentially as the voltage across C_2 approaches the final value (Figure 60), the rate being dependent upon the output impedance of the driving

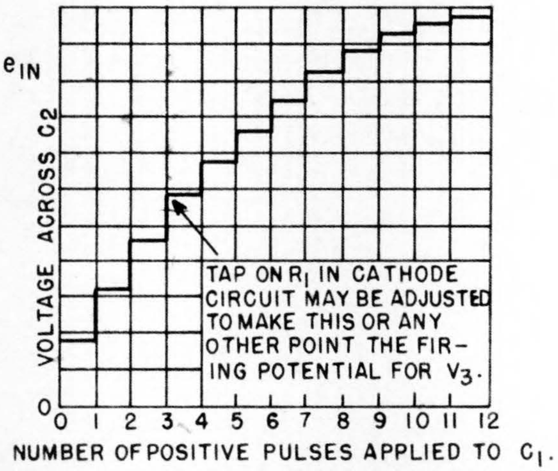

Figure 60. Step Voltage Developed Across C_2

circuit. As long as there is no path through which C_2 can discharge, the voltage across it continues to increase with each successive pulse until it is equal to the amplitude of the applied signals. At this point the cathode of V_2 is held at a positive voltage equal to that on the plate during the pulse time and the tube fails to conduct.

(4) The output of a step-by-step counter is generally fed to the grid of a following tube circuit, perhaps a blocking oscillator or thyratron.

E. PHANTASTRONS. (1) The phantastron circuit is a device used to control the opening of a gate for a precise duration of time. It is often referred to as a "one-shot" circuit. The time delay produced by a phantastron is a linear function of the control voltage.

(2) When the phantastron is not operating (see Figure 61), the plate current is cut off by the negative potential of the suppressor grid, and the control

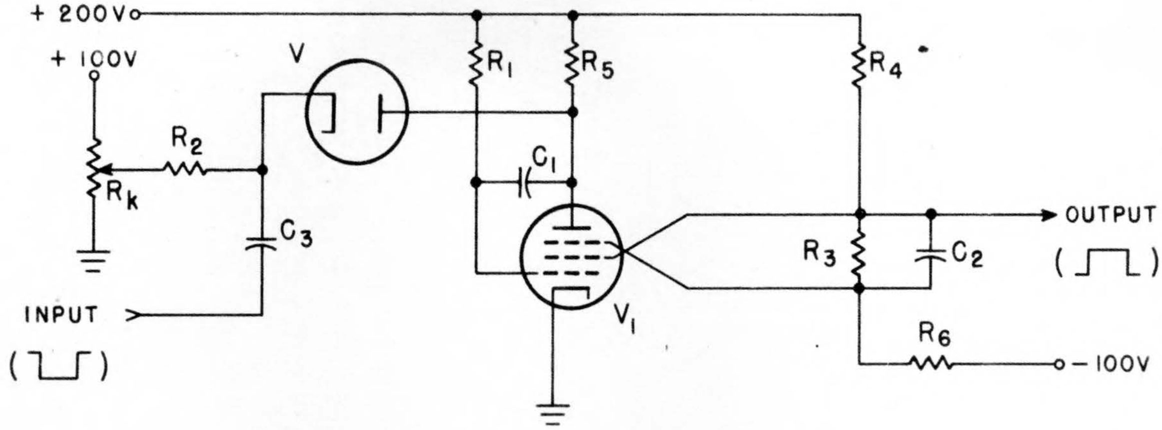

Figure 61. Schematic of Phantastron Circuit

grid is slightly positive because of the positive grid return and the grid current through the large resistor R_1. The screen, therefore, conducts all of the space current keeping the output potential low.

(3) When a negative input pulse is applied to the diode V, its cathode voltage drops, causing the diode current to increase and reduce the plate potential of V_1. This change of plate potential is reflected to the control grid of V_1 through the coupling capacitor C_1, reducing the total space current and consequently increasing the output potential. This increase in output potential will be reflected through C_2, increasing the suppressor grid potential which will in turn cause the plate to conduct.

(4) As the plate begins to conduct, its potential will decrease and in turn be reflected over to the control grid through C_1, making the control grid more negative and reducing the total space current. This reduction in space current is in opposition to the increase in plate current flow, thus limiting the rate at which the plate current builds up.

(5) The plate current will increase until the plate potential is of such a low value that the screen grid will again conduct. This will decrease the potential on the suppressor grid which will then cut off the plate current. When the plate current goes to zero, the control grid voltage will also drop to zero, according to the time constant R_1C_1.

(6) The phantastron output voltage drops because of the increase of screen current. The duration of the pulse on the output voltage is thus determined by the R_1C_1 time constant, and the setting of the potentiometer R_k determines the non-operating potential of the plate.

F. DELAY LINES. (1) It is often necessary in computer equipments to have a pulse which occurs at some definite time following another pulse. The multivibrators that have been described are one means of obtaining this

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result; another means, and one that is more accurate for very short delays, is by the use of delay lines.

(2) Figure 62 shows a ten-section artificial transmission or delay line. Lines may contain any number of sections and may be built of T, π , or L sections. A pulse is applied to the input end of the line and it is desired that the pulse travel along the line just as it might along a real line. By properly adjusting the electrical length of the line, the time required for the pulse to traverse the line may be made equal to a required delay time.

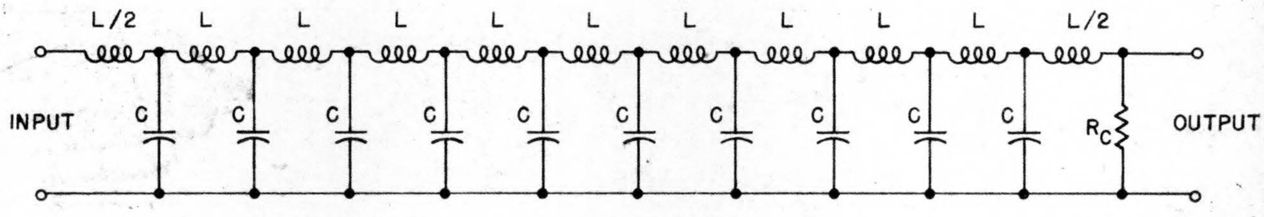

Figure 62. A Ten-Section Delay Line

(3) An artificial line operates in the same manner as a real line provided the inductance L and capacitance C in each section are small so that the wave-length of the highest- frequency Fourier component of the pulse spans enough sections to make the line behave as though its inductance and capacitance were distributed. A cut-off frequency, f_{co}, exists, which is given by

$$f_{co} = \frac{1}{\pi\sqrt{LC}} \tag{143}$$

Above the cut-off frequency, negligible transmission occurs. Below it the pulses are transmitted, but unless the Fourier components are all of low frequency compared with f_{co} the delay and characteristic resistance of the line depend upon frequency. For all frequencies much smaller than f_{co} the characteristic resistance is

$$R = \sqrt{\frac{L}{C}} \tag{144}$$

and the delay is

$$\text{Delay per section} = \sqrt{LC} \tag{145}$$

These relations are the same as the corresponding ones for a real transmission line.

(4) Delay lines in timers are constructed with small L and C in each section so that f_{co} is much higher than the highest frequency to be transmitted. The number of sections is chosen to produce the required delay, and the line

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is terminated in the characteristic resistance so that no reflections occur at the end. The pulses travel from input to output but do not return.

(5) A variable delay may be had by connecting a multipoint switch to the various junctions between sections of the line. A circuit connected to this switch receives a pulse delayed by an amount dependent on the setting of the switch. The impedance of the circuit should be much greater than the characteristic resistance of the line in order that negligible reflections occur at the point of connection.

(6) Since the line is terminated in its characteristic resistance, its input impedance is also the characteristic resistance. Thus the input of the line may be used in place of the plate load resistor for a vacuum tube. The operation of the tube is the same as it would be if its load were a resistor R_c.

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SECTION VI

POWER SUPPLY CIRCUITS

17. RECTIFIER CIRCUITS. A. GENERAL. (1) A rectifier is a device by means of which an alternating current is changed into a direct current. In general, the magnitude of this direct current is not constant, as it may contain a pulsating component called ripple. A few of the devices which perform this rectifying function are electronic tubes, metallic-oxide (or dry contact) rectifiers, crystal rectifiers, electrolytic rectifiers, and mechanical rectifiers. Of these, electronic rectifier tubes are by far the most important.

(2) The operation of most electronic circuits requires that a direct voltage be applied to the plate and screen-grid circuits of tubes. This d-c supply may be obtained from batteries if the total amount of power required is not large. If more power is needed than can be supplied conveniently from batteries, a d-c generator may be used. However, most electrical energy now is generated as alternating current, which must be rectified for use in electronic circuits. Electronic rectifiers, which are capable of rectifying very large amounts of power, can supply direct current to even the largest of electronic equipments.

(3) There are two general types of electronic rectifiers. The first type, the high-vacuum or "hard" tube rectifier, is used where a small or moderate current is needed or where very high voltage must be rectified. The second type, the gas or vapor-filled or "soft" tube rectifier, is used where a large current is required.

B. HALF-WAVE RECTIFIER. (1) A half-wave rectifier is a device by means of which alternating current is changed into pulsating direct current by eliminating one-half of each cycle.

(2) In a diode, electrons are attracted to the plate when it is more positive than the cathode. When the plate becomes negative relative to the cathode, electrons are repelled by it and no electron current can flow in the tube. A single diode may thus be used as a half-wave rectifier because a current can flow in the tube during only that half of the cycle when the plate is positive relative to the cathode.

(3) Figure 63 shows two simple half-wave rectifier circuits. In (a), an

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alternating voltage supplied by a 115-volt a-c line is applied across the diode and the load resistor R, which is used to limit the current in the tube during the period of conduction. In (b), a transformer is added to increase the voltage applied to the tube. By selecting a transformer with the proper ratio, a very wide range of voltages can be obtained from a rectifier.

(4) On the positive half-cycle of the applied voltage, the plate of the diode is more positive than the cathode, and current flows through the diode from plate to cathode and then through the load resistor to ground. As the plate of the diode becomes more positive, the current increases until the maximum value of the positive half-cycle is reached. As the voltage decreases, the current also decreases until at zero voltage between plate and

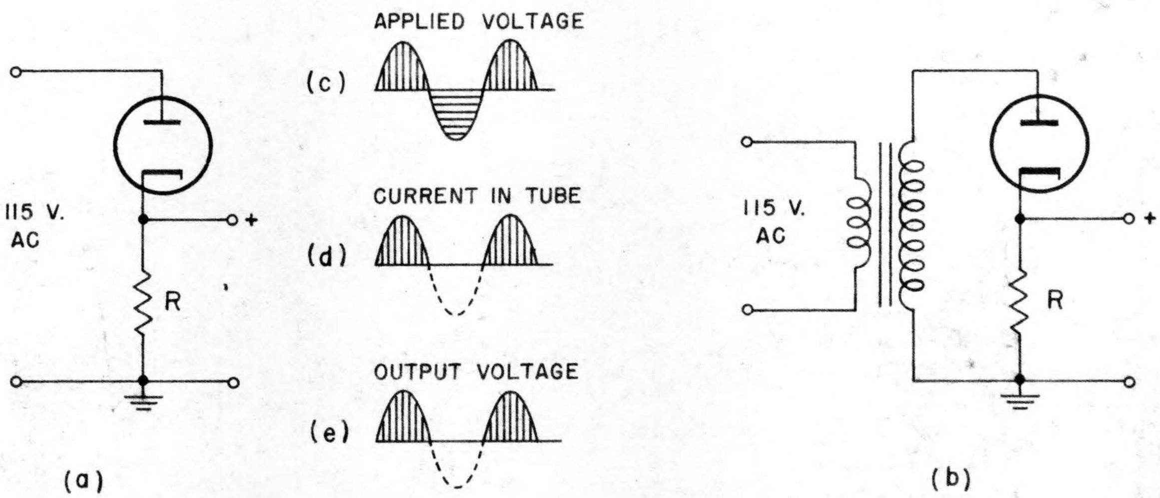

Figure 63. Simple Half-Wave Rectifier Circuits

cathode, conduction ceases entirely. No current can flow during the negative half-cycle. Thus there is a positive pulse of voltage across the load resistor, R, for every cycle of the applied voltage.

(5) Since the current flow in the diode and in the load resistor is always in one direction, the applied a-c voltage, (c), is changed into a pulsating d-c voltage. The waveform of the current in the diode is shown at (d) in Figure 63, and the load voltage at (e).

(6) Because the half-wave rectifier uses only one-half the input wave its efficiency is low, and the direct-voltage output is small if a current in excess of a few milliamperes is required by the load. These disadvantages limit the use of the half-wave rectifier to applications which require a very small current drain. A common application of the half-wave rectifier is for the accelerating voltage supply anode of an oscilloscope.

C. FULL-WAVE RECTIFIER. (1) A full-wave rectifier is a device which has two or more elements so arranged that the current output flows in the same

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direction during each half-cycle of the alternating-current supply.

(2) Full-wave rectification may be accomplished by using two diodes connected as in Figure 64(a). The cathodes of the two diodes are tied together, and the junction is tied to one end of the load resistor. The other end of the resistor is tied to the center-tap C of the transformer secondary. The two halves of the secondary winding, AC and BC, may be a center-tapped winding as shown, or may be separate windings. Some way must always be provided to connect the load to a point midway in potential between A and B.

(3) The part AC of the secondary winding may be considered a voltage source which produces a voltage of the shape shown in Figure 64(b). This voltage is impressed on the tube V_1 and the load resistor R in series. During the half-cycle marked t_1 the plate of V_1 is positive relative to its cathode. Therefore, a current flows in the direction shown by the solid arrows. This current causes a voltage drop across R such that the upper end of R is more positive than the lower end. During this same half-cycle the voltage across BC makes the plate of V_2 negative relative to its cathode, as in (c), and this tube is nonconducting. A half-cycle later, at t_2, the voltages on the plates of the two tubes are reversed. V_2 now is conducting and V_1 nonconducting. The

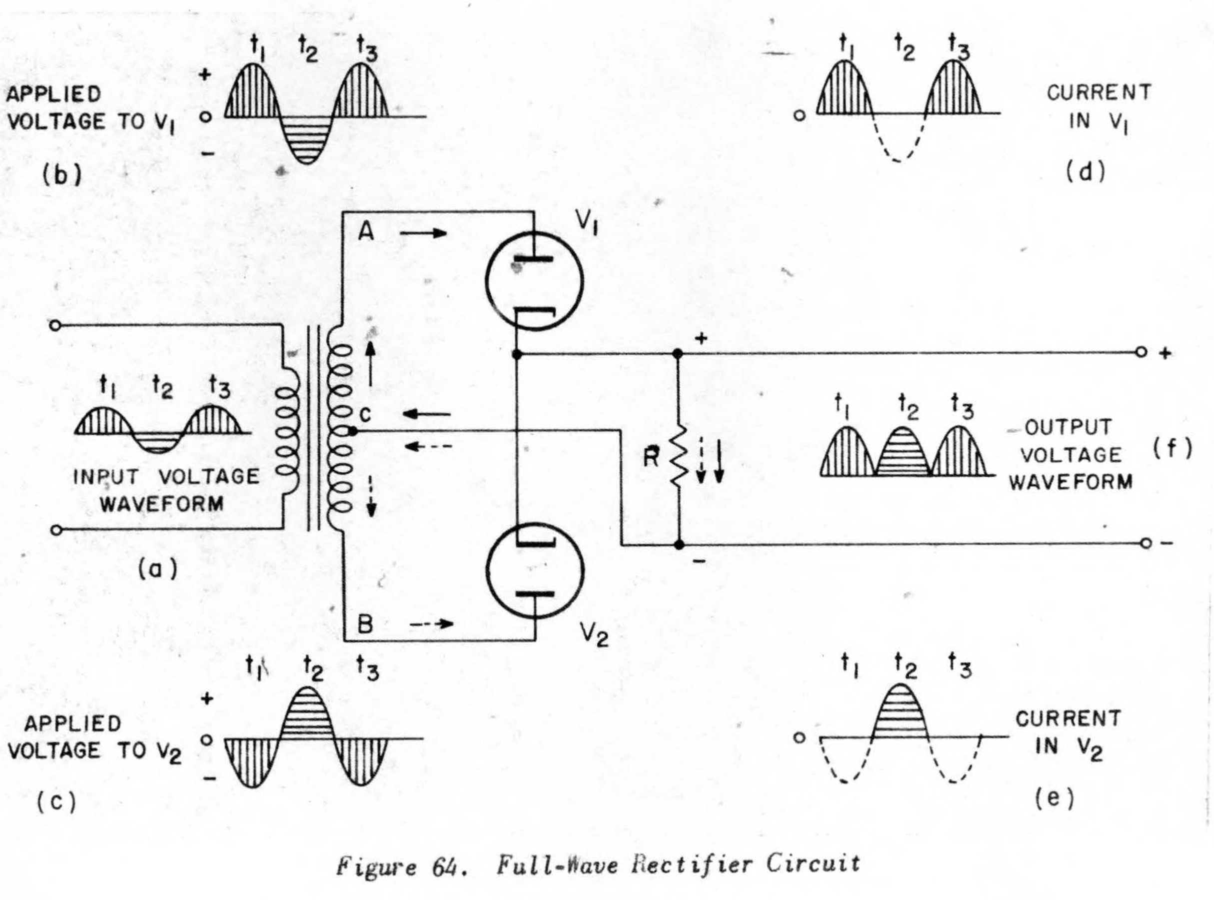

Figure 64. Full-Wave Rectifier Circuit

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current which passes through V_2 flows in the direction indicated by the dotted arrows. This current also produces a positive pulse of voltage across the load resistor, as at t_2 in (f). A comparison of (d) with (e) shows that only one tube is conducting at any given instant. The electron current contributed by V_2 flows through the external circuit R in the same direction as the electron current contributed by V_1.

(4) Since there are two pulsations of current in the output for each cycle of the applied alternating current, the full-wave rectifier is more efficient than the half-wave rectifier, has less ripple effect, and may be used for a much wider variety of applications.

D. BRIDGE RECTIFIER. (1) If four rectifiers are connected as shown in Figure 65(a), the circuit is called a <u>bridge rectifier</u>. The input to such a circuit is applied to diagonally opposite corners of the network, and the output is taken from the remaining two corners.

