SUBCOURSE
MM5000

EDITION
7

TIMING CIRCUITS

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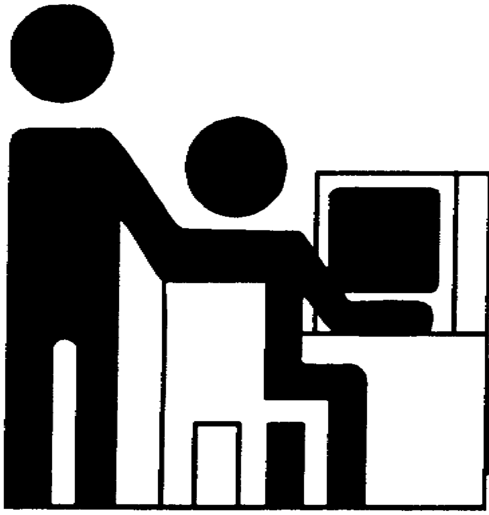
READINESS/
PROFESSIONALISM
THRU
GROWTH

THE ARMY INSTITUTE FOR PROFESSIONAL DEVELOPMENT

ARMY CORRESPONDENCE COURSE PROGRAM



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TIMING CIRCUITS

Subcourse MM5000
Edition 7

United States Army Combined Arms Support Command
Fort Lee, VA 23801-1809

Development Date: 31 March 1986

5 CREDIT HOURS

GENERAL

The timing circuits subcourse, part of the Air Traffic Control Systems Subsystems Equipment Repair Course, MOS 93D. This subcourse is designed to teach the knowledge necessary to troubleshoot and repair the timing circuits of the ATCSS equipment. This subcourse is presented in one lesson consisting of two learning events that correspond to the learning objective listed below.

TASK: 113-584-0065 Troubleshoot Radar Set AN/TPN-18A

CONDITIONS: (Performance-oriented) Given this subcourse, pencil, paper, and supervision.

STANDARD: (Performance-oriented) The standard is met when you can correctly answer 70 percent of the multiple-choice questions of the final examination.

(This objective supports SM Task 113-584-0066 Troubleshoot Radar Set AN/TPN-18A.)

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PLEASE NOTE

Proponency for this subcourse has changed
from Aviation (AV) to Missile & Munitions (MM).

Whenever pronouns or other references denoting gender appear in this document, they are written to refer to either male or female unless otherwise indicated.

SUBCOURSE MM5000 TIMING CIRCUITS

INTRODUCTION

Radar was a natural outgrowth of intensive radio research over a period of many years. In 1922 Dr. A. Hoyt Taylor of the Naval Research Laboratory observed that a ship passing between a radio transmitter and a radio receiver reflected some of the waves back toward the transmitter. Further research led, in 1934, to the determination of range by a single radar set. A pulse radar set for aircraft detection was demonstrated on land in 1936 and afloat on the destroyer "Leary" in 1937. The accuracy of the range measurements of this type of radar set depends upon the accuracy of the locally generated timing signals.

The circuits used to develop the timing signals for radars are also widely used in other types of electronic equipment. The sweep signals for televisions and oscilloscopes are generated and shaped by several different types of timing circuits. Frequency synthesizers and multiplexers rely upon timing circuits to provide the correct frequencies and the desired output waveshapes. Since military communications are beginning to utilize digital techniques for signal development and processing, precise signal generation, timing, and shaping circuits are to be found in many types of communication equipment.

Upon completion of this subcourse, you will know how various waveforms are generated and shaped for use in electronic timing systems.

This subcourse consists of two lessons and an examination, as follows:

Lesson 1. Introduction to Timers

Lesson 2. Applications of RC and RL Circuits

Reviewed and reprinted with minor revisions, January 1987.

LESSON 1

INTRODUCTION TO TIMERS

SCOPE..........................	Introduction to timers; basic operating principles of timing systems; block diagram and function of each element in a basic timing system; analysis of timing waveforms.
TEXT ASSIGNMENT.................	Pages 1 through 23
MATERIALS REQUIRED.............	None
SUGGESTIONS.....................	Do not become confused when you see the term "pulse recurrence time." It has the same meaning as pulse repetition period.