(2) During the first half-cycle of the applied alternating voltage (Figure 65(b)), point A is positive with respect to point B. During this interval the voltage across AB may be considered to be impressed across a load

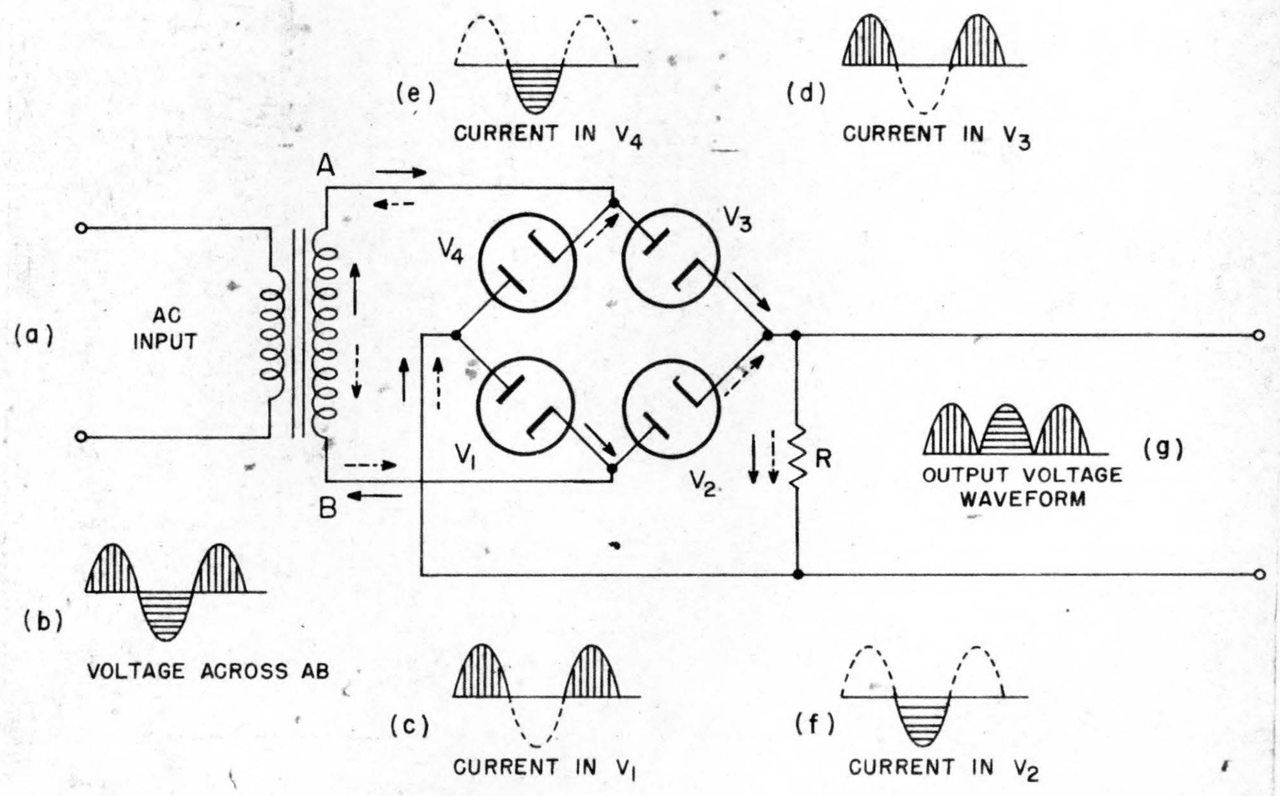

Figure 65. Bridge-Rectifier Circuit

consisting of V_3, load resistor R, and V_1 in series. The voltage applied across these tubes makes their plates more positive than their cathodes, and a current flows in the path indicated by the solid arrows. The waveform of this current is shown in (c) and (d). One-half cycle later, V_1 and V_3 are nonconducting, and a current (Figure 65(e) and (f)) flows through tubes V_2 and V_4 and the load resistor in the direction indicated by the dotted arrows. The current through the external load R is always in the same direction. This current in flowing through R develops a voltage of the type shown in (g). The bridge rectifier is a full-wave rectifier since current flows in the load during both halves of a cycle of the applied alternating current.

(3) One advantage of a bridge rectifier over a conventional full-wave rectifier is that with a given transformer the bridge circuit produces a voltage output nearly twice that of the full-wave circuit. This may be shown by assigning values to some of the components in Figures 64 and 65. Assume that the same transformer is used in both figures and that the peak voltage developed between A and B is 1,000 volts. In the full-wave circuit in Figure 64, the peak voltage from the center tap C to either A or B is 500 volts. Since either V_1 or V_2 is conducting at any instant, the maximum voltage that can be rectified at any instant is 500 volts. Therefore, the maximum voltage that can be developed across the load resistor R is 500 volts, less the small voltage drop across the tube which is conducting. In the bridge circuit in Figure 65, however, the maximum voltage that can be rectified is the full voltage of the secondary of the transformer, or 1,000 volts. Therefore, the voltage than can be developed across the load resistor R is 1,000 volts less the voltage drop across the two tubes which are conducting. Thus the full-wave bridge circuit produces a higher output voltage than the conventional full-wave rectifier does with the same transformer.

(4) A second advantage of the bridge circuit is that the <u>inverse voltage</u> across each tube is half the inverse voltage impressed on a tube in a conventional full-wave rectifier which is designed for the same output voltage. For example, if the two circuits are to produce the same output voltage, the transformer secondary in the full-wave rectifier (Figure 64) has to have a 2,000-volt peak developed across it, while that for the bridge rectifier (Figure 65) has only a 1,000-volt peak. When V_1 in Figure 64 is not conducting, its plate is made negative relative to its cathode by a maximum voltage of 1,000 volts. This negative voltage is called the <u>inverse peak voltage</u>, which is a stress that tends to cause breakdown within the tube. In Figure 65, however, when the tubes V_1 and V_2 are not conducting, the maximum inverse voltage applied to the two tubes in series is 1,000 volts. The inverse peak voltage for any one tube is then 500 volts, which is half of the inverse voltage across either tube in Figure 64.

(5) Vacuum tubes are not used as widely in bridge-rectifier circuits as they are in other types of rectifier circuits because of the greater number of tubes required and because three separate filament transformer windings are needed. The filaments of V_2 and V_3 in Figure 65 are at the same potential, but the filament of V_1 is at a different potential from either V_4 or V_2. The

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three filament transformers must be well insulated from each other and from ground because of the high potentials to which they are subjected.

E. METALLIC-OXIDE RECTIFIERS. (1) Certain combinations of thin films of metals permit electrons to flow more readily in one direction than in the other. At least two combinations show this characteristic sufficiently well to warrant their commercial production for use as rectifiers. One combination is a thin film of copper oxide on a copper plate. The other is an especially prepared film of selenium on a metallic surface such as iron. These metallic-oxide rectifiers generally are represented by the symbol shown in Figure 66. The triangular part of the figure may be considered to be an arrowhead which points in the direction in which current may pass through the rectifier most easily. In the copper-oxide rectifier, current can pass from the copper-oxide to the copper much more easily than in the opposite direction.

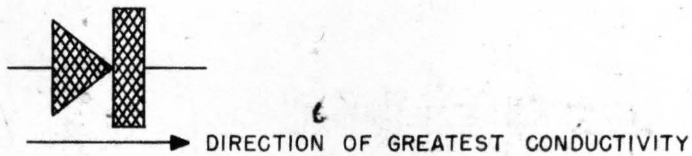

Figure 66. Metallic-Oxide Rectifier - Schematic Representation

(2) Figure 67(a) shows a half-wave rectifier in which a metallic-oxide rectifier is used instead of a vacuum tube. Current flows freely from the copper-oxide to the copper when the former is more positive than the latter (at times t_1 and t_3 in (b)). At time t_2, when the copper is positive relative to the copper-oxide, a very small current flows, as indicated in (c). The voltage output of this circuit is shown in (d).

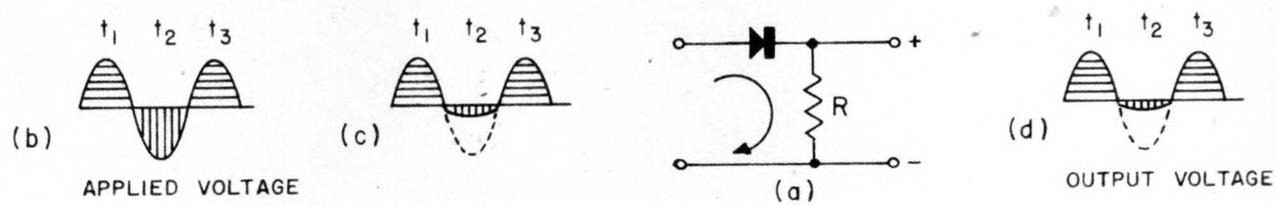

Figure 67. Half-Wave Copper-Oxide Rectifier

(3) Because the copper-oxide film is thin, the copper-oxide rectifier cannot withstand a very large voltage. Where moderate voltages must be used, several layers of copper and copper-oxide are built up into a stack. A washer of soft metal, generally lead, is placed between the elements to provide uniform pressure between the copper and the copper-oxide. Because of the low inverse voltage which causes breakdown, the copper-oxide rectifier is not often used in the half-wave circuit shown in Figure 67.

(4) Since a bridge-rectifier has a relatively low inverse-peak voltage

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across each rectifying element, this circuit (Figure 68(a)) generally is used with copper-oxide and selenium rectifiers. When the point A is positive relative to point B, sections 1 and 3 conduct, as shown by the solid arrows. A half-cycle later, when B is positive with respect to A, sections 2 and 4 conduct, as shown by the dotted arrows. The current in R is always in the same direction. Figure 68 (b) shows how the same circuit generally appears physically.

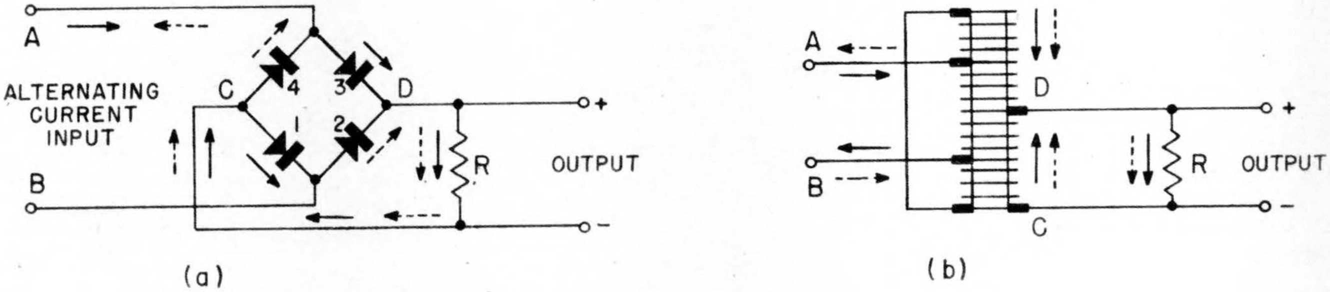

Figure 68. Copper-Oxide Full-Wave Rectifier

(5) A transformer seldom is used to raise the voltage applied to a copper-oxide rectifier because of the low inverse-peak voltage rating. The bridge circuit is especially advantageous in this case because it eliminates the need for a transformer to provide a center tap for full wave rectification, and because it reduces the inverse-peak voltage.

(6) This type of rectifier is particularly suitable for supplying a relatively large direct-current because the rings of copper and copper-oxide may be made large in area, and cooling fins may be employed easily with the stack of washers. The resistance of the selenium rectifier in the forward or conducting direction is less than that of the copper-oxide rectifiers. For this reason, the selenium rectifier is somewhat more efficient and can pass a greater current than can a copper-oxide rectifier of similar size. The metallic-oxide rectifiers are used to run small d-c motors, to operate relays, to supply bias, and to charge storage batteries.

F. VOLTAGE DOUBLER. (1) A voltage doubler is a circuit in which two capacitors are charged on alternate half-cycles and are so arranged that the voltages on the two capacitors add in the output. Such a circuit is capable of delivering at the output a voltage which is twice the peak voltage of the applied alternating voltage.

(2) The conventional voltage doubler is shown in Figure 69(a). When point A on the transformer secondary is more positive than point B, a voltage is impressed across the tube V_1 in series with capacitor C_1. Since the plate of V_1 is more positive than its cathode, current flows around the circuit as shown by the solid arrow. Capacitor C_1 is charged with polarity shown to a voltage equal to the peak voltage of the input sine wave. During the next half-cycle, since V_1 does not conduct, and C_1 discharges slightly.

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Meanwhile, capacitor C_2 is being charged by the current which flows through V_2 . This current flows in the direction shown by the dotted arrow. The output voltage is taken between point C and ground and therefore is equal to the sum of the voltages on C_1 and C_2 which is twice the peak voltage developed across the transformer secondary.

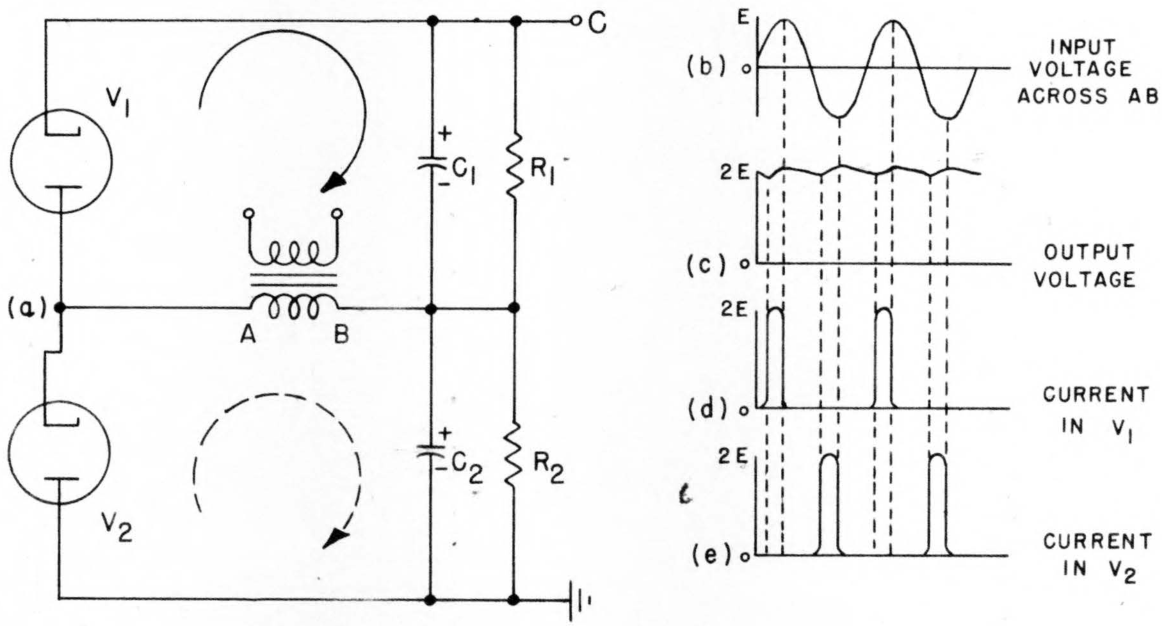

Figure 69. Conventional Voltage Doubler

(3) The waveforms of the input and output voltages are shown in Figure 69 (b) and (c). Since a current flows in V_1 only when the voltage across the transformer is greater than the voltage across C_1 , Figure 69 (d) shows that current flows for only a very short time in each cycle. This current begins to flow when the input sine wave rises above the voltage on the capacitor and stops flowing as soon as the sine wave begins to fall away from its peak voltage. Similarly, Figure 69 (e) shows that tube V_2 conducts during the half-cycles in which V_1 is nonconducting.

(4) The resistors R_1 and R_2 have a very large resistance, generally about 5 to 10 megohms each. These resistors are used to allow the charge on the capacitors to leak off when the power supply is turned off. This is necessary as a safety measure to prevent injury from the high voltage.

(5) Because the energy delivered to the load must come from discharging the capacitors C_1 and C_2 in series, the application of this type of circuit is limited to uses where the average load current is small. If a large current is drawn, the voltage across C_1 and C_2 falls off rapidly. However, if these capacitors are made large, i.e., about 10 microfarads, a large current can be supplied with reasonably good voltage regulation if the load is on for only a few microseconds at a time. When the capacitors are made large, the rectifier tubes are likely to be damaged by the excessive peak current that flows

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during the short period of conduction. To protect the rectifier tubes in such a case, resistors of a few thousand ohms resistance are placed in series with the rectifiers.

(6) A different form of voltage-doubling circuit is the cascade voltage doubler (Figure 70 (a)). When point B becomes positive, V_1 conducts and C_1 charges nearly to the peak transformer voltage and with polarity as shown. During the next half-cycle, point A is positive and V_1 is nonconducting. V_2 conducts, however, and charges C_2 to nearly twice the peak transformer voltage because of the combined effect of the transformer and C_1 in series.

(7) The circuit of Figure 70 (a) may be extended to perform multiplication of the transformer voltage by any integral factor. Figure 70 (b) shows a voltage quadrupler.

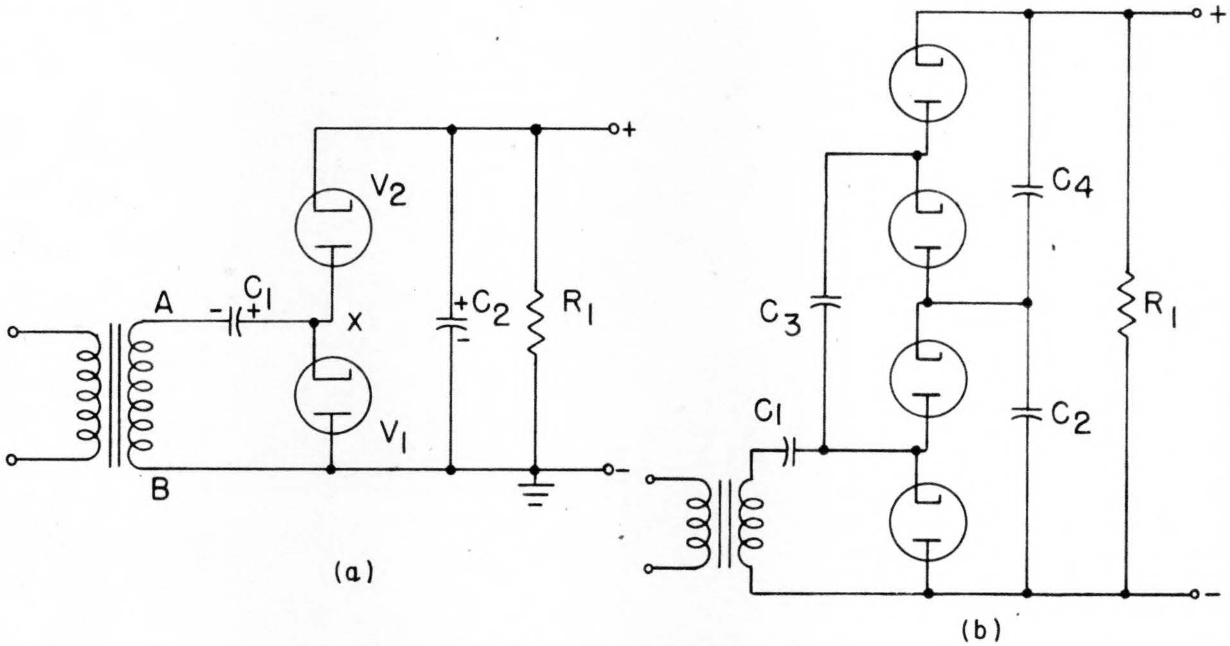

Figure 70. Cascade Voltage Doubler

(8) Voltage multiplying circuits are used where it is inconvenient to use a transformer large enough to supply the high voltage required or where it is desired to obtain sufficient plate voltage to operate properly small vacuum tubes from a 115-volt a-c source without using a transformer. The voltage regulation in either type of voltage multiplier is poor if the average load current exceeds a few milliamperes.

18. FILTER CIRCUITS. A. GENERAL. (1) The output voltage of a rectifier always has the same polarity, but its magnitude fluctuates about an average value as the successive pulses of energy are delivered to the load. In Figure 71 the average voltage is shown as the line which divides the waveshape so that area A equals area B. The fluctuation of voltage above and below this average value is called ripple. The frequency of the main component

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of the ripple for the full-wave rectifier output shown in Figure 71 is twice the frequency of the voltage which is being rectified. In the case of a half-wave rectifier the ripple has the same frequency as the input alternating voltage. Thus, if the input voltage is obtained from a 60-cycle-per-second source, the main component of the ripple in the output of a half-wave rectifier is 60 cycles per second and in a full-wave rectifier is 120 cycles per second.