LESSON OBJECTIVES

When you have completed this lesson, you will be able to:

a. Derive the frequency composition of basic nonsinusoidal waveforms.

b. Determine the circuit bandwidth that is needed to pass waveforms without distortion.

c. Recognize poor high and low frequency response by analyzing the input and output waveforms for a circuit.

d. Identify and describe the waveshaping actions of various waveshaping circuits.

e. Analyze the operation of a basic timing system to determine the shapes and frequencies of the output waveforms.

INTRODUCTION TO NONSINUSOIDAL WAVEFORMS

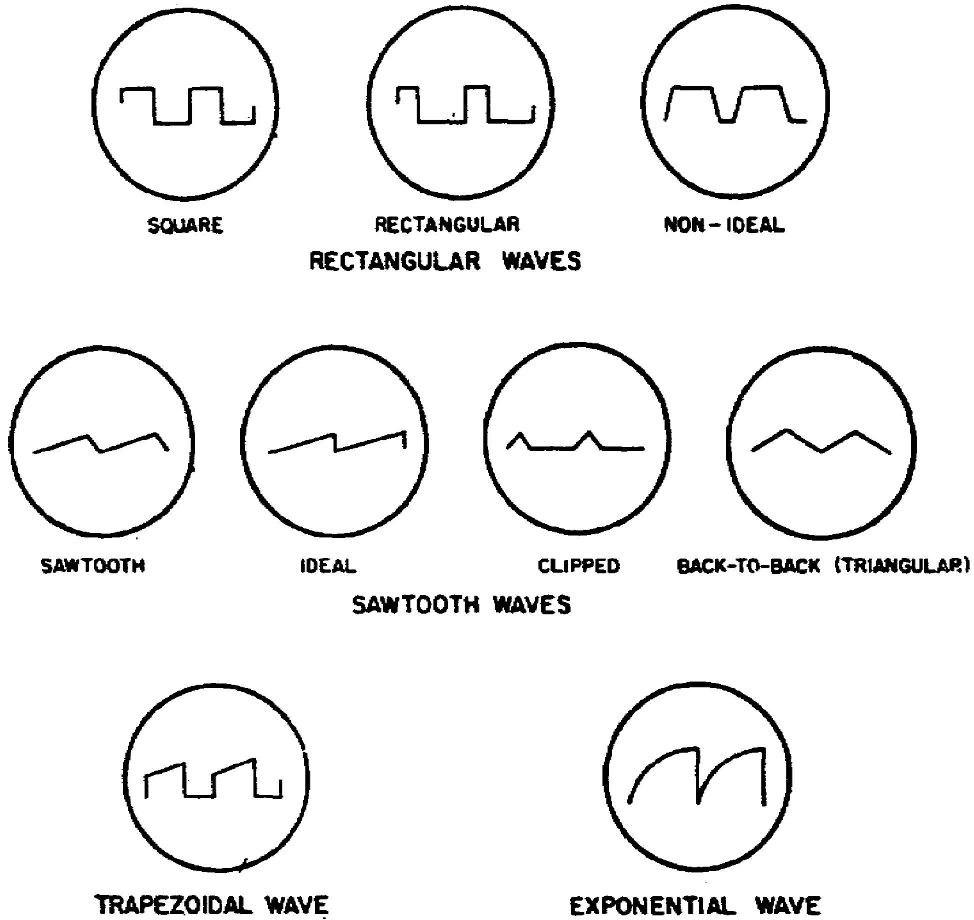
Section I. METHODS OF NONSINUSOIDAL WAVEFORM ANALYSIS

1. INTRODUCTION.

a. This special text presents information which will enable you to understand the performance of circuits containing resistance, inductance, and capacitance, and to analyze the response of these circuits. In addition, this text discusses the application of these principles to specific circuits in electronic equipment.

b. A waveform can best be described as any rise or fall of voltage or current over a finite period of time. A variety of waveforms are produced by electronic circuits. Waveforms that do not follow the conventional pattern of the sine wave are called nonsinusoidal waveforms (Figure 1). Originally, nonsinusoidal waves were regarded as undesirable distortions of sine waves. Today, their study has been extended to determine new ways of producing and utilizing them.

Figure 1. Periodic nonsinusoidal waveforms



c. There are two types of nonsinusoidal waves: the aperiodic wave which appears at irregular intervals, or only once, and the periodic wave which is repeated at constant intervals. Unless specifically referred to as aperiodic, all waves discussed will be periodic waves.