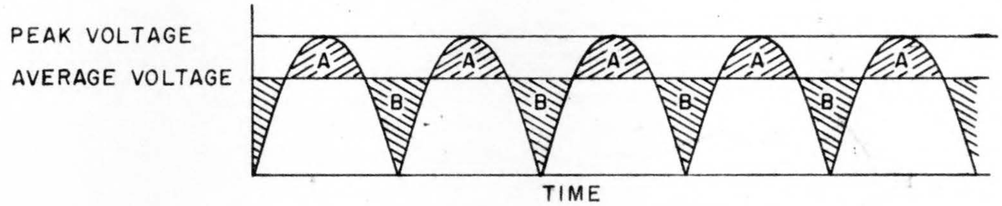

Figure 71. Average Value of a Rectifier Output

(2) The output of any rectifier is composed of a d-c voltage and an alternating ripple voltage. For most applications, the ripple voltage must be reduced to a very low amplitude. The amount of ripple that can be tolerated varies with different applications of vacuum tubes.

(3) A circuit which eliminates the ripple voltage from the rectifier output is called a <u>filter</u>. Filter systems in general are composed of a combination of capacitors, inductors, and in some cases resistors.

B. CAPACITANCE FILTER. (1) Ripple voltage exists because the rectifier supplies pulses of energy to the load. The fluctuations can be reduced considerably if some energy can be stored in a capacitor during the pulses and then allowed to discharge from the capacitor between pulses.

(2) Figure 72 (a) shows the output of a half-wave rectifier. This pulsating voltage is applied across a <u>filter capacitor</u> C to supply the load R (Figure 72 (b)). Since the rate of charging C is limited only by the reactance of the transformer secondary and the plate resistance of the tube in the rectifier, the voltage across the capacitor can rise nearly as fast as the half-sine wave voltage output from the rectifier. The capacitor C, therefore, is charged to the peak voltage of the rectifier within a few cycles. The charge on the capacitor represents a storage of energy. When the rectifier output drops to zero, the voltage across the capacitor does not fall immediately. Instead, the energy stored in the capacitor is discharged through the load during the time that the rectifier is not supplying energy. The voltage across the capacitor falls off slowly if a large capacitance is used, and the amplitude of the ripple therefore is decreased (Figure 72 (c)).

(3) After the capacitor has been charged, the rectifier does not begin to pass current until the output voltage of the rectifier exceeds the voltage across the capacitor. Thus, in Figure 72 (c) and (e), current begins to flow in the rectifier when the rectifier output reaches a voltage equal to the capacitor voltage. This occurs at some time t_1 when the voltage has a magnitude of E_1. Current continues to flow in the rectifier until slightly after the peak

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of the half-sine wave, at time t_2. At this time the sine-wave voltage is falling faster than the capacitor can discharge. A short pulse of current which begins at t_1 and ends at t_2 is supplied, therefore, to the capacitor by the power supply.

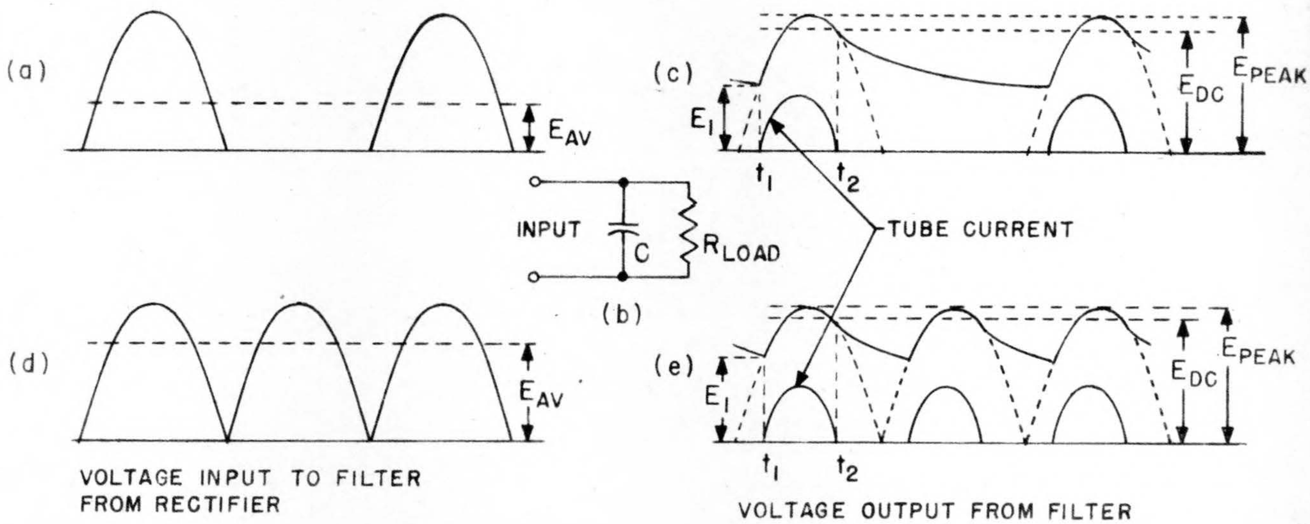

Figure 72. Capacitance-Filter Action

(4) The average voltage of the rectifier output is shown in Figure 72 (a) and (d). Because the capacitor absorbs energy during the pulse and delivers this energy to the load between pulses, the output voltage can never fall to zero. Hence, the average voltage of the filtered output is greater than that of the unfiltered input, as shown by Figure 72 (c) and (e). However, if the resistance of the load is small, a heavy current is drawn by the load and the average d-c voltage falls. For this reason, the simple capacitor filter is not used with rectifiers which must supply a large load current.

C. INDUCTANCE FILTER. (1) Since an inductor resists changes in the magnitude of current flowing through it, an inductor can be placed in series with the rectifier output to help prevent abrupt changes in the magnitude of the current. A circuit such as shown in Figure 73 (a) is called an <u>inductance filter</u>.

(2) Suppose input from a half- or full-wave rectifier (Figure 73 (b) and (c), respectively) is made to the circuit in (a). The dotted waveforms in Figure 73 (d) and (e) show the type of load current that is supplied with a pure resistance load and no filtering. If an inductor is added in series with the load resistor, the current is modified as shown by the solid curves in (d) and (e). The modification takes place because the inductance of the load tends to prevent the current from building up or from dying down. If the inductance can be made large enough, the current becomes nearly constant.

(3) The inductance prevents the current from ever reaching the peak value that is reached without the inductance. Consequently, the output voltage never reaches the peak value of the applied sine wave. Thus a rectifier

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whose output is filtered by an inductor cannot produce as high a voltage as can one whose output is filtered by a capacitor. However, the inductance filter permits a larger current drain without a serious change of output voltage.

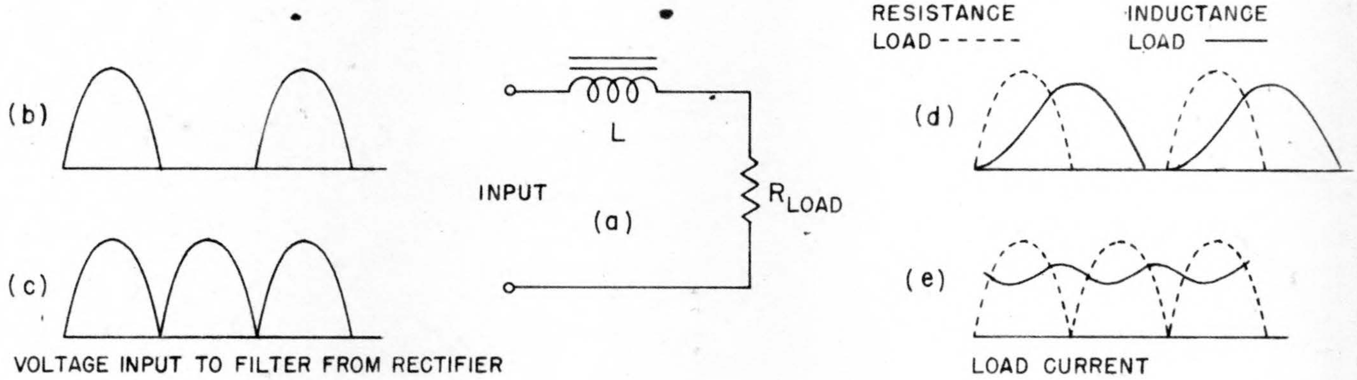

Figure 73. Inductance-Filter Action

D. INDUCTANCE-CAPACITANCE FILTER. (1) The ripple voltage present in a rectifier output cannot be eliminated adequately in many cases by either the simple capacitor or inductor filter. Much more effective filters can be made if both inductors and capacitors are used. The capacitors store and release energy, while the inductors simultaneously tend to prevent change in the magnitude of the current. The result of these two actions is nearly to remove the ripple from the rectifier output and to produce a voltage with an almost constant magnitude.

(2) Two inductance-capacitance filters are shown in Figure 74. In the

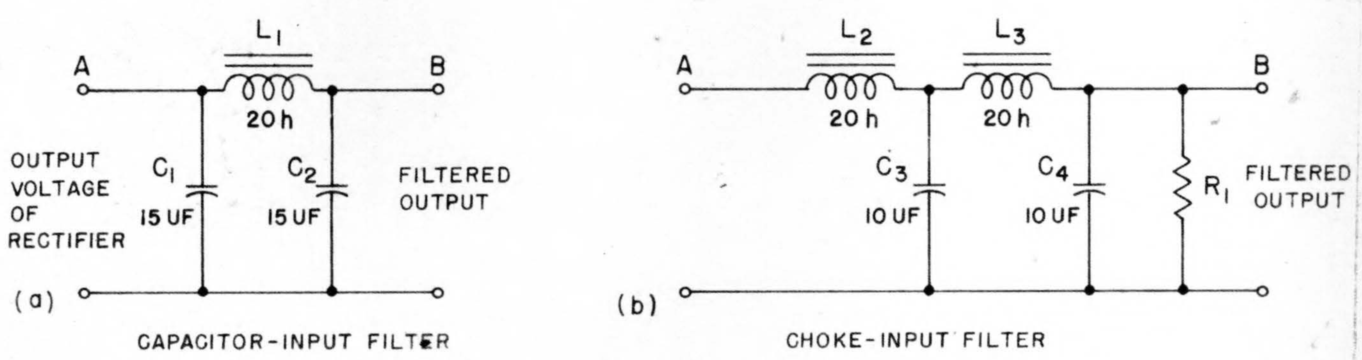

Figure 74. Inductance-Capacitance Filters

circuit of (a), the capacitor C_1 has infinite impedance to the d-c voltage but a very low impedance to the ripple voltage, so that most of the ripple voltage is bypassed by C_1. The remaining ripple voltage at A encounters a very

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high impedance in the inductor L_1. What little ripple voltage passes from A to B is largely shunted to ground by the low impedance of C_2. The result is that the voltage at point B has very little ripple. A similar analysis may be made for the circuit of (b).

(3) Inductors which are used in rectifier filter circuits generally are called chokes because they serve to choke or stop the passage of the ripple current into the load. A circuit of the form of Figure 74 (b) is called a choke-input filter since the input to the circuit passes through a choke coil. The circuit in (a) is called a capacitor-input filter for a similar reason.

(4) When a load is placed on a power supply, the terminal voltage generally falls. This fall of voltage, expressed in percent, is called regulation. A circuit has poor regulation if a large drop occurs in the terminal voltage when full load is applied.

(5) A capacitor-input filter at no load produces a terminal voltage which is nearly equal to the peak voltage of the applied alternating voltage. As the load is increased, the terminal voltage falls, because the current drawn by the load prevents the capacitor from retaining its charge. The capacitor-input filter is undesirable for applications which require a large current, because the peak current that must flow in the rectifier tubes to charge the input capacitor may either damage the tubes or require the use of large, expensive ones. Since the output voltage falls considerably as the load current is increased, this type of filter is said to have relatively poor regulation (curve a of Figure 75). It may be used, however, where the load is light or relatively constant.

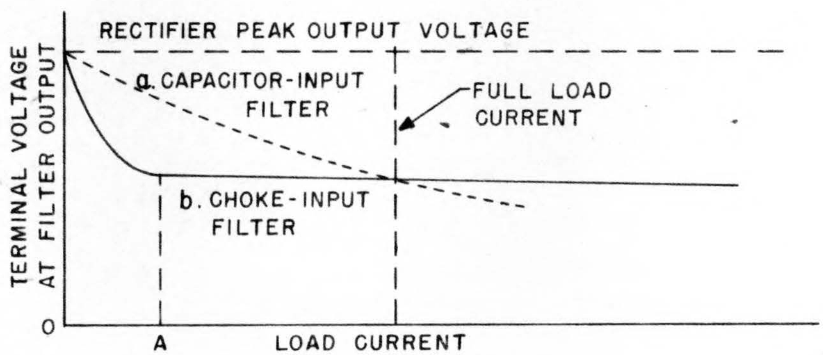

Figure 75. Effect of Load on Terminal Voltage of Capacitor and Choke Input Filters

(6) At no load the output voltage of the choke-input filter is nearly equal to the peak voltage of the sine-wave applied. This high voltage can be obtained, because, with no load being drawn, capacitor C_3 in Figure 74 (b) can be charged to the peak voltage. However, if only a small load current is drawn, the output voltage falls sharply to some lower value (curve b of Figure 75). This sharp drop occurs because the inductance of L_2 prevents a

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surge of current from charging C_3 to the peak voltage, as happened to C_1 in Figure 75 (a). However, as the load increases beyond the value indicated at A in Figure 75, there is very little change in output voltage, except for the drop that takes place in the resistance of the two choke coils L_2 and L_3. Since the voltage at the output of this filter changes very little over a wide range of load, this circuit has good regulation. In practice, a fixed load (or bleeder) which will draw a current of the magnitude A usually is put across the terminals of the filter to prevent the large change of voltage which takes place between no load and A.

E. RESISTANCE-CAPACITANCE FILTER. (1) In some applications a resistor may be substituted for an inductor in a filter circuit. Since the filtering action of the circuit with the resistor is not as effective as that of an inductor, such a filter is used only where some ripple may be tolerated. A resistance-capacitance filter is not used where large load current must be supplied because of the excessive voltage drop that takes place across the filter resistor.

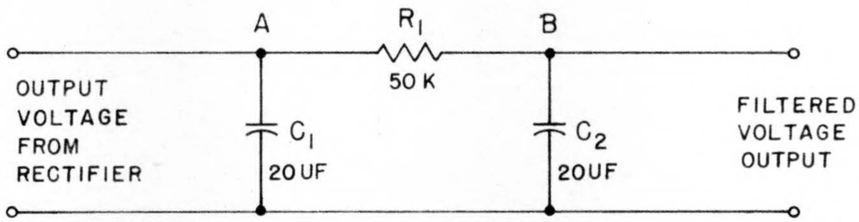

Figure 76. Resistance-Capacitance Filter

(2) In Figure 76, the capacitor C_1 is made large enough to have a very low impedance to the ripple frequency. The d-c component of the voltage at A sees an infinite impedance looking into C_1, and 50,000 ohms looking into R_1 in series with the load. The d-c component therefore drives a current through R_1. The ripple component of the voltage sees a very low impedance looking into C_1 and a relatively high impedance looking into R_1. Most of the current produced by the ripple voltage therefore passes through C_1. A little of this current passes through R_1 and a very small ripple voltage tends to appear at B. However, the capacitor C_2 offers a lower impedance to the ripple frequency than the load does, and most of the remaining ripple at B is shunted by C_2.

(3) The resistance-capacitance filter is used in oscilloscope power supplies. In other applications this type of filter is used to keep the screen-grid of a pentode at a constant potential, and as a decoupling network to isolate the variations of voltage at the plate of an amplifier.

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F. EFFECT OF FREQUENCY. (1) Most power-supply units are designed for operation from a-c power lines whose frequency is 60 cycles per second. However, if the frequency of the input voltage is increased, the rectifier and its filter can be made smaller and lighter. The filters can become smaller because, as the frequency is increased, the reactance of a given capacitor decreases and the reactance of a given inductor increases. Therefore, much more effective filtering can be obtained with the same circuit elements. Another important factor is that transformers of the same ratio of transformation and power rating become smaller in size and lighter in weight as the frequency is increased. In order to save weight and space, some special equipments are designed for operation from an 800-cycle-per-second source.

19. VOLTAGE REGULATORS. A. GENERAL. (1) A device which causes the output voltage of a power supply to remain constant, in spite of changes of load current drawn from the power supply or changes in the input voltage, is called a voltage regulator. Electronic voltage regulators most frequently are used with rectifier power supplies. Other types of regulators generally are used with rotating machines.

(2) The regulator which is used to stabilize the output voltage of a rectifier usually takes the form of a variable resistance in series with the output. This variable resistance and the load resistance form a voltage divider. The variable element is controlled so that the voltage across the load is held constant.

(3) Figure 77 shows a simple circuit which demonstrates this principle. The variable resistor R and the resistance of the load comprise a voltage divider which is connected across the rectifier output terminals. All the load current passes through R and causes a voltage drop across it. If the rectifier output voltage rises, the voltage across the load rises in proportion. To counteract this rise, the resistance R is increased so that a greater

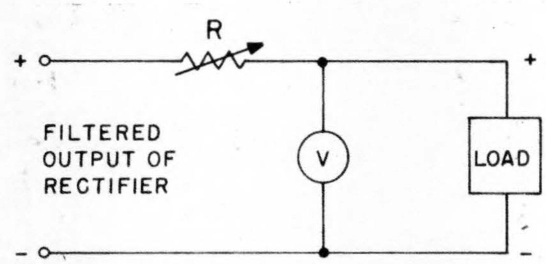

Figure 77. Fundamental Voltage Regulator

portion of the available voltage appears across R. The voltage across the load therefore is held constant if the resistance of R is increased sufficiently to neutralize the increase of rectifier output. If the resistance of the load increases, a greater fraction of the available voltage appears across the load. Therefore, the resistance of R must be increased in order to hold the voltage across the load constant.

(4) In the system shown in Figure 77, the resistor R must be varied manually according to the reading of the voltmeter. If the voltmeter reading increases, R must be increased; if the voltmeter reading decreases, the resistance of R must be decreased. This same type of action must take place in all of the voltage regulators that are to be discussed. The more complicated

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circuits which follow are more desirable than this simple circuit because they are more accurate and can respond more quickly to changes.

B. GLOW-TUBE REGULATOR. (1) In a glow-discharge tube, such as the neon-glow tube, the voltage across the tube remains constant over a fairly wide range of current through the tube. This property exists because the degree of ionization of the gas in the tube varies with the amount of current that the tube conducts. When a large current is passed, the gas is very highly ionized and the internal impedance of the tube is low. When a small current is passed, the gas is lightly ionized and the internal impedance of the tube is high. Over the operating range of the tube, the product (IR) of the current through the tube and the internal impedance of the tube is practically constant.

(2) A simple glow-tube regulator is shown in Figure 78. The load current and the current that flows in the neon-glow tube both pass through the series resistor R. If the supply voltage drops, the voltage across the neon tube tends to drop. Instead, the gas in the neon tube deionizes slightly and less current passes through this tube. The current in R is decreased by the amount of this current decrease in the tube. Since the current through R is less, the voltage drop across R is less. If the resistor is of the proper

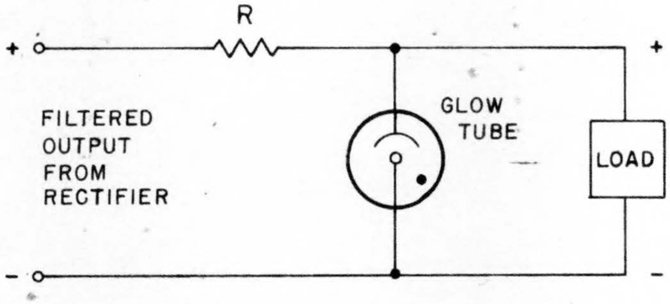

Figure 78. Glow-Tube Voltage Regulator

value relative to the load and to the glow tube which is used, the voltage across the load is held nearly constant. In any case, the value of R must not be so large that the neon will not fire.

(3) Glow tubes such as the 874, OA3/VR75, OC3/VR105, and OD3/VR150 are designed to operate at different useful values of voltage. The letters "VR" refer to the tube's function as a voltage regulator.