2. METHODS OF ANALYSIS.

There are two methods of analyzing nonsinusoidal waveforms: the frequency-response method and the transient-response method. The frequency-response method analyzes the composition of the nonsinusoidal wave by considering the wave to be the sum of a large number of sine waves having different frequencies and/or phases and amplitudes. The transient-response method considers

the wave to be a rapid change in voltage or current, caused by circuit components, which is followed after a certain interval by another, similar change. This method analyzes the responses of a circuit to a transient waveform.

Section II. FREQUENCY-RESPONSE ANALYSIS AND TRANSIENT RESPONSE

3. FREQUENCY-RESPONSE METHOD OF ANALYSIS.

a. Using the frequency-response method of analysis, a waveform can be analyzed by determining the number, amplitude, frequency, and phase of sine waves required to reproduce it. The rate at which a waveform is repeated is known as the fundamental or first-harmonic frequency. If a waveform is repeated 1000 times per second, the fundamental frequency is 1000 Hz (hertz per second). The second harmonic of this waveform has a frequency equal to twice the fundamental frequency of 2000 Hz, and the third harmonic of this waveform has a frequency equal to three times that of the fundamental frequency or 3000 Hz. After the harmonic frequencies have been determined, reactance and frequency concepts can be applied to determine various circuit responses.

b. An important factor to consider in the frequency response method of analysis is the number of harmonics that must be included in forming the waveshape. A helpful rule to remember is that the maximum number of harmonics varies inversely with the width of the pulse being formed. Therefore, the narrower the pulse width, the greater the number of harmonics required to produce the pulse.

4. TRANSIENT-RESPONSE METHOD OF ANALYSIS.

a. Originally, the term transient was used to describe what occurred during the period immediately after a piece of equipment was turned off or on, or after some unusual disturbance occurred in the equipment. When nonsinusoidal voltages were introduced in electronic equipment, it was found that the methods developed to study transients could be applied to nonsinusoidal waveforms. The meaning of transient was then expanded to include the effects of the nonsinusoidal waveforms. Today, a transient is considered as any brief change in voltage in a circuit followed, after a period, by a similar change. Transient time is the period of time during which this change occurs. Conversely, a steady state is a period when the output pulse does not experience a change in voltage or current.

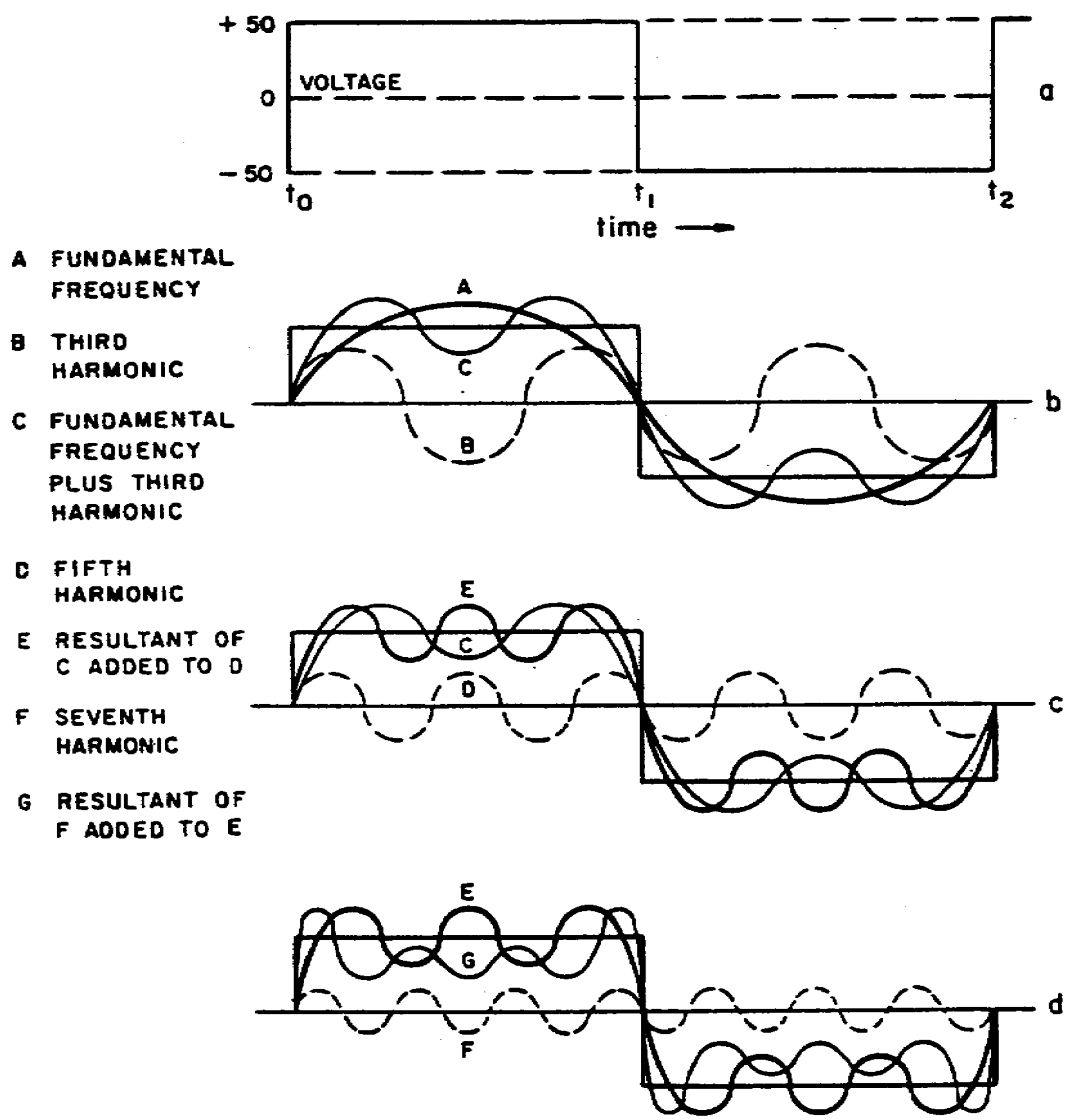
b. The transient-response method of waveform analysis is used to determine the response of a circuit to a transient waveform. Since voltages are nonsinusoidal during the transient time, the study of transients can be considered as the study of the response of a circuit to nonsinusoidal voltages.

Section III. NONSINUSOIDAL WAVEFORM COMPOSITION

5. NONSINUSOIDAL WAVEFORMS IN COMMON USE.

a. Composition of a square wave. A waveform commonly employed in electronic circuits is the square wave which has equal time durations during its periods of maximum and minimum amplitudes. Figure 2a illustrates a square wave in which voltage is plotted against time. This wave is called symmetrical because it varies equally, in time and amplitude, above and below the zero volt axis.

Figure 2. Square wave composition



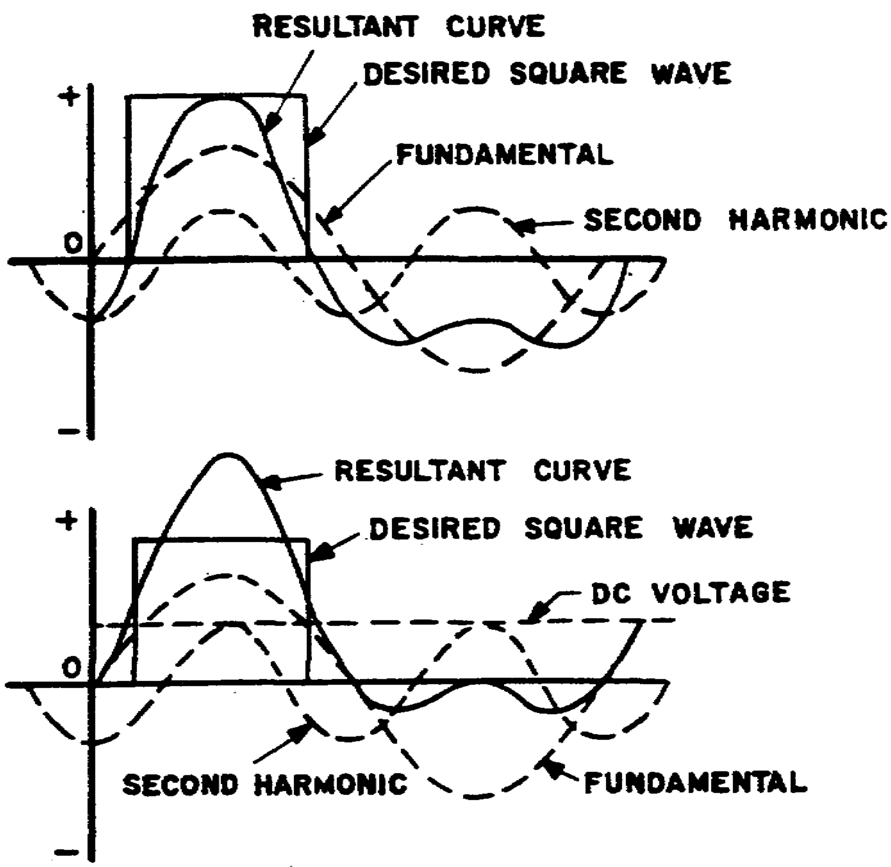
(1) Using the transient-response method of analysis, the square wave in the illustration can be considered as a voltage which rises instantaneously from -50 volts to +50 volts at time t_0. It remains at this value until time t_1, then drops instantaneously to minus 50 volts and remains at this value until time t_2, and so on.