(4) In applications where a regulated voltage in excess of the voltage of one glow tube is required, two or more may be placed in series (Figure 79). This permits several regulated voltages with small current drains to be obtained from a single rectifier power supply.

(5) The voltage required to cause ionization of the glow tubes when the circuit is first energized is approximately 30 per cent greater than the operating terminal voltage. The voltage quickly drops to the operating value as the tube begins to conduct. In order to maintain stable operation, the tubes

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should be operated within their maximum and minimum current ratings. In the case of the OA3/VR75, OC3/VR105, and OD3/VR150 tubes, a minimum current of 5 milliamperes should flow through the tube, and the maximum current should be kept below the maximum rated current of 40 milliamperes.

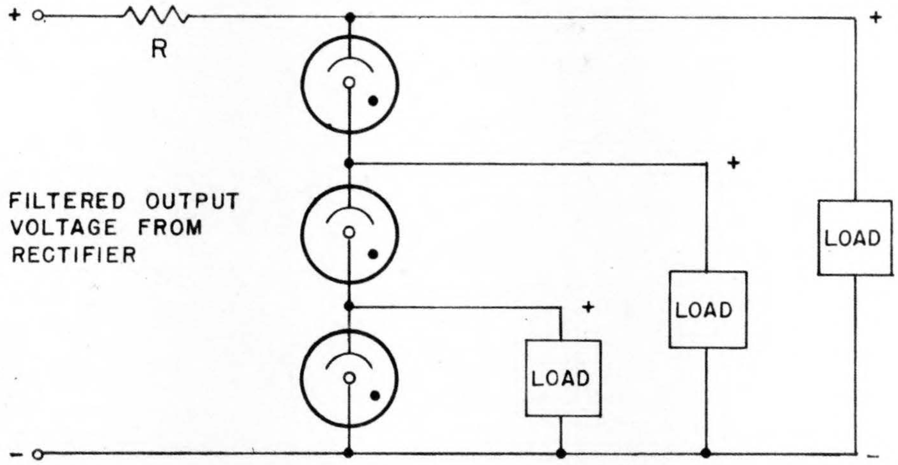

Figure 79. Use of Several Glow Tubes in Series to Obtain Stabilized High Voltage

C. SIMPLE VACUUM-TUBE REGULATOR. (1) A vacuum tube may be considered as a variable resistance. When the tube is conducting a direct current, this resistance is simply the plate-to-cathode voltage divided by the current through the tube and is called the d-c plate resistance, R_p. For a given plate voltage the value of R_p depends upon the tube current, which in turn depends upon the grid bias.

(2) The variable resistance R of Figure 77 can be replaced by a vacuum tube (Figure 80) since the vacuum tube is also a variable resistance. The effective resistance of V_1 in the circuit is established initially by the bias on the tube. Assume that the voltage across the load is at the desired value. Under this condition, the cathode is positive relative to ground by some voltage E_1. The grid can be made positive relative to ground by a voltage E_2 which is less than E_1. The potentiometer R_2 is adjusted until the bias, which is $E_1 - E_2$, is sufficient to allow V_1 to pass the desired load current. With this bias, the resistance of V_1 is established at the proper value to reduce the rectifier output voltage to the desired load voltage.

(3) If the rectifier output voltage increases in the circuit of Figure 80, E_1 and therefore the negative bias on V_1 will increase also. This tends to reduce the current flowing through V_1 and thus brings the voltage drop E_1 across the load down again.

(4) The resistor R_1 is used to limit the grid current, and is necessary in this particular circuit because the battery is not disconnected when the power is turned off. However, the battery can be eliminated from the circuit by use of a glow tube to supply a fixed bias for the grid of the tube (Figure 81). In this circuit, the grid voltage is held constant by the glow tube V_2. The action of the circuit is exactly the same as the action of the circuit shown in Figure 80.

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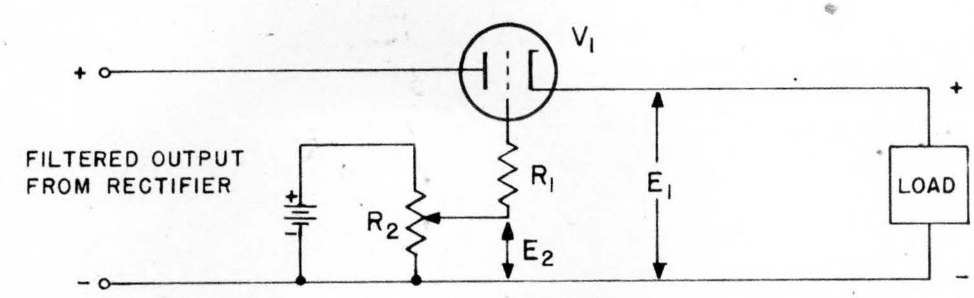

Figure 80. Simple Vacuum-Tube Voltage Regulator

(5) The output voltage of the simple voltage regulators shown in Figures 80 and 81 cannot be absolutely constant. As the rectifier output voltage increases, the voltage at the cathode of V_1 must rise slightly if the regulator is to function. However, if the characteristics of the tube V_1 are carefully chosen, the rise of load voltage is not large.

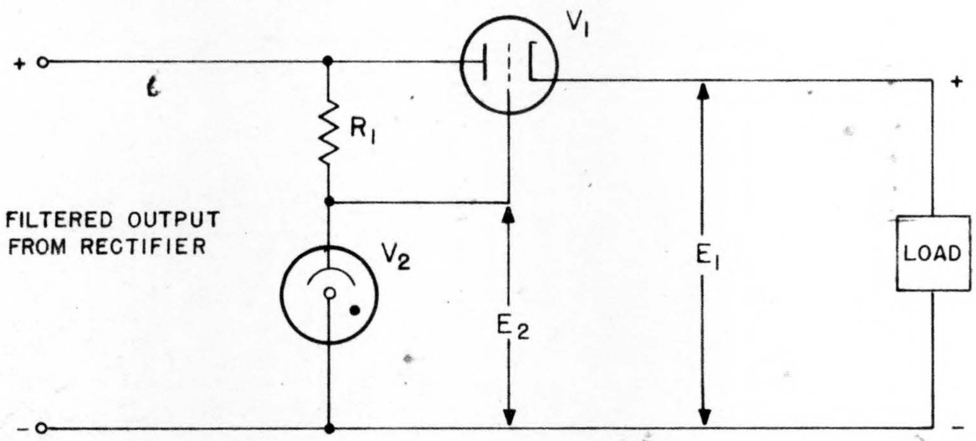

Figure 81. Simple Vacuum-Tube Voltage Regulator

(6) The voltage regulators of Figures 80 and 81 are greatly superior to those discussed before, because the amplification of tube V_1 permits operation of the regulator on small variations of load voltage, whether the variations are caused by supply-voltage fluctuations or changes in load. For example, in Figure 81, if the load resistance decreases, the load current increases and lowers the voltage E_1 by the increased voltage drop in V_1. The cathode of V_1 therefore becomes less positive than before, and the bias on V_1 is decreased, since this bias is made up of $E_1 - E_2$. The decrease in bias lowers the resistance of V_1 sufficiently to allow the load voltage to rise to normal. The result is that the total resistance across the power source is less, but the voltage division is changed to provide the desired voltage

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across the load.

D. IMPROVED VOLTAGE REGULATOR. (1) A very stable voltage regulator can be made by taking advantage of the high-amplification possible with a pentode vacuum tube. This voltage regulator (Figure 82) produces an output voltage which is independent of fluctuations in the a-c supply and changes in load over a wide range.

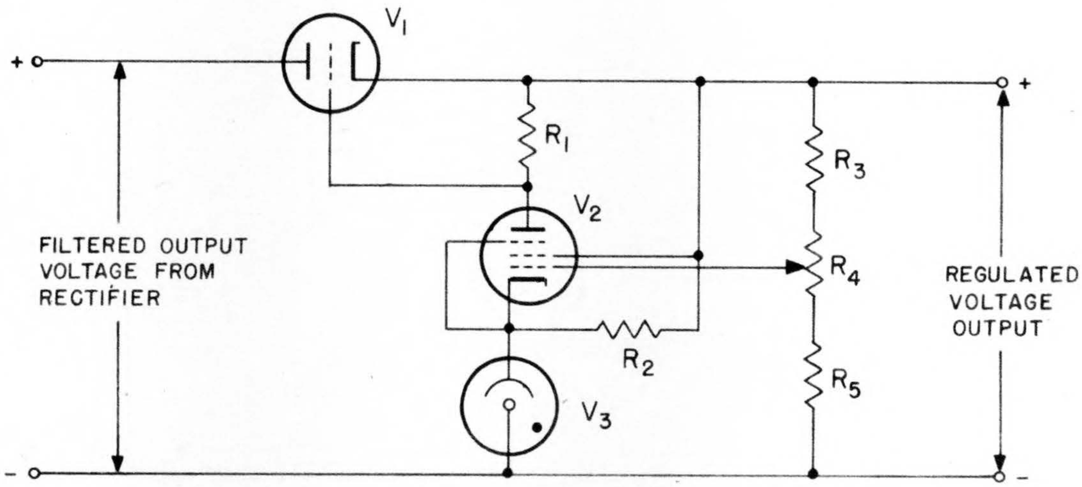

Figure 82. Improved Voltage-Regulator Circuit

(2) The screen voltage of V_2 is the regulated voltage output of the regulator. The potential of the cathode of V_2 is held at a constant positive value by the glow tube V_3. The grid potential of V_2 is a voltage selected by the potentiometer R_4. This potentiometer is set so that the grid voltage is less positive than the cathode by an amount which causes V_2 to pass a certain plate current. This plate current flows through the plate load resistor R_1 and causes a drop across it. The magnitude of the voltage across R_1 is the bias on tube V_1. Therefore, the adjustment of the potentiometer R_4 establishes the normal resistance of V_1. This adjustment is used to set the value of load voltage which the regulator is to maintain.

(3) If the load voltage tends to rise, whether from a decrease in the load current or from an increase in the input voltage, the voltages on the control and screen grids of V_2 also tend to rise, the cathode voltage remaining practically constant. V_2 then conducts more heavily (because the bias is smaller and the amplification factor larger) and draws more current through R_1. The increased voltage drop in R_1, which is the bias voltage for V_1, causes the plate resistance of V_1 to increase. A larger portion of the available voltage appears across the higher resistance of V_1, and the load voltage remains practically constant. The action is similar if the load voltage tends to fall.

(4) A pentode is used for V_2 because of the high amplification possible with this type of tube. The use of such a tube makes the output voltage much

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more constant since small variations of load voltage are amplified sufficiently to cause operation of the circuit.

(5) The anode of the glow tube V_3 is connected to the cathode of V_2 and to the regulated voltage output through resistor R_2. It is necessary to connect the glow tube to B+ in this way in order to cause the gas in this tube to ionize when the power supply is first turned on.

(6) All of the load current must pass through V_1. For this reason, this tube must be capable of passing a large current. In some regulators a single tube does not have sufficient capacity to pass the required current, and in such cases, several identical tubes may be put in parallel.

E. VOLTAGE STABILIZER. (1) A circuit which is designed to remove from a rectifier output the fluctuations that may occur in an a-c line is called a voltage stabilizer. It differs from a regulator in that it does not control the average value of the output voltage, but it does remove the a-c components superimposed on the direct voltage.

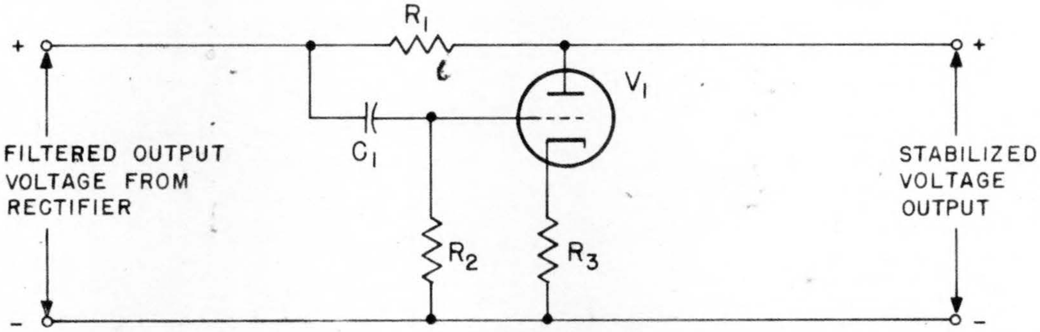

Figure 83. Voltage-Stabilizer Circuit

(2) One type of voltage stabilizer is shown in Figure 83. Slow changes in the rectifier output voltage do not affect this circuit because such voltages cannot pass through the coupling capacitor C_1. However, the ripple voltages and transient voltages are coupled to the grid of V_1. If the transients attempt to raise the rectifier output voltage, the grid of V_1 is driven in a positive direction, causing V_1 to pass a larger current. The increased drop across the plate load resistor caused by the increased plate current cancels the rise of voltage caused by the transient. Thus, the voltage remains relatively constant. In the same way, a negative swing of input voltage reduces the current flowing in V_1 and in R_1, thereby stabilizing the output voltage of this circuit.

(3) If the amplification of the tube is 1, a 10 volt rise at the grid causes a 10 volt drop at the plate. This property makes this circuit very useful in applications where the a-c supply voltage is likely to fluctuate badly, or where it is impractical to include an adequate filter to eliminate ripple from the output.

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SECTION VII

CATHODE-RAY OSCILLOSCOPE APPLICATIONS

20. OBSERVATION OF WAVEFORMS. A. GENERAL. (1) The cathode-ray oscilloscope is most generally used in the observation of waveforms in electrical circuits. Since it is the voltage waveshape that is commonly required, the electrostatic cathode-ray tube is generally used in test oscilloscopes. The electromagnetic cathode-ray tube is a current-operated device. It is used for certain applications other than general testing where its properties make it more suitable than the electrostatic tube.

(2) In order to obtain an accurate representation of the voltage waveform, a few precautions must be observed. For the protection of both the operator and the oscilloscope, the approximate magnitude of the voltages in the circuit under test must be known. Dependable data can be obtained from the oscilloscope only if its sensitivity and its frequency characteristics are known. To make certain that the waveform will not be distorted, it is essential that the manner in which the distortion takes place be understood and that precautions be taken to minimize such distortion.

B. INPUT CIRCUIT. (1) The input to most oscilloscopes is between an input terminal and ground. The input terminal is almost always coupled through a capacitor to the grid of a voltage amplifier. The capacitors used seldom have voltage ratings in excess of 600 volts. Unless the approximate magnitude of the voltage under test is known, damage to the oscilloscope through breakdown of the input capacitor may easily result.

C. VOLTAGE DIVIDERS. (1) In some cases, it may be necessary to observe waveforms in circuits where the voltage is much greater than the components within the oscilloscope can withstand. A voltage divider may be used in such instances to reduce the voltage to a value that will not damage the equipment. In any case, however, it is very important that the oscilloscope be adequately grounded. Grounding the oscilloscope is a precaution that must be taken for the protection of the operator, since a failure of some part of the voltage divider can raise the potential of the whole oscilloscope to a dangerous level if the case is not solidly connected to ground.

(2) If the voltage divider is a capacitance divider, a wise precaution is to shunt each capacitor with a high resistance, in order to maintain proper voltage distribution across the chain. In Figure 84, two voltage dividers are

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shown. In Figure 84 (a), the voltage across C_2 is one-tenth of the voltage across C_1, owing to the capacitance alone. However, the leakage resistances R_1 and R_2 may be of such values that they divide the voltage by a very different ratio. If this is true, the voltage distribution across the capacitors will be upset, and one of them may break down. To prevent this unbalanced distribution of voltage, resistors R_3 and R_4 may be added, as in Figure 84 (b). Since the leakage resistance of a good capacitor is of the order of 1,000 megohms, R_3 and R_4 fix the voltage division at the same ratio as do the capacitors, and the voltage divider may be easily designed to withstand the high voltage.

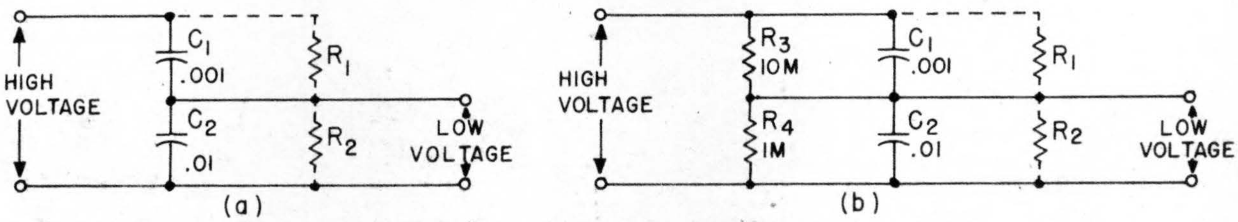

Figure 84. Typical Voltage Dividers

D. FREQUENCY RANGES. (1) The range of sweep frequencies in a given oscilloscope is usually indicated directly on the front panel of the instrument. The frequency range that the vertical and horizontal amplifiers are capable of amplifying properly is given in the manufacturer's instruction book. As a rule, only the best oscilloscopes use amplifiers which will amplify a voltage whose frequency is below 20 cycles per second or above 100,000 cycles per second. Such instruments are satisfactory for most uses, but distortion is likely to occur when sawtooth or rectangular wave shapes of a high recurrence rate are investigated. High-grade oscilloscopes are capable of amplifying over a broader frequency range, and they may; therefore, be used on rectangular and sawtooth waveshapes of high recurrence rates without distorting the shape of the waveform.

E. DEFLECTION SENSITIVITY. (1) The deflection sensitivity of an oscilloscope may be defined as the distance in millimeters that the spot is moved on the screen when 1 volt is applied to the deflecting plates, expressed in millimeters per volt. The most accurate way of measuring this quantity is to apply a known d-c potential directly to the deflecting plates and to measure the distance that the spot is moved by this voltage. Most electrostatic cathode-ray tubes have sensitivities which are less than 1 millimeter per volt. This same figure may be expressed in terms of voltage required to move the spot 1 inch. To convert from millimeters per volt to volts per inch, divide 25.4 by the sensitivity in millimeters per volt.

(2) When it is desired to use the amplifier with the oscilloscope, the gain of the amplifier must be calibrated. However, a more direct procedure is to set the gain control to a value that is satisfactory, apply sine-wave voltage to the input terminal, and measure the amplitude of the deflection on the screen. The magnitude of the input sine-wave voltage may be measured with an

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accurate a-c voltmeter. Most a-c voltmeters indicate the root-mean-square (rms) value of voltage, but the deflection of the spot on the screen is proportional to the peak voltage of the sine wave. The total height of the image on the screen is proportional to the amplitude of the sine wave from the positive peak to the negative peak (peak-to-peak voltage). To convert the rms voltage to peak-to-peak voltage, therefore, the meter reading must be multiplied by 2.828. Thus, the effective sensitivity of the oscilloscope in volts per inch is the peak-to-peak voltage applied divided by the peak-to-peak amplitude of the trace. If the gain control is changed, the effective sensitivity will also change. It must be remembered that the sensitivity of the cathode-ray tube is not affected by the use of the amplifier. The only factor changed is the amplitude of the voltage applied to the deflecting plates.

F. STRAY PICK-UP. (1) In order to avoid pick-up of stray signals, the leads from the circuit under test to the oscilloscope should be as short as possible. If the leads are long, a greater voltage can be induced in them by any stray field which may be present than if they are short. The pick-up may be so disturbing in some cases that it will be almost impossible to use the oscilloscope. A few things can be done to reduce the effect on the oscilloscope of stray fields. First, the cathode-ray tube itself must be very carefully shielded from all stray fields. In most cases, this shielding is provided by the aquadag within the tube and by a metallic shield outside the tube. Second, the common side of the oscilloscope circuit should be connected to a ground point in the circuit under test and to a good external ground connection. This connection will aid in eliminating most of the stray voltages that are picked up by the leads. Third, a low capacitance coaxial cable may be used to reduce still more the effects of stray fields.

G. DISTORTION. (1) Several sources of distortion are possible in observing waveforms. While distortion can be eliminated by simple precautions in some cases, it can be very difficult to eliminate in other cases.

(2) Perhaps the most obvious point at which distortion can enter is in the deflection amplifier. It is important, therefore, to know the frequency response of the amplifier being used, so that an estimate may be made of the possibility of distortion for a given signal.

(3) If the sweep is non-linear, the shape of the wave on the screen will not be a true picture of the voltage under test. However, if the oscilloscope is not defective, the sweep will generally be linear enough for most purposes.

(4) When signals of relatively high frequency are to be observed, the time of fly-back may become an appreciable fraction of the period of the signal. To avoid distortion from this source, it is well to adjust the sweep frequency so that several cycles of the signal appear on the screen.

(5) If the magnitude of the synchronizing voltage is too great, the image may be distorted by the fact that the sweep is terminated too soon. This may be avoided most simply by setting the synchronization control to zero while the sweep frequency is being adjusted. When the sweep frequency is as nearly as possible some integral sub-multiple of the signal frequency, the image will

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be almost stationary on the screen. The synchronizing voltage should then be turned up just enough to stop the apparent motion of the image on the screen.

(6) In general the input impedance of the oscilloscope will be much higher than the impedance at the point under test. The oscilloscope will not, therefore, change the time constant nor the voltage at the point, and a true picture of the voltage may be observed. In some circuits, however, the impedance is very high (up to 100 megohms), and the oscilloscope will change the voltage or the time constant so radically that it will be impossible to obtain a true picture.

(7) The input capacitance of an oscilloscope is generally small (of the order of 20-60 micromicrofarads), but it may be sufficient to alter the characteristics of a video amplifier or the tuning of a high-frequency oscillator.

(8) When one specific type of equipment is to be maintained, many of these sources of distortion become meaningless. When, for example, the same oscilloscope is used with the same pair of leads to check a given set of wave shapes, the distortion will always be the same. If the waveshapes through the system are recorded when the system is operating properly, the maintenance testing need consist only of a comparison of the waveshapes obtained with the recorded standard waveshapes. In such a case, it is not necessary to eliminate all distortion,because the test will consist of a comparison of two sets of data that are distorted in the same way. It is desirable to eliminate distortion as much as possible in order that the operation of the circuit under test may be better understood; however, successful testing may be performed regardless of distortion, if the same test equipment is used the same way in every check.

21. OSCILLOSCOPE AS A MEASURING DEVICE. A. D-C VOLTMETER. (1) The electrostatic cathode-ray tube is a voltage-operated device. The amount of deflection of the spot is proportional to the magnitude of the voltage applied to the deflecting plates. If the deflection sensitivity of the cathode-ray tube is known, the oscilloscope can be used as a voltmeter on either direct or alternating voltages. The oscilloscope has the advantage of extremely high input impedance when the voltage to be measured is applied directly to the deflecting plates. However, since both the range of voltage and the accuracy of indication are less than that available in commercial d-c voltmeters, the oscilloscope is not widely used for measurement of d-c voltage.

B. A-C VOLTMETER. (1) The cathode-ray oscilloscope is a better device for measuring alternating voltages than most conventional a-c voltmeters. The principle difficulty with the oscilloscope is the calibration of its deflection sensitivity. If this factor can be determined accurately, the magnitude of an alternating voltage can be determined very simply. The advantages of an oscilloscope as an a-c voltmeter are its very high input impedance, its ability to measure equally well voltages of a very wide frequency range, and its ability to indicate magnitude regardless of waveform. The oscilloscope

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measures the peak value of the a-c voltage applied. The standard a-c meters show the rms value of a sine-wave a-c voltage, which may be converted to a peak value, but the results may be very misleading for voltages whose waveforms are other than sinusoidal.

C. AMMETER. (1) The electromagnetic cathode-ray tube is a current-operated device. It could be used, therefore, to measure current magnitudes directly if it were calibrated. This type of tube, however, is rarely used in test oscilloscopes. The electrostatic cathode-ray tube, on the other hand, is widely used in test oscilloscopes, and may be used to measure currents indirectly. If the current to be measured is passed through a calibrated resistor, the resulting voltage across the resistor may be indicated on the oscilloscope screen. By application of Ohm's Law, the current may be calculated.

D. WATTMETER. (1) The same method that is used to measure current can also be employed to measure power. It is known that the power dissipated in a resistor is equal to the product of the current through the resistor and the voltage across it, (EI). The power dissipated in the resistor may therefore be expressed as

$$P = EI = \frac{E^2}{R},$$

and by substituting in this expression the voltage measured by the oscilloscope, the power may be calculated.

22. LISSAJOUS FIGURES. A. GENERAL. (1) A Lissajous figure is a pattern created on an oscilloscope screen when sine wave voltages are applied to both the horizontal and vertical deflecting plates. One type of Lissajous figure is a circle. The principle use of the Lissajous figure is the determination of an unknown frequency by comparison with a standard frequency.

B. DEVELOPMENT OF A SIMPLE FIGURE. (1) The development of one type of Lissajous figure is shown in Figure 85. The ratio of the frequencies applied to the two plates is 1:2. It does not matter what the actual frequency is. The important point is that the frequency on the vertical deflecting plates is twice that on the horizontal deflecting plates. If the two voltages are in phase - that is, if both voltages are passing through zero and going positive at the same instant - a figure-eight pattern will be traced (Figure 85 (a)). As the phase changes slightly, the pattern will change as shown in (b), (c), and (d). When the phase angle is 90°, the loops close in, as in (c). If the phase angle is greater than 180° the pattern will be inverted, as in (d).

C. INTERPRETATION OF PATTERN. (1) One feature that all these possible images have in common is that the horizontal line A-A or B-B (Figure 85 (a)) will touch the pattern at two points. This is true even for the line tangent to the top of (c), because the trace passes the point 1 on the figure twice during each cycle. Likewise, a vertical line, such as C-C in (d), will touch the

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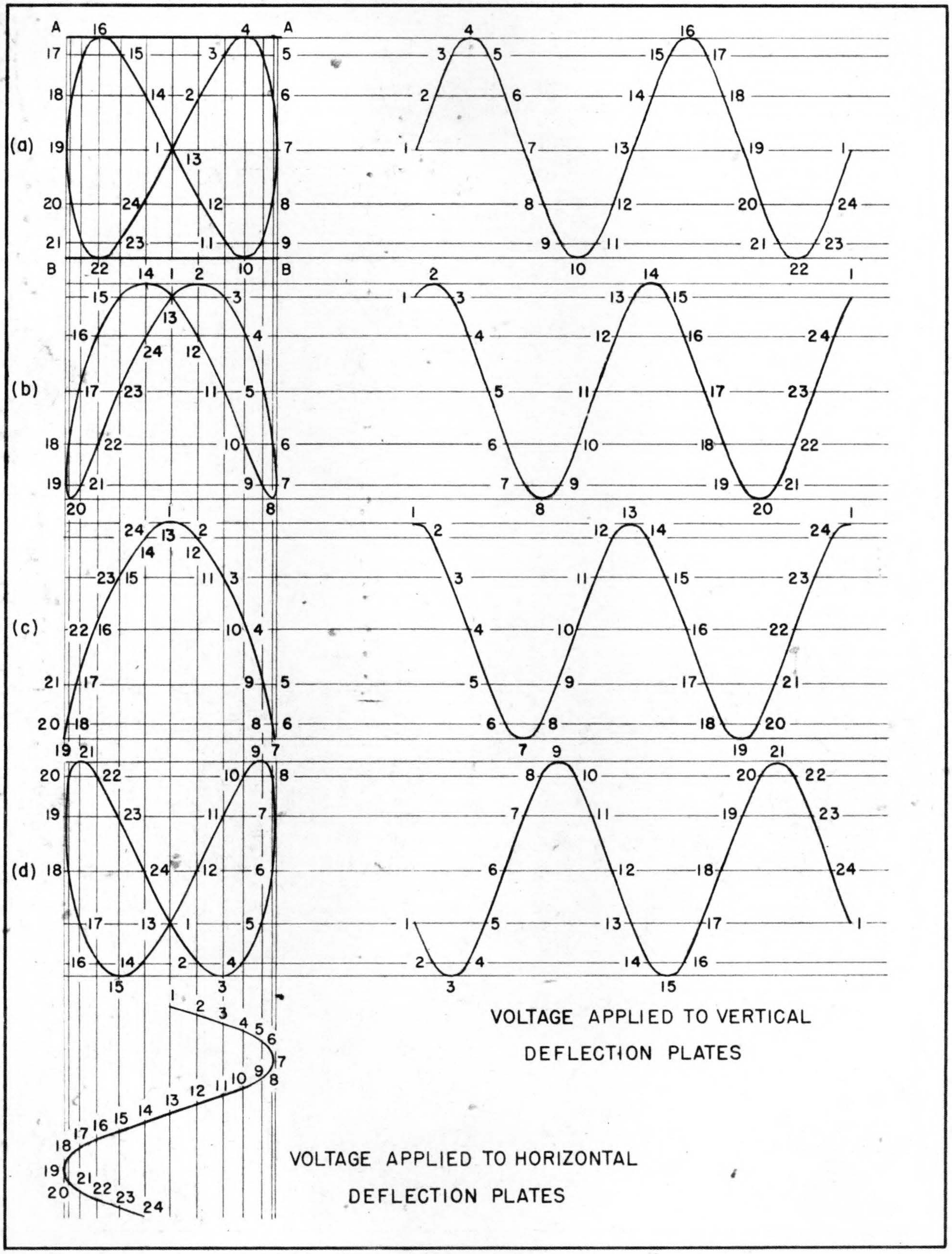

Figure 85. Lissajous Figures for 1:2 Frequency Ratio

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pattern at only one point. It is from these points of tangency that the ratio of the two frequencies may be obtained. The means of determining the ratio of the frequencies may then be stated as

$$\frac{\text{Frequency applied to horizontal deflection plates}}{\text{Frequency applied to vertical deflection plates}} = \frac{\text{Number of points at which the figure is tangent to a vertical line}}{\text{Number of points at which the figure is tangent to a horizontal line.}}$$

(2) Miscellaneous figures. In Figure 86 several varieties of Lissajous figures are shown. The ratio is indicated in each case. Unless the oscilloscope screen is very large, ratios of higher than 10:1 are difficult to interpret. The circle shown at Figure 86 (a) is the simplest type of Lissajous figure. The pattern at (b) is for a 2:1 ratio. Compare this with the pattern shown in Figure 85. The patterns in (e) and (f) indicate the complexity that may be encountered in ratios of a higher order.

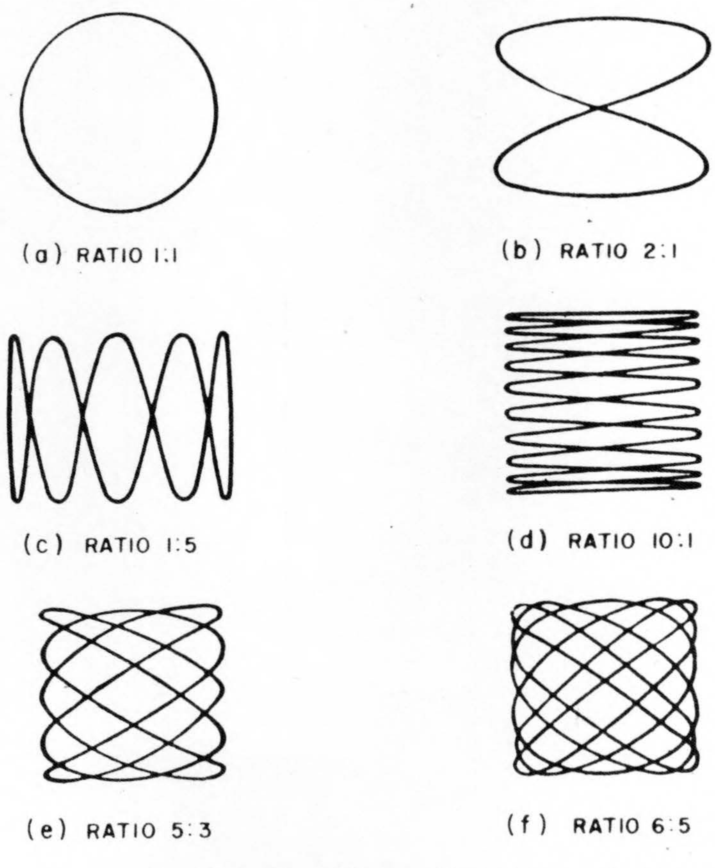

Figure 86. Lissajous Figures for Various Ratios

23. MEASUREMENT OF SHORT TIME INTERVALS. A. LINEAR TIME BASE. (1) When it is required to measure time intervals by means of an oscilloscope,

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it is desirable for the spot to move a uniform distance along the screen during each interval. If such motion of the spot can be obtained, the trace may be very simply calibrated with a linear scale, and the accuracy of measurement will be the same at all parts of the sweep. However, if the motion is not uniform, the accuracy of measurement will vary. A non-linear sweep may be useful for some applications.

B. SYNCHROSCOPE. (1) An oscilloscope which has a sweep of very short duration generated only when a synchronizing signal is provided, is called a synchroscope. Synchroscopes have several calibrated sweeps, which are approximately 50 microseconds, 200 microseconds, and 1,000 microseconds in duration. Such instruments are useful in observing the shape of very short pulse voltages. They may also be used to measure the duration of pulses or the time between two pulses. The sweep may be synchronized from an external source or from an internal oscillator.

(2) In general, an oscilloscope with a fast sweep, or a synchroscope, will have a sweep voltage of the kind shown in Figure 87 (a). The voltage rises very quickly to its maximum value along the line A-B, which may be as short as 50 microseconds, as shown. In order that the very swiftly moving spot may produce a visible trace on the screen during this very short time, a positive gate pulse of the same duration as the sweep is applied to the grid to increase the number of electrons that flow in the cathode-ray beam. During the time BC, the spot does not move. Unless the grid potential were reduced by the trailing edge of the gate pulse, a very bright spot would appear at the right hand end of the trace, and the screen might be damaged at this point.

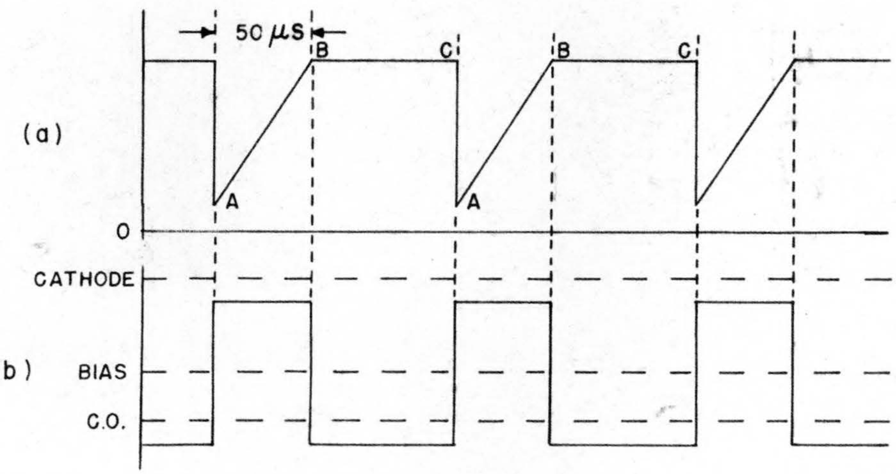

Figure 87. Sweep Voltage and Gate Voltage for Synchroscope

C. EXPANDED SWEEPS. (1) For accurate measurement of time intervals, it is desirable to extend the sweep, which may also be called a time base, so that a longer line will represent the same interval of time as the single straight line considered before. Obviously, the time base can be extended by using a large cathode-ray tube, but tubes which have screens larger in

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diameter than 7 inches are rather awkward in size. Various means, therefore, are employed to produce a longer trace on the more convenient sizes of cathode-ray tubes.

(2) One way of producing a longer time-base line on a given oscilloscope screen is to trace a circular line around the screen instead of a single straight line across it. The circular trace is approximately three times longer than the single straight trace, so that a given time interval is shown by an arc three times longer. This permits a more accurate measurement of the time interval. For some applications, a spiral trace will extend the accuracy of the time-interval measurement well beyond the accuracy possible with a single straight trace. This is especially useful with relatively long time intervals which must be measured with great accuracy.

(3) Another simple way of extending the length of the time base is to make the trace double back on itself, and to separate the forward and backward traces. This can be done simply by applying waveforms of the type shown in Figure 88 (a) and (b). At the instant A, the spot is pulled up by the square wave on the vertical deflecting plates to the point A in Figure 88 (c). The spot moves linearly from A to B as the voltage increases on the horizontal deflecting plates. When the spot arrives at B, it is pulled down to C by the decrease in voltage on the vertical plates. At the same instant, the voltage on the horizontal deflecting plates begins to decrease at a linear rate, and the spot retreats from C toward D. At D, the voltage on the vertical deflecting plates is suddenly increased, and the spot jumps to point A, having traced a rectangle. The rectangle doubles the length of the trace and, therefore, permits greater accuracy in the measurement of time intervals.

(4) A third method of increasing the length of the time base is the use of the "zig-zag" trace. By this method, 10 or more horizontal lines can be traced, and high accuracy of time measurement is possible for long time intervals.

D. TIME-BASE CALIBRATION. (1) When the sweep on an oscilloscope is to be used as a time base, it must be calibrated if the measurement of time intervals is to be made accurately. Calibration is frequently accomplished by applying the output of a shock-excited oscillator to the vertical deflecting plates. The oscillations are produced in this oscillator by the same pulse which initiates the sweep. The sine waves produced divide the time base into intervals equal to the period of one cycle. To make this calibration more precise, the sine waves are sometimes shaped into sharp pulses which may be applied to the deflecting plates to produce pips, or to the grid of the cathode-ray tube to produce equally spaced bright spots.