(2) Using the frequency-response method, the square wave can be analyzed by determining what sine waves are required to reproduce it. To reproduce a symmetrical square wave, it is necessary to start with a sine wave having the same frequency as the square wave repetition frequency, and add to it the odd harmonics of this frequency as shown graphically in Figures 2b, 2c, and 2d. Waveshape C (Figure 2b) is formed by adding the fundamental frequency A and its third harmonic B, which has an amplitude equal to one-third of the amplitude of the fundamental. The resultant waveform already slightly resembles a square wave, as can be seen by the square wave superimposed on the diagram. Figure 2c shows the result of adding the fifth harmonic, at one-fifth of the amplitude of the fundamental, to the resultant waveform C. In the resultant waveform E, the corners are much sharper and the top is somewhat flatter. The seventh harmonic, at one-seventh of the amplitude of the fundamental, is added (Figure 2d) to form the resultant waveform G. This wave is fairly smooth across the top and fairly sharp at the corners. Adding the ninth harmonic at one-ninth of the amplitude of the fundamental, the eleventh harmonic at one-eleventh of the amplitude, etc., would further sharpen the corners and flatten the top of the wave. An infinite number of odd harmonics would produce a perfect square wave. However, in practice, the addition of 10 odd harmonics is usually sufficient for a satisfactory reproduction of a square wave.

(3) Many waveforms used in electronic circuits consist of short pulses separated by long time intervals. These pulses, called rectangular pulses, are constructed in a manner similar to the construction of symmetrical square waves. However, in addition to the sine waves of the fundamental pulse frequency and many harmonics of fractional amplitudes, a small DC voltage usually is added to create a reference level other than zero. In the construction of this type of waveform, both odd and even harmonics are used. The addition of the DC voltages causes the resultant wave to be formed about the DC voltage axis, thus increasing the amplitude of the positive portion and decreasing the amplitude of the negative portion with reference to the zero axis. The duration of the desired pulse in Figure 3 is one-third of the time required to complete one full cycle. To reconstruct this pulse, a DC voltage equal to one-third of the desired pulse amplitude is added to a sine wave of the fundamental frequency with an amplitude two-thirds of the desired pulse amplitude, the second harmonic with an amplitude of one-third the desired pulse amplitude, etc.

If the pulse repetition frequency is 1000 Hz, then the fundamental frequency (Figure 3A) will be 1000 Hz with an amplitude equal to two-thirds of the desired pulse amplitude. The second harmonic will be a 2000 Hz sine wave with an amplitude equal to one-third of the desired pulse amplitude. It can be seen that there is a resemblance between the desired square wave and the resultant curve. As each additional harmonic frequency is added in the proper phase and amplitude, the resultant waveform more closely resembles the desired pulse.