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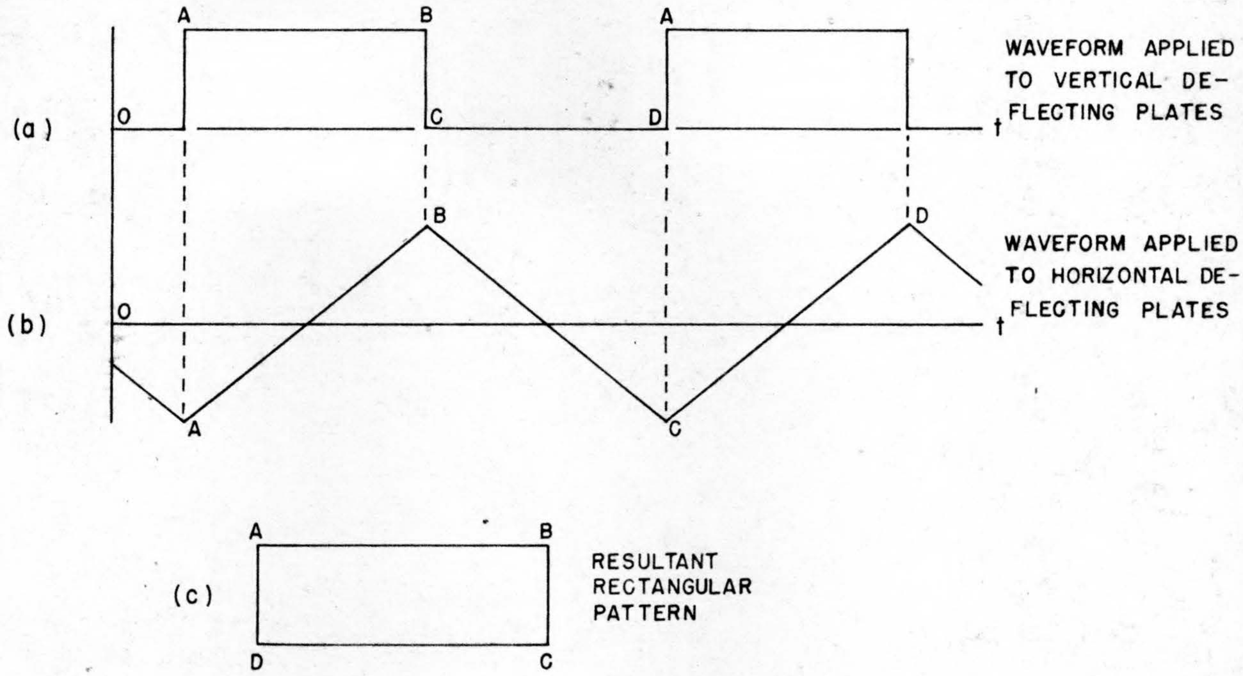

Figure 88. Rectangular Pattern Used to Extend Length of Time Base

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SECTION VIII

RELAY TECHNIQUES

24. INTRODUCTION. A. TYPES OF RELAYS. (1) Fundamentally, a relay is a switch which is actuated by an electromagnet. It is designed to make or break a circuit when current through its coil is caused either to flow or to cease flowing - or in other cases is merely varied in magnitude. Relays can be divided into three rather distinct types according to current carrying capacity of their contacts: (1) contactors, capable of handling heavy currents at power voltages, used for the control of motors, etc.; (2) industrial relays, capable of handling smaller amounts of power than contactors but having greater sensitivity and power economy, used in power supply switching circuits; and (3) quick-acting, multiple-contact (telephone) relays, designed to handle small currents at moderate voltages, used in control circuits and in pulsed circuits for counting, storage, delay, etc.

(2) Contactors are used in computing equipment for such applications as motor-generator set and blower motor control. The coils are usually operated from commercial power supply systems and are designed with temperature rise as the basic limitation. The contacts are large and may be equipped with blow-out coils or other forms of arc-extinguishing devices. Since contactors are relatively large and positive in action their maintenance presents no great problem and will not be discussed further in this section.

(3) Industrial relays are frequently used in computing equipment for switching a-c and d-c power supply circuits to provide required time delay or sequencing of operations. They are designed with power economy and sensitivity as limitations more than heating. The contacts are capable of handling smaller amounts of power than contactors and are not equipped with arc-extinguishing means. The armatures are held open by gravity or by means of a separate spring, usually of the coil type.

(4) Quick-acting, multiple-contact (telephone) relays are used extensively in computing equipment. They are usually small in size and are designed for quick reliable operation on small amounts of power. The contacts are small and are mounted on leaf springs. The armature has a short stroke and is held open by the contact springs instead of by a separate coil spring. Since large numbers of these relays are used in computing equipment, this section will bear mainly on this type of relay.

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B. RELAY CHARACTERISTIC. (1) The sensitivity of a relay depends on the values assigned to the following factors:

1. Contact pressure. This determines the operating force for which the magnet must be designed.

2. Contact deflection and tolerance. The necessary contact deflection, multiplied by the proper lever arm ratio, determines the minimum stroke of the armature at the air gap. To this must be added the minimum variation in stroke required for manufacturing tolerance to obtain the maximum required stroke.

3. Differential current sensitivity. In some cases the relay is designed to release on a current value other than zero.

4. Minimum air gap. This is determined by the residual magnetism of the relay core and frame. It may be limited by a stop, or it may be inherent, as that provided by beryllium copper reed-type hinges.

5. Size and weight. Increasing the coil size will increase the sensitivity, but the mass of the armature and the long time constant of the inductive circuit will make the relay sluggish. Small sizes are generally used to permit quick action.

(2) A quick-acting relay of the telephone type operates in about 10 to 20 milliseconds; shorter times are obtained with special designs or circuits. Relays are generally called "high-speed" when their pick-up time is 5 milliseconds or less. Such operation is possible with relays of the polar (keying) type which are also inherently sensitive.

(3) Delay in pick-up or drop-out may be provided by a number of external devices such as motors, escapements, dashpots, mercury tubes, thermal elements, etc. Short delays on the order of 0.1 second on operate and 0.35 second on release are obtained inherently by means of copper slugs or sleeves built into the relay. A slug is a heavy copper toroid which constitutes a low-resistance short-circuited turn around the relay coil. A slug will delay the drop-out time of a relay more than it will the pick-up time. If the slug surrounds the coil at the end opposite the armature, it will delay the closing time much less than it would if it were located near the armature. A sleeve - that is, a slug extending the full length of the core - will produce a greater delay in pick-up and drop-out than will an equal amount of copper in the form of an end slug. Delay in pick-up is also obtained in some applications by the use of capacitor-charging or other delay-introducing electrical circuits.

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C. CONTACTS. (1) In general a relay is used to control a load. When a relay contact closes it must energize the load. While the contact is closed it must carry the load current. Upon opening, the contact must break the load current. The current handled by the contact during these three states may vary widely depending upon the nature of the load. The reliability of a contact depends upon many factors, among which are:

1. contact material
2. contact pressure
3. contact deflection and follow through
4. contact size (in relation to current)
5. arrangements for arc suppression.

(2) The principal materials used for contacts are silver, tungsten, and platinum. Gold and molybdenum are sometimes used as well as special alloys such as platinum iridium, copper tungsten, silver tungsten, silver tungsten-carbide, silver molybdenum, silver molybdenum-carbide and other alloys having gold, palladium, silver, or platinum as a base.

(3) The material chosen for a contact depends upon such factors as:

1. type of load
2. type of break (slow or quick)
3. frequency of use
4. voltage and current.

A circuit containing an inductive load is more difficult to break than one containing resistance only, since the stored energy of the inductance is generally dissipated in the arc at the breaking contact. If an alloy with a low melting point is used, the contacts may fuse together. A slow break will permit the normal circuit voltage to build up a sustained arc across the contacts. The use of arc suppression circuits will help prevent this.

(4) The characteristics of some of the basic contact materials are as follows:

1. <u>Silver</u>. Pure silver and silver alloys are used where the service is not severe. Silver has high electrical conductivity, high thermal conductivity, and low contact resistance. The oxides are also relatively good conductors. Also silver is inexpensive. The chief disadvantages are that it is soft and has low melting and boiling points. These properties produce a tendency for the contacts to sustain arcs and to weld.

2. <u>Tungsten</u>. Tungsten has high melting and boiling points, is tough and of sufficient hardness. It has the disadvantages of having relatively high contact resistance and of requiring high contact pressure.

3. <u>Platinum</u>. Platinum is usually alloyed with iridium to increase its hardness and wear-resistant qualities. The alloys have a very high melting point and do not oxidize. They are generally used on sensitive relays which operate at low contact pressures and where low contact resistance and freedom from possibility of fusion are required.

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4. Palladium. Palladium is similar in many respects to platinum and is used in a similar manner, either pure or in alloys.

(5) Contact pressure plays a very important part in reliability. In ordinary service a thin film of dust or dirt usually forms on the contacts. If the contact pressure is insufficient, this layer may prevent the contacts from making actual metal-to-metal contact. Frequency of use also affects reliability since a contact which is frequently used is less likely to accumulate a layer of dust or dirt.

(6) The contact pressure for a particular relay is determined during the design of the relay since it is balanced with such considerations as coil winding, number of contacts, sensitivity, speed, air gap, mechanical design, and contact deflection and tolerance to produce a relay having characteristics suitable for the application. Contact pressure may vary between models of the same type; therefore, no arbitrary statement regarding correct value of contact pressure can safely be made.

(7) The contact deflection is made up of (a) the physical separation of the contacts and (b) the follow through. The surge voltage produced on opening and the arcing characteristics determine the minimum physical separation required on the contacts. Separation of contacts on the telepone relays is but a few thousandths of an inch.

(8) Follow-through is the name given to that part of the contact motion after physical contact has been made. In the telephone-type relays such motion is necessary so that contact pressure can be built up on the spring-mounted contacts. The follow-through provides a slight wiping action which tends to keep the contacts clean.

D. RELAYS AS CIRCUIT ELEMENTS. (1) A relay coil is an inductive element having two values of inductance - one with the armature open and a higher value with it closed. When voltage is applied to the relay coil, the current begins to build up as shown in Figure 89. Voltage is placed across the coil at time T1. At some later time, T2, the current has built up to the pick-up point and the armature begins to close. The armature closes during the time T2 - T3, and, in so doing, generates a back voltage (counter emf) which opposes the applied voltage. The armature accelerates as it closes, and as a result, the counter emf increases until the armature closes at T3. The increased counter emf reduces the current as shown. When the armature is closed the counter emf no longer exists, and the full line voltage gain appears across the coil.

(2) The closing of the armature increases the inductance of the coil; the current, therefore, builds up at a slower rate from T3 until it reaches its final value at time T4.

(3) If the relay coil is kept energized over an extended period of time, the coil heats and the resistance increases. This causes the current to decrease slightly during the interval T5 to T6.

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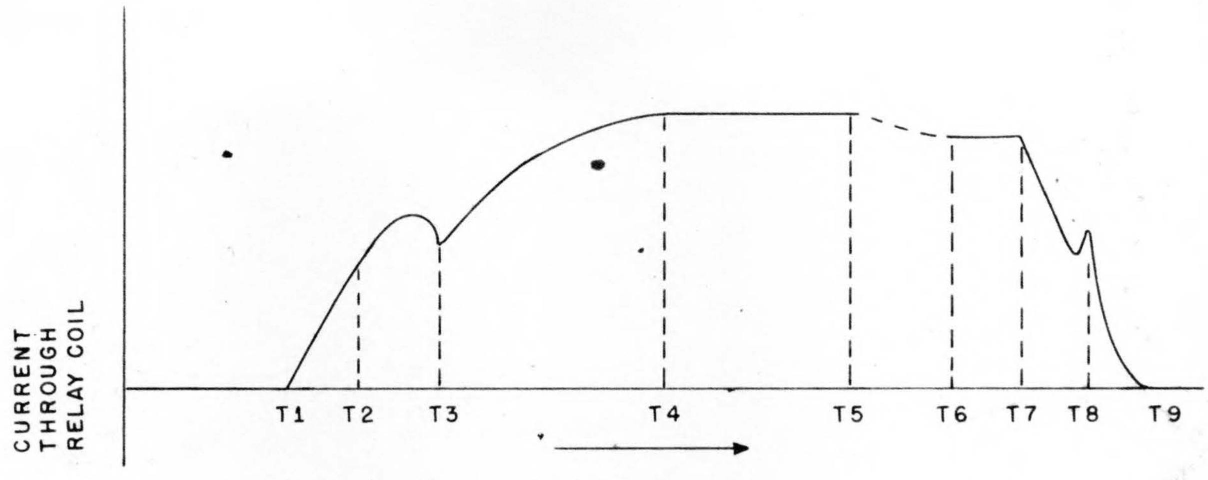

Figure 89. Current Growth and Decay in a Relay Coil

(4) When the coil circuit is opened at time T7, the current decreases in a manner depending upon the arc-suppression methods used. In Figure 89 the current shown would result if a rectifier were connected across the coil to permit a gradual discharge of current. (This method of arc suppression will be discussed in more detail in a later paragraph.) The current decreases until the drop-out point is reached when the armature begins to open. As the armature opens it generates a back voltage in the same direction as the original energizing voltage. This causes a slight increase in the decay current until the armature is fully opened at time T8. When the armature is fully open the inductance of the relay is lower, and the current decreases at a faster rate until it reaches zero at time T9.

(5) When a circuit containing an inductive element - such as a relay coil - is broken, the voltage induced by collapse of the magnetic field tends to maintain the flow of current and an arc forms if some type of arc suppression is not used. The induced voltage at the break may be many times the normal voltage applied but does not reach that peak value due to the formation of the arc. The energy stored in the magnetic field of the inductance is dissipated in the form of heat in the arc.

E. DROPPING RESISTORS. (1) 60-volt relays are sometimes used with suitable dropping resistors to permit operation from a 120-volt supply. This shortens the operate time of the relay by providing a high initial voltage across the relay coil to increase the rate at which the current builds up to the pick-up point. This may be seen by examining Figure 90.

(2) If no dropping resistor is used and the relay is operated by a 60-volt supply as shown in Figure 90 (a), the closing of S_1 applies 60 volts to the relay coil, the voltage marked E_{k1} in Figure 90 (c) starting at the time T_0. The current will build up as shown by the curve I_1. The relay will close at time T_2 when the current I_1 reaches the pick-up value.

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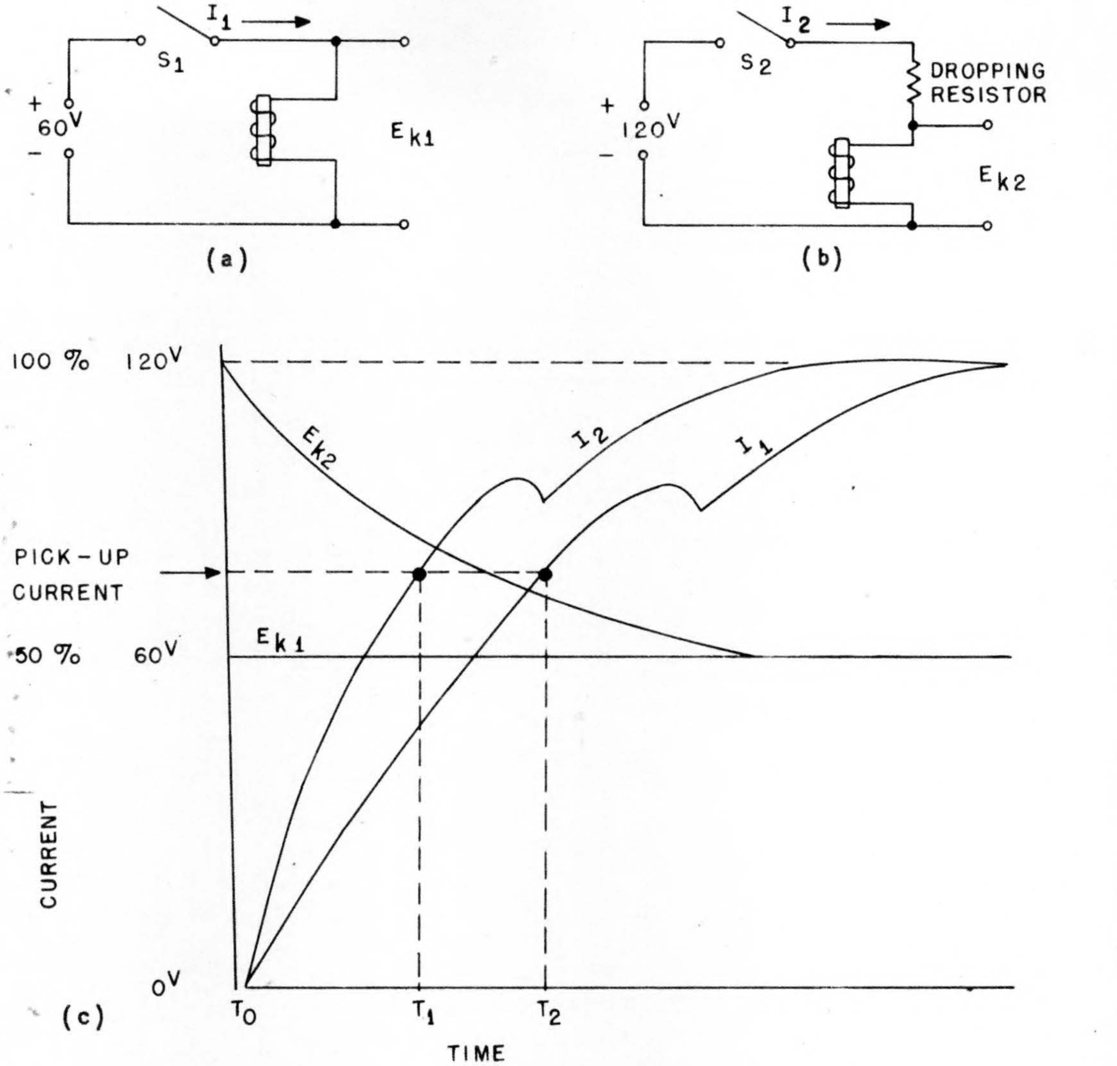

Figure 90. Effect of Dropping Resistor on Pick-Up Point

(3) If the dropping resistor is used as shown in Figure 90 (b), the closing of switch S_2 will apply 120 volts to the series combination of relay and resistor. At the initial instant, due to the inductance of the relay, nearly all the 120 volts will appear across the relay coil and very little across the resistor as shown by curve E_{k2} in Figure 90 (c). As the current starts to flow, the voltage drop across the resistor increases and the voltage across the coil decreases by the same amount. The voltage across the relay coil will continue to decrease until it reaches a steady-state value determined by the dropping resistor. The current I_2 through the relay will rise at a faster rate due to the higher initial voltage, and will reach the pick-up value at time T_1 which is earlier than the time T_2 for pick-up in the circuit shown in Figure 90 (a).

(4) The pick-up time of a Clare Type K relay with a 60-volt, 2500-ohm

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coil is on the order of 11 milliseconds when operated on 60 volts directly. By using a 2500-ohm dropping resistor and operating on 120 volts, the pick-up time is reduced to 7 or 8 milliseconds. The drop-out time is not affected, being about 3 to 4 milliseconds in either case.

25. ARC SUPPRESSION. A. GENERAL. (1) Visible sparking at the contacts of a relay may be due to flashing as the contacts close, to arcing as the contacts break, or to a combination of the two. Both flashing and arcing are detrimental since they damage the contacts by burning and pitting. In addition, the sharp peaks and the oscillations involved produce radio-frequency interference which may cause trouble in other circuits or equipments.

(2) Flashing on the make of the contact is usually caused by high inrush current, but it may be aggravated by bounce of the contacts. Inrush currents of many times normal may be drawn by loads such as tungsten-filament lamps, a-c solenoids, motors, capacitors, or rectifiers feeding into a capacitance filter network. It is sometimes necessary to provide special inrush-reducing or current-limiting circuits to reduce flashing.

(3) Some arcing may be expected on the break of any unsuppressed contact except in the case of negligible loads. Contacts operating in a-c circuits having moderate voltages and currents do not, in general, require suppression. In a-c circuits the voltage across the contacts passes through zero twice each cycle, extinguishing any arc that may tend to form. Once extinguished the arc will not re-establish itself.

(4) Contacts operating in d-c circuits containing inductive elements such as solenoids, relay coils, and motor fields will arc on the break unless adequate suppression means are provided. When a contact in a d-c inductive circuit begins to open, the current starts to diminish, but the decrease in current and the resulting collapse of the magnetic field induces a voltage in the inductance proportional to the rate of change. This induced voltage aids the flow of current. The induced voltage does not prevent a change in current, for its existence depends upon the existence of a rate of change of current. The induced voltage will, however, make the change of current more gradual. The inductance will act for the moment as a source of high voltage as it supplies energy to maintain the flow of current, and this excess voltage will appear between the opening contacts. The induced voltage is high enough to cause an arc to form at the contacts and current will continue to flow through the arc, although at a diminishing rate. The current will diminish just rapidly enough to supply the induced voltage needed to maintain the current until the current has diminished to zero and the transient period of decay is ended.

(5) There will always be a perfect balance between the voltage needed to maintain current in the circuit and the voltage induced in the inductance. If the induced voltage were too small to maintain current through the arc after the contact has just opened, the current would have to cease at once, or at least would diminish more rapidly. A more rapidly diminishing current would induce a greater voltage, however, until the induced voltage did become

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sufficient to maintain the current. If the current stopped instantly, an infinite voltage would be induced; this, of course is impossible, for an infinite voltage would maintain a current no matter how rapidly the switch were opened. The relation between induced voltage, current, and time could be expressed approximately in an equation, but for this discussion it will be sufficient to say that the more rapidly the contacts are opened, the higher the induced voltage will be. The only limit to the induced voltage is the amount of voltage needed to maintain the current.

(6) There are four major methods of arc suppression:

1. resistor across contacts
2. capacitor across contacts
3. capacitor across inductance
4. rectifier across inductance.

All of these methods are based upon providing an alternate path for the decay current. The energy stored in the inductance is dissipated as heat in the various resistances in the circuit instead of in an arc at the contacts. When capacitors are used in a suppression circuit, flashing may result unless a resistor is placed in series with the capacitor to limit the charging current.

(7) The need for, as well as the effectiveness of, arc suppression circuits may be checked by visual inspection of the contacts under operation, by the use of headphones connected across the coil of the inductance, or by the use of an oscilloscope. In general, the visible checking of arcing in a subdued light or darkness will prove sufficient. If it is not possible to darken the room, the headphone method may be used. Arcing or flashing will be heard as an irregular cracking or rushing noise; harmless inductive peaks occurring after suppression will be audible as sharp clicks. A final check may be made by observing, on an oscilloscope, the voltage across the inductance and contacts and the current through the inductance and contacts (as observed across a small series resistor).

(8) The four major types of arc suppression are explained in detail in succeeding paragraphs. In each case the relay coil is considered the inductance since in computing circuits relay coils are the most common inductive load encountered. All contacts are shown as normally open, although theory applies equally as well to normally closed contacts, the only difference being the greater susceptibility of the latter to "bounce" troubles. No attempt is made to evaluate any one method as being superior since the suitability depends upon many factors - relay speed, space, economy, location of components, etc.

B. RESISTOR ACROSS CONTACTS. (1) A resistor connected across the relay contacts will reduce the arcing since it allows a gradual decay of the stored energy of the inductance. This method is not frequently used since it is then not possible to open the load circuit completely. If the resistor is made sufficiently large to reduce the current to a negligible value, the arc suppressing is nullified.

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D. CAPACITOR ACROSS THE CONTACTS. (1) A capacitor connected across the relay contacts will permit the stored energy of the inductance to be dissipated in an ordinary oscillatory discharge. A resistor is usually connected in series with the capacitor to limit the discharge current. A circuit of this type, together with typical waveforms, is shown in Figure 91.

(2) The action of the capacitor can be analyzed as follows: with the contacts open, the capacitor is charged to supply voltage. When the contacts close, the capacitor is short-circuited and discharges, the resistor limiting the discharge current. As shown in the curve I_S in Figure 91, the high peak is followed by the gradual build-up of current in the relay coil (L) and the dip caused by the closing of the armature as previously explained. When the current through the contacts (I_S) drops to zero, the current through the coil charges the capacitor as shown both by the decrease in I_L and the peak in I_{RC}. Since this is a series RLC circuit, the action will be oscillatory; it will, however, decay in about two cycles. The relay armature releases on the initial dip of the coil current as indicated by the "drop-out" irregularity on the I_L curve.

(3) The proper values for the capacitor and resistor are best determined experimentally. The capacitor should be selected first; progressively larger sizes should be chosen until there is no evidence of arcing. In general, quick-acting telephone-type relays will require between 0.1 and 0.5 microfarads. The resistor should be large enough to prevent visible flashing, but should not be so large that arcing occurs on the break of the contact. An arbitrary method is to first determine the minimum size that will prevent flashing, then next find the maximum size possible to use without arcing, and finally select a value half-way between these limits.

(4) After determining the values by the method outlined above, a safety factor may be included by increasing one of the components to the next larger size. Mechanical fatigue of the contact springs or other wear-induced changes in the relay may slow the contact break and cause the contacts to start arcing. Increasing the values of the components will compensate for these changes.

D. CAPACITOR ACROSS INDUCTANCE. (1) A capacitor connected across the inductance in the circuit will, when the contacts open, dissipate the stored energy in what might be considered a tank circuit. This arrangement together with typical waveforms, is shown in Figure 92. The resistor is added to limit the charging current of the capacitor.

(2) The circuit functions in much the same manner as the capacitor-across-contact arrangement except that the energy stored in the inductance is dissipated in a tank circuit instead of through the power supply circuit. Also the capacitor is initially uncharged and is charged from the power supply as the contacts close. This method is convenient to use when a number of contacts control one relay since only one capacitor and resistor need be used. It is especially useful when the controlling contacts are distributed throughout a number of chassis.

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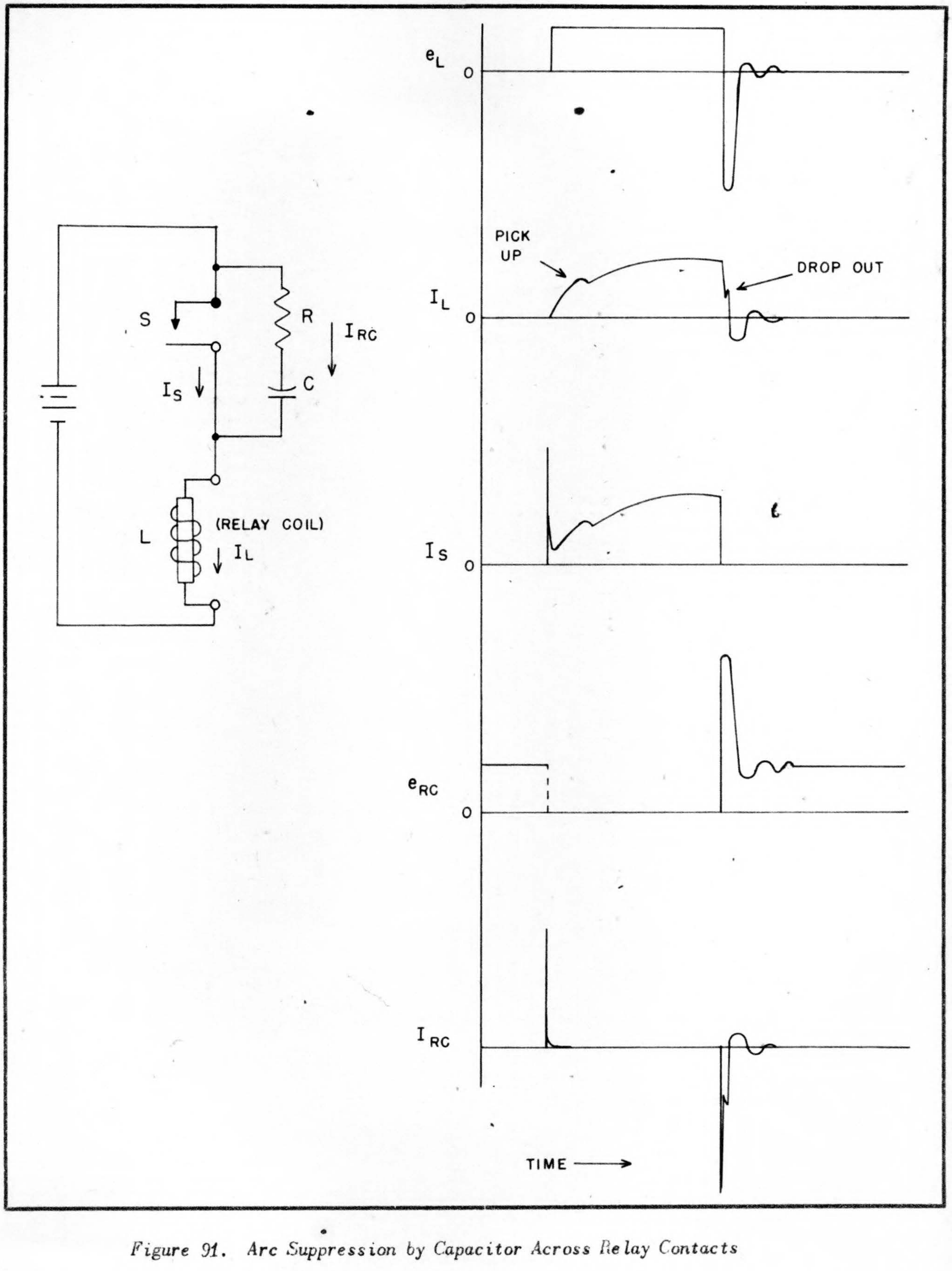

Figure 91. Arc Suppression by Capacitor Across Relay Contacts

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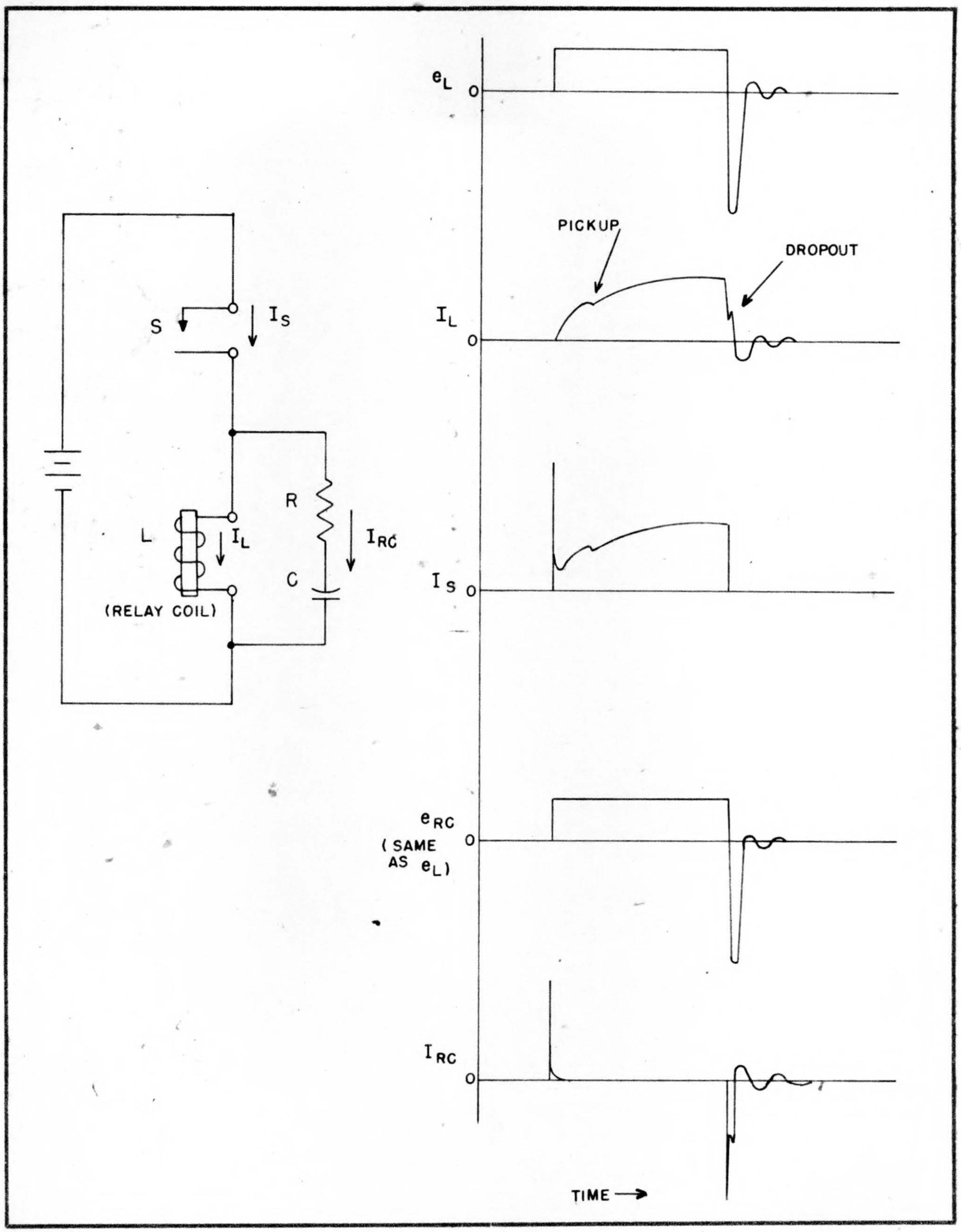

Figure 92. Arc Suppression by Capacitor Across Inductive Load

(3) The method of selecting component values is similar to that used in the capacitor-across-contact arrangement. If dropping resistors are used to speed the closing of the relay, no current-limiting resistor need be used since the dropping resistor limits the charging current. A circuit of this type is shown in Figure 93.

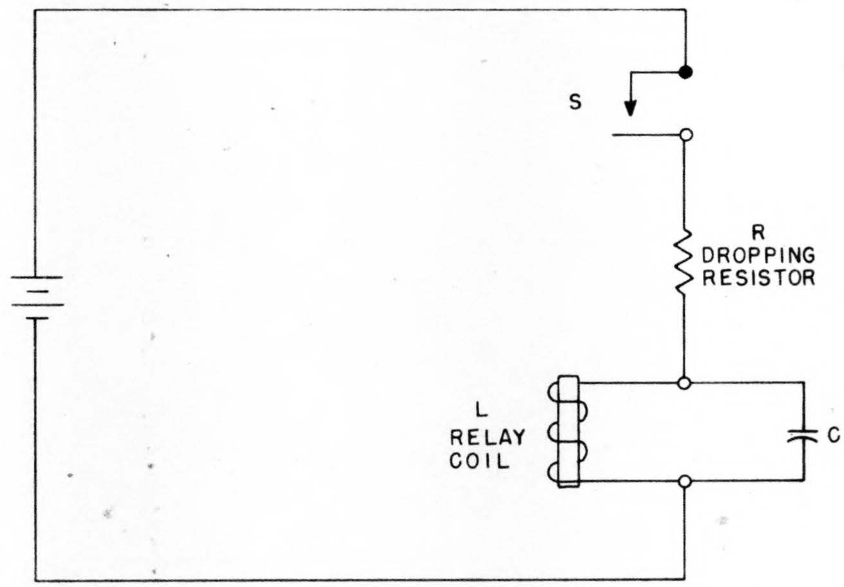

Figure 93. Arc Suppression by Dropping Resistor

E. RECTIFIER ACROSS INDUCTANCE. (1) An effective method of arc suppression uses a rectifier shunted across the load inductance. A circuit of this type is shown in Figure 94, together with typical waveforms. The resistor in series with the rectifier is, in some cases, necessary to limit the current to within the rated value.

(2) The rectifier is connected in the circuit so as to oppose the conventional current flow from the power supply when the contacts are closed. A relatively small leakage current may flow since the back resistance is not infinite. When the contacts open, the rectifier shorts the inductive discharge and the stored energy is dissipated in a gradual decay of current through the rectifier and series resistor. Since the rectifier has a very low resistance in the conducting direction, there is no induced high voltage built up across it.

(3) The rectifier can be a diode, a selenium rectifier, or a germanium crystal. Diode vacuum tubes are seldom used due to cost, space, and wiring considerations. Selenium rectifiers are relatively large. Germanium crystals are perhaps the most widely used, their application being limited by their low voltage rating - 60 to 90 volts - and thus small current-handling ability.

(4) In using a rectifier for suppression, the breakdown voltage must be

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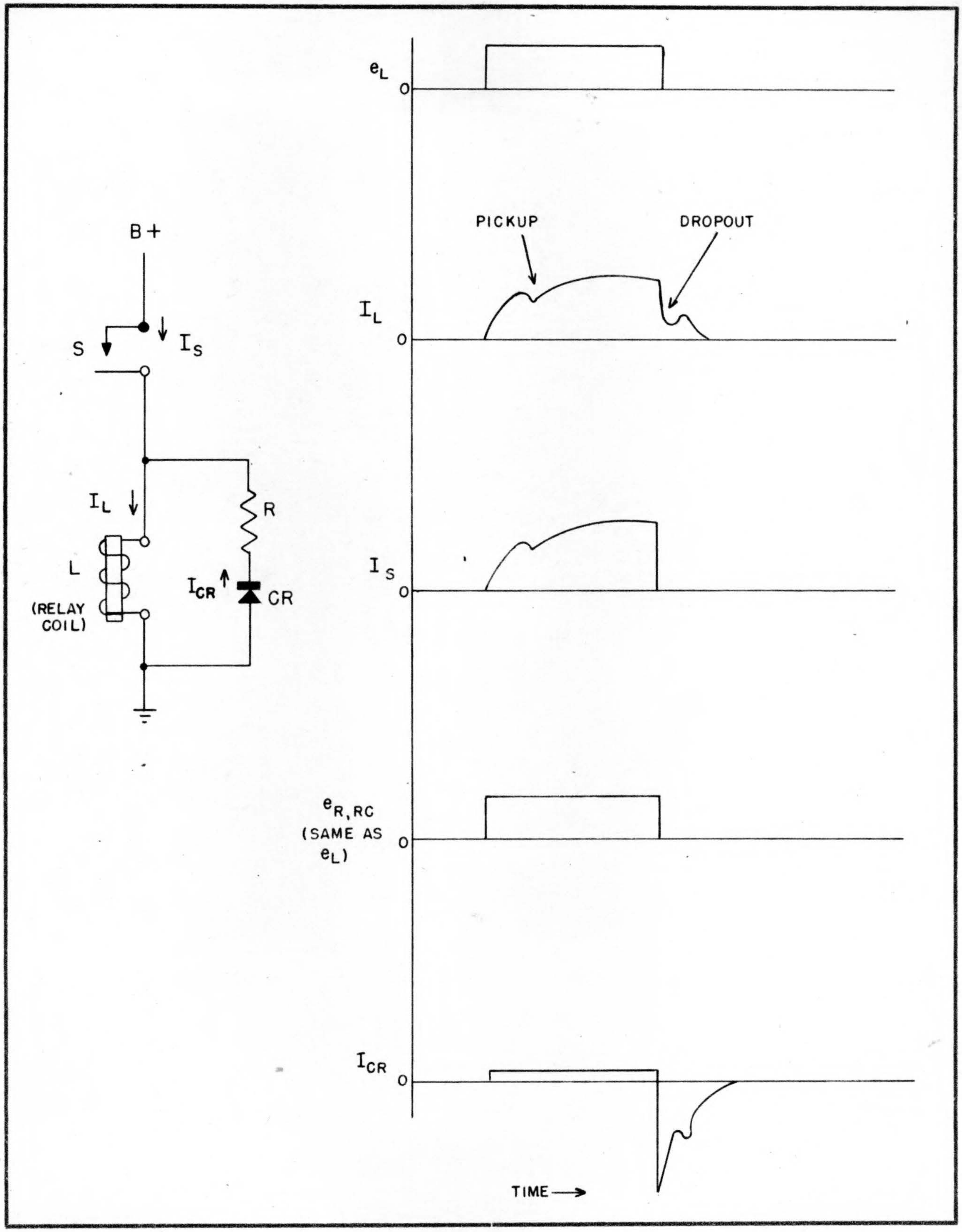

Figure 94. Arc Suppression by Rectifier Across Inductive Load

less than the supply voltage. The peak discharge current must be less than the maximum current rating of the rectifier. This peak current may be calculated by:

$$I_{(peak)} = \frac{E}{R_L + R_R}$$

where E = supply voltage
R_L = resistance of relay coil
R_R = resistance of series resistor

The resistance (R_R) chosen should be sufficient to limit this peak current to well below the rating of the rectifier.