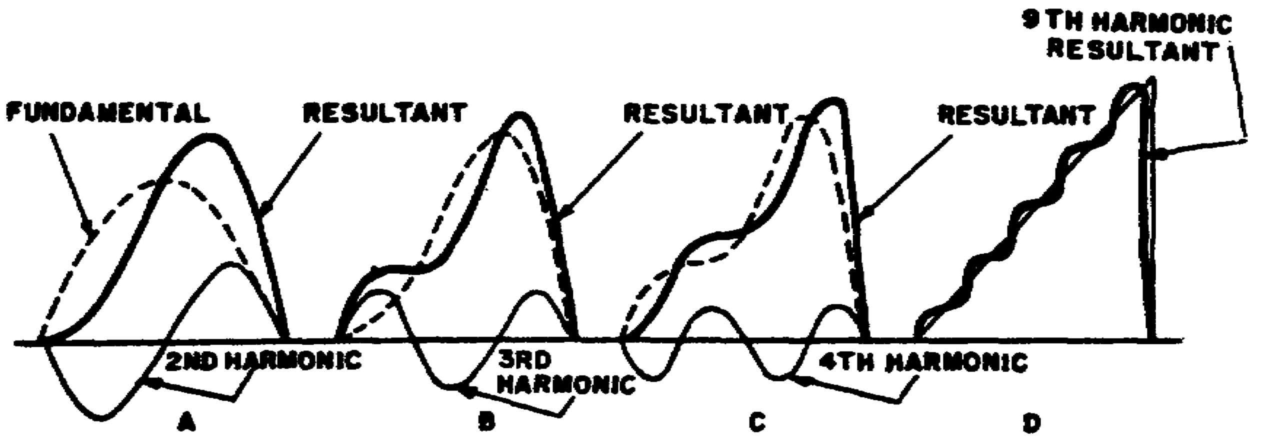
Figure 3. Composition of a short pulse with a long-time interval



b. Composition of a sawtooth wave. A sawtooth wave is formed by the addition of a fundamental frequency and both its even and odd harmonics. The effect of adding the fundamental frequency and its second harmonic is shown in Figure 4A. The resultant wave resembles the sawtooth wave more than the fundamental frequency wave alone because the peak is pushed to one side. Figure 4B shows the resultant wave when the third harmonic is added to the resultant wave of Figure 4A. In the illustrations,

it can be seen that the even and odd harmonics are added with opposite phase relationships. As each harmonic is added, the resultant wave more closely resembles the sawtooth voltage. This is illustrated by the addition of the fourth harmonic in Figure 4C, and up to the ninth harmonic in Figure 4D. Triangular waves can be constructed similarly by adding a series of sine waves in proper phase and amplitude to the fundamental frequency.

Figure 4. Sawtooth wave composition



Section IV. BANDWIDTH

6. EFFECTS OF BANDWIDTH ON NONSINUSOIDAL WAVEFORMS.

a. Bandwidth represents the range of frequencies that a circuit will pass. When a nonsinusoidal wave is applied to a circuit, the number of harmonics that appear at the output depends upon the bandwidth of the circuit. Consider the effect of a circuit with a 3-kHz (3000 kHz) bandwidth (from 0 Hz to 3 kHz) on a square wave having a pulse repetition frequency (prf) of 1 kHz. Since the circuit will pass only frequencies up to 3 kHz, only the fundamental frequency (1 kHz) and the third harmonic (3 kHz) will appear in the output (Figure 5A). Although a square wave is applied at the input, the output waveform is badly distorted. If the bandwidth of this circuit is increased to 7 kHz (from 0 Hz to 7 kHz), all of the harmonics up to and including the seventh will be passed (Figure 5B), and the output waveform is less distorted. As the bandwidth of this circuit is increased, more harmonics are passed and the output waveform more closely resembles the input waveform.

Figure 5. A square wave with low harmonic content

b. The relationship of harmonics to the waveform determines the practical bandwidth limits necessary to pass a nonsinusoidal wave. In some waveshapes, the amplitudes of the higher harmonics decrease rapidly, thereby decreasing the number of harmonics necessary for good waveform reproduction. This reduces the upper frequency limit and, in turn, narrows the bandwidth requirement. Similarly, a wide pulse reduces the number of harmonics necessary for good waveform reproduction, which also narrows the bandwidth requirement.