26. INTERFERENCE REDUCTION. A. GENERAL. (1) Arcing, flashing, and sparking at electrical contacts generate impulses of a steep-wavefront character which may be picked up by sensitive electronic circuits. These pulses cause interference by appearing as "hash" or spurious pulses which produce errors in computing circuits and malfunctioning in control circuits. The interference may be picked up by leads, may enter circuits directly, or may enter by power lines.

(2) Typical sources of interference are d-c relay contacts, a-c relay contacts, cam-operated contacts, and commutators. Interference may be produced by such devices even though they are not a part of the immediate equipment since disturbances may be propagated along power lines.

(3) Due to the nature of the circuits used in computing equipment, the pick-up is usually inductive rather than radio-frequency in nature. The r-f components may produce noise in adjacent r-f equipment, however.

(4) In many cases the interference can be reduced or eliminated at its source by suppression, filtering, or shielding. If this does not prove sufficient or feasible, such precautions as separation of lines and leads, shielding at the point of pick-up, filtering near the circuits affected, and more thorough grounding may be employed. In designing circuits, limiters and clippers are sometimes included to eliminate possible interference from low-level variations or "hash".

B. REDUCTION AT SOURCE. (1) The arc suppression circuits described in detail in Paragraph 25 of this section will eliminate visible arcing on d-c contacts to prevent contact damage; in so doing they will also eliminate most of the interference. Some additional interference reduction may be required, however.

(2) Contacts in a-c circuits may require arc suppression for interference reduction even though there is little danger of contact damage. The circuits described in the preceding paragraph, with the exception of the rectifier type, are suitable for use with a-c contacts.

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(3) Where arc suppression circuits do not sufficiently reduce the interference (or in a location where it is not feasible to place the necessary components) a filter circuit may be used to prevent a-c lines from carrying the interference. In some cases it may be necessary to use an LC type filter with the inductance in the a-c line to prevent the disturbances from gaining access to the a-c distribution system.

C. REDUCTION OF PICK-UP. (1) Physical separation of relay-pulsed or interference-bearing leads from other leads in sensitive electronic circuits will reduce the possibility of inductive pick-up. If physical separation alone is not sufficient, shielding of either or both sets of leads further reduces the possibility of interference being picked up. The shields should, of course, be adequately grounded.

(2) The importance of adequate grounding in interference reduction cannot be over-emphasized. "Floating" grounds are particularly likely to pick up and carry interference to sensitive portions of the equipment. The exclusive use of power line grounds is, in general, inadvisable due to the possibility of picking up interference produced by equipment farther out on the distribution system. In one specific case, spurious pulses appearing on a power line ground were fed into an inadequately grounded circuit through an oscilloscope ground connection.

(4) Filtering at or near the point where the interference produces trouble is sometimes employed. In one case spurious pulses were produced by an inverter stage. Upon investigation, the trouble was found to be caused by interference picked up by a power supply lead. The fluctuations appearing at the plate of a gate tube were applied to the grid of the inverter stage through the coupling capacitor, causing spurious pulses to appear at the inverter output. The trouble was remedied by installing a small filter capacitor from the plate supply to ground.

27. CONTACT FORMS AND ARRANGEMENT. A. GENERAL. (1) The relay circuits used in computing equipment for such functions as counting, storage, translation, control, etc., are quite complex. However, when broken down into individual stages, the circuits are found to be made up of combinations of simple relays. A thorough knowledge of the basic principles of operation of a simple relay will prove to be an advantage in understanding the complex circuits encountered.

(2) The most simple form of relay is shown in Figure 95 (a). The diagram symbolizes a movable armature (1) which is pulled toward the magnet core, closing relay spring contacts (1) and (2) and completing the circuit. This type of contact is known as Form A, make, or normally-open contact. Figure 95 (b) shows other commonly used contact forms. The Form A, Form B, and Form C contacts are the most frequently used.

B. CONTACT ARRANGEMENT. (1) Extensive use is made of the quick-acting multiple-contact, telephone-type relay in computing equipment. The shorthand descriptive code of Form A, etc., was developed to simplify the

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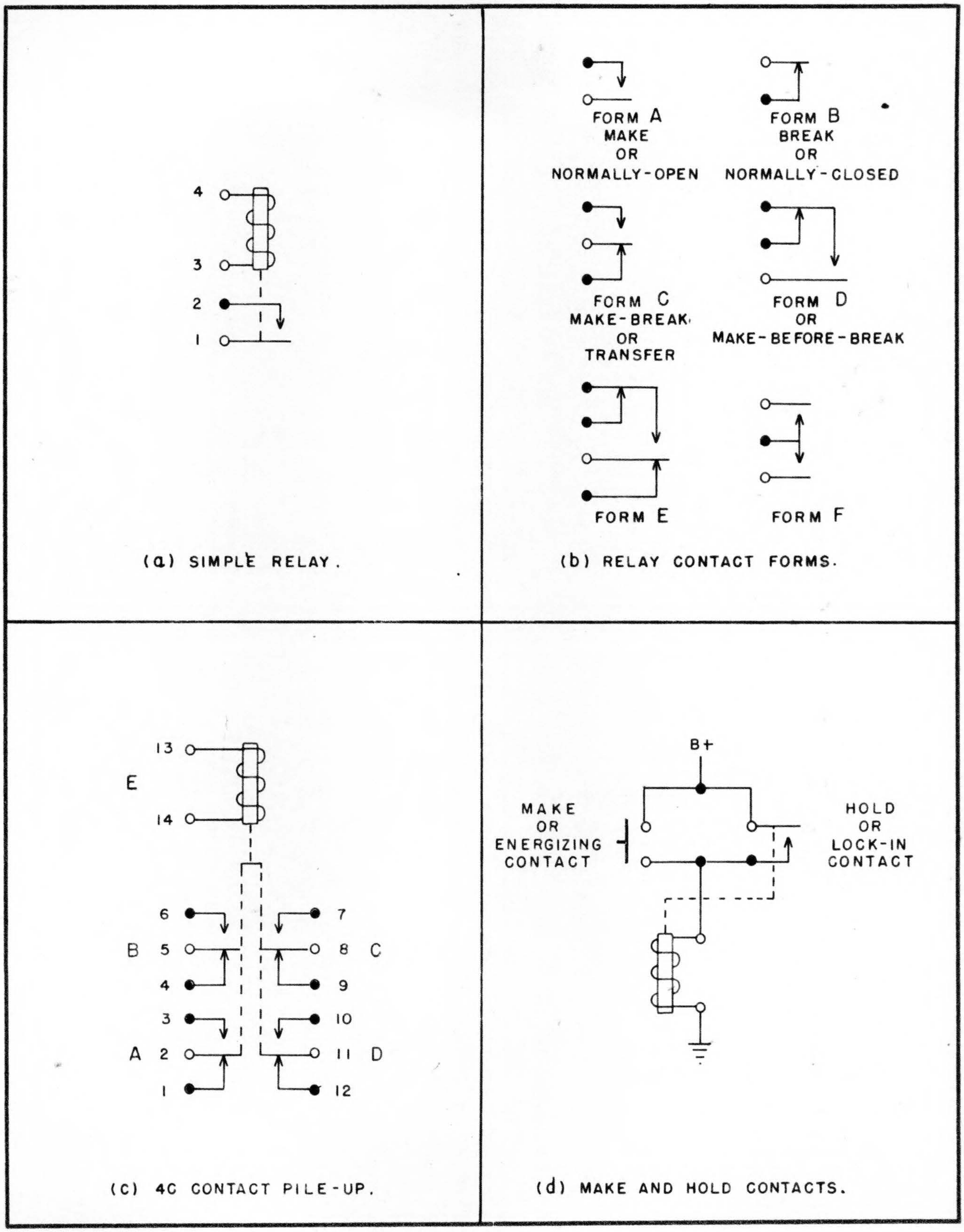

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Figure 95. Relay Forms and Contact Arrangements

description of multiple contact arrangements. This contact code, as shown in Figure 95 (b), is listed in Appendix A of The Manual of Standard Descriptions, JANP 109, and is in common use among relay manufacturers. The contacts, then, which are usually arranged in one or more stacks or pile-ups, may be specified by a description such as 1A2B1C, 4C, or 2C1D.

(2) Due to the large number of relays used in a computer, it is common practice to standardize on a few types of relays. This facilitates design, construction, maintenance, and the handling of spare parts. One of the most commonly used types of relay is a quick-acting relay containing four Form C contacts as shown in Figure 95 (c). This relay provides a sufficient number of contacts for most applications. If a greater number is needed, a number of relays may be connected in parallel, or, for an extremely large number of contacts, special relays may be employed.

C. RELAY CIRCUIT ELEMENTS. (1) The coil circuit of each individual relay stage in a relay circuit may contain one or more of the following elements:

1. an energizing or make contact
2. a hold or lock-in contact
3. a disabling or release contact
4. an enabling or set-up contact.

The hold contact is operated by its own relay coil while the others are operated by other relay coils. The relay coil being energized may, in turn, control similar contacts in the coil-operating circuits of other relays; it may also operate condition-indicating contacts to energize indicators or supply information to other circuits of an equipment.

(2) A relay is energized when sufficient current flows through its coil to cause the relay to operate its contacts. The relay may be energized by various means, among which are (1) the closing of a normally-open contact such as a relay contact, push-button, or cam-operated switch, or (2) through the action of an electronic tube such as a vacuum tube plate circuit or grounding through the firing of a thyratron. If the energizing is accomplished by means of a contact, the contact is called the make or energizing contact. In Figure 95 (d) the relay is made or energized by the closing of a normally-open push-button switch.

(3) After a relay has been energized it will release upon the opening of the make contact unless a holding contact is used. In Figure 95 (d) a typical hold or lock-in contact is shown. This contact is operated when the relay is energized and is connected in parallel with the energizing push-button so that the relay will remain energized after the energizing push-button is released.

(4) In order to release or de-energize a relay having a lock-in (hold) contact, it is necessary to include a Form B (normally-closed) contact in the B+ supply as shown in Figure 96 (a). In some cases the release contact may be located in series with the hold contact as shown in Figure 96 (b). The release

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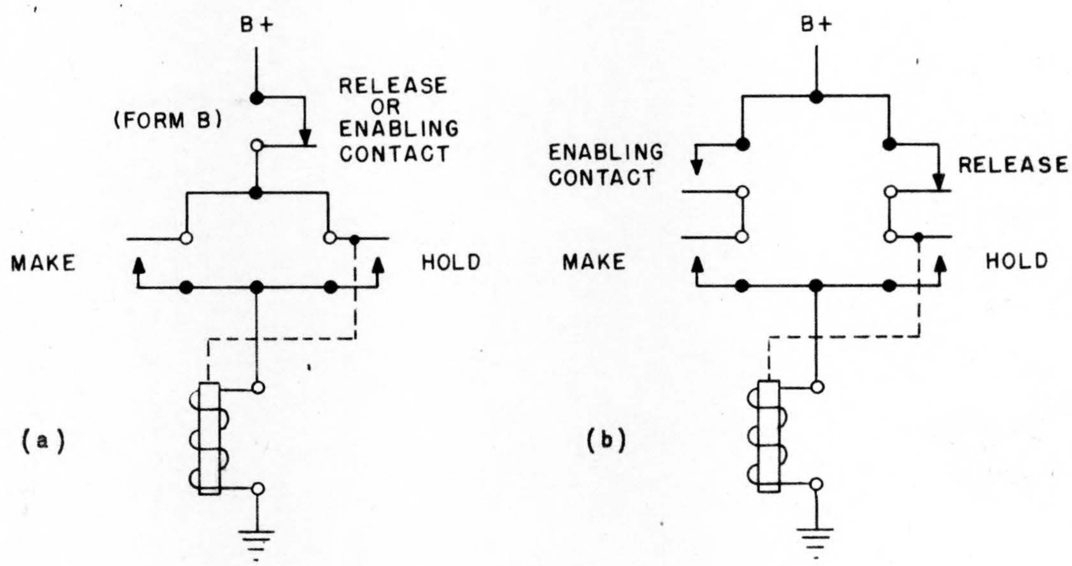

Figure 96. Release and Enabling Contacts

or disabling contact is operated by another relay, usually by a relay in a succeeding stage of the circuit. A disabling contact may also be operated by a preceding relay to prevent the relay from being energized or to reset the relay.

(5) A normally-open enabling contact may be added in series with the make contact if it is required that a relay not operate until some predetermined sequence has occurred, or that a coincidence operate a relay - that is, operation similar to a gate or coincidence tube. This is shown in Figure 96 (b). The Form A enabling contact prevents the Form A make contact from energizing the relay until the enabling contact closes. The enabling contact may appear in the B+ supply if control of both energizing and holding is required.

D. RESETTING. (1) To reset a relay circuit is to restore it to some predetermined condition. In general, a circuit is reset by de-energizing all of the relays. This may be accomplished by breaking either the B+ or ground connection.

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E. SYMBOLS. (1) In simple relay diagrams it is customary to symbolize a relay in a simple mechanical manner by indicating the contacts at either end of the relay coil, the armature being assumed to move toward the coil when the coil is energized. In diagrams of circuits containing relays having a number of contacts operating in widely separated stages, it is not feasible to adhere to such presentation because of the resulting complexity of interlacing electrical lines. In these more complex diagrams the electric circuit is drawn in a simple schematic manner with the relay contacts located where they occur in the circuit. The different forms of contacts (Form A, B, C, etc.) are drawn as standard symbols, and, in simple repetitive circuits, the contacts may be connected to the coil which operates them by a dotted line. The position of the armature in relation to the coil is not significant. In non-repetitive, complex diagrams (such as are found in control circuits), the relay contacts may be coded to the operating coil by means of symbol numbers instead of being connected by dotted lines.

(2) In diagramming relay circuits the following conventions are generally used:

1. The d-c supply or B+ bus is shown at the top of the diagram or relay bank. The relays tie between this bus and ground in conventional across-the-line manner.

2. Relay circuits read from left to right.

3. Coil energizing and holding contacts are shown above the relay.

4. Contacts connected to external (or indicating) circuits are shown above the relay.

5. So far as possible, make or energizing contacts are shown first in order, followed to the right by the holding contacts.

6. Where one stage of a circuit is composed of a number of relays, these relays are grouped together. Subsequent similar stages are shown in similar fashion.

28. STEPPING SWITCHES. A. GENERAL. (1) Stepping switches are a special type of relay used in computer circuits to perform three types of control operations:

a. Selecting one circuit from among a number.

b. Consecutively performing operations in separate individual circuits.

c. Providing timed pulses at accurately spaced equal or unequal intervals.

(2) Stepping switches consist essentially of one or more wiper arms,

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fixed on a shaft which is moved by a pawl-and-ratchet mechanism. This mechanism is actuated by an electro-magnet, which responds to momentary impulses of current. At each impulse the pawl engages the ratchet, moving the wipers one step forward over a bank of contacts

(3) There are two main types of stepping switches. These are referred to as direct-drive and spring-drive.

DIRECT DRIVE - Operation of the stepping magnet drives the pawl into the ratchet and moves the wiper assembly; a detent holds the wipers in place when the stepping magnet is de-energized and the driving pawl is returned to normal by a spring. The switching operation is complete the moment the magnet operates; the circuit of the stepping magnet may be held closed for any desired time after the final step. With this method of operation, the pawl is normally disengaged from the ratchet; thus, the wiper assembly can be returned to normal by simply disengaging the holding detent through the use of a release magnet. One type of direct drive stepping switch is shown in Figure 97.

SPRING DRIVE - Operation of the stepping magnet moves the driving pawl out of the ratchet and drops it over the succeeding tooth, but does not move the wiper assembly. When the magnet is de-energized, the wiper assembly is driven forward by a spring. The switching operation is not completed until the magnet circuit is opened after the final step. As the pawl is at all times engaged in the ratchet, homing can be provided only by stepping the wiper assembly forward.

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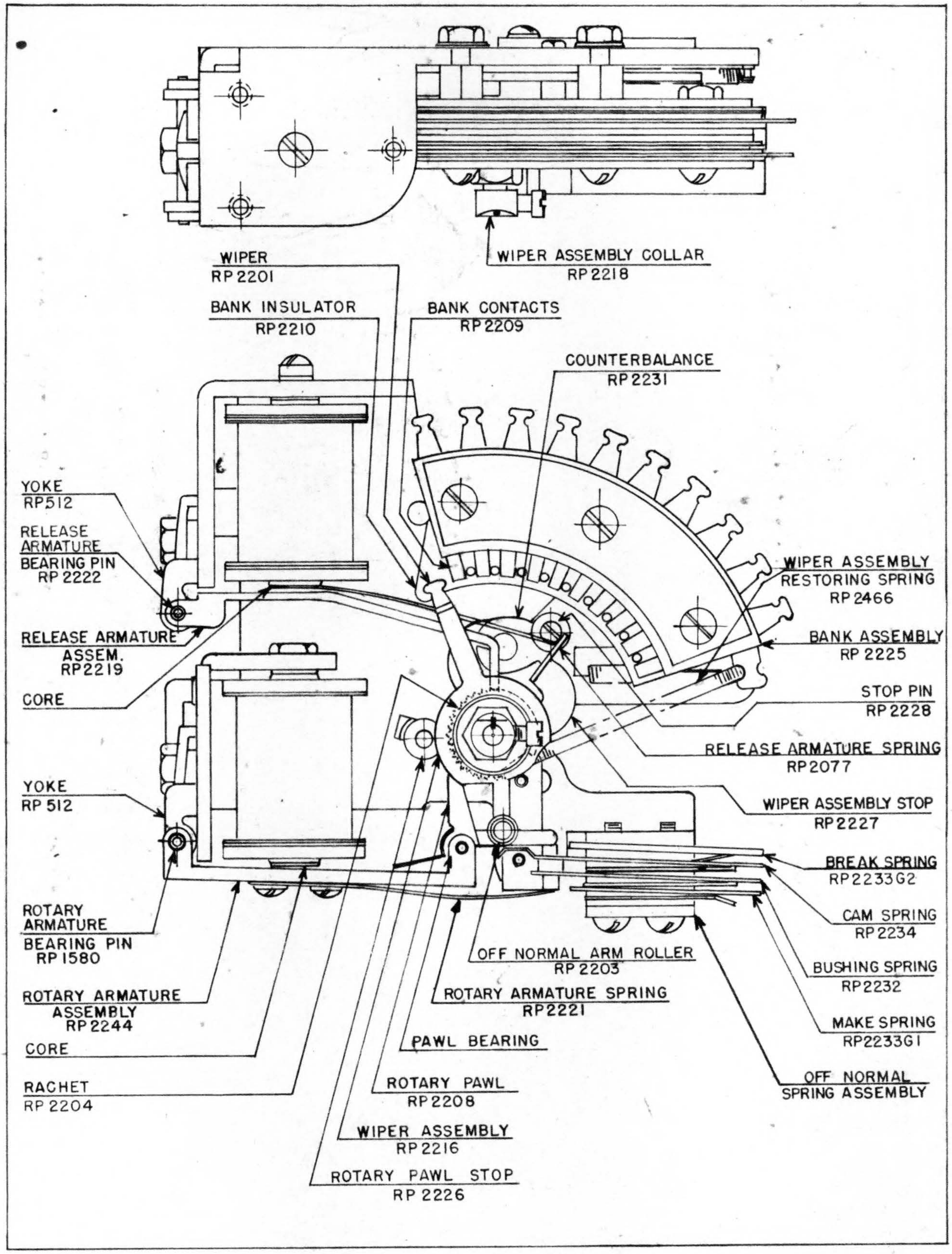

Figure 97. Direct Drive Stepping Switch

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This bibliography tabulates a number of books which the student technician may find useful either for a more detailed treatment of subjects presented in this book or for a discussion of specialized topics which have not been considered in the present book. Some of the books listed require a knowledge relatively little mathematical background while others require a knowledge of calculus for complete understanding. Books are grouped according to general subject matter, but a book may be listed in more than one group.

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