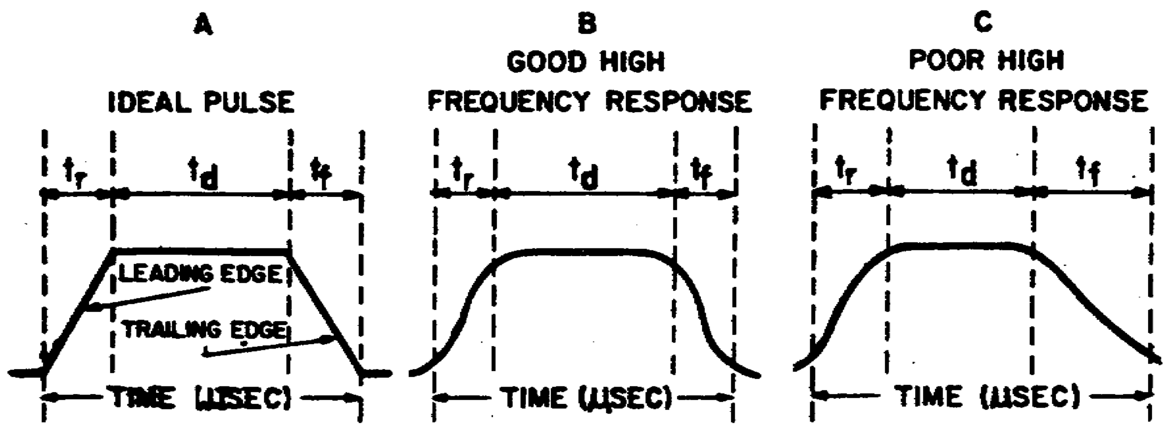
c. The function of a waveform in a circuit also determines the practical bandwidth limits. If fidelity of waveform reproduction is vital, a suitably wide bandwidth must be used. If a waveform can be modified without affecting the circuit, a narrow bandwidth which will not provide passage of all harmonics considered desirable for good waveform reproduction may be used.

7. PULSE BANDWIDTH REQUIREMENTS.

a. Definition of a pulse. A pulse can best be defined as a sudden rise and fall of voltage or current. Square waves and rectangular waves are examples of pulses.

b. Pulse parameters. Pulse parameters are characteristic properties that describe a pulse. The pulse rise time, t_r, the leading edge of the pulse, is the time required for a pulse to rise from 10 percent to 90 percent of its maximum amplitude (Figure 6A). The pulse duration, t_d, is the time that the pulse remains at maximum amplitude. The decay time, t_f, the trailing edge of the pulse, is the time required for the pulse to return to zero. These times, t_r, t_d, and t_f, are the pulse parameters.

Figure 6. High-frequency response to a rectangular wave



c. Effects of harmonics on pulse rise and decay times.

(1) A rectangular pulse with finite rise and decay times is shown in Figure 6A. Practical circuits modify the shape of this pulse. When a circuit has good, high-frequency response, the corners of the pulse are rounded only slightly (Figure 6B), and the pulse rise and decay times are not too greatly modified. When the circuit has poor, high-frequency response (Figure 6C), the rise and decay times of the pulse increase greatly and an undesirable rounding of the corners occurs.

(2) In the composition of a square wave (Figure 2), the rise and decay times of the resultant waves became shorter as the higher order of harmonics were added. If a square wave is applied to a circuit, the high-frequency response of the circuit determines the shape of the output pulse during the rise and decay times. If the circuit has good, high-frequency response, good reproduction is developed at the output. If the circuit has poor, high-frequency response, the higher order of harmonics are not reproduced, and the rise and decay times are lengthened.

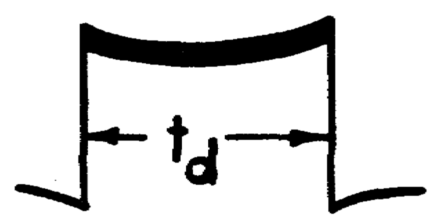
(3) The highest frequency that must be passed by a circuit can be determined by using the formula $f_h = 1/2t_r$, where f_h represents the high frequency response or upper bandwidth limit of a circuit; Assuming the rise time to be 0.5 usec, the high-frequency response of the circuit must be $f_h = 1/2t_r = 1/2\ (.5 \times 10^{-6}) = 1 \times 10^6$ or 1 MHz (megahertz). The upper limit of

the bandwidth must be 1 MHz in order to reproduce the leading edge of the pulse. This formula also applies to the trailing edge by substituting decay time t_f for rise time t_r.

d. Effects of harmonics on pulse-duration time.

(1) The duration time (t_d) of a pulse depends on the low-frequency response of a circuit for good reproduction. Figure 7 is a square wave that was passed through a circuit having poor, low-frequency response. Notice that the waveform is not flat on top during the duration time. To obtain good reproduction of the waveform, the circuit must have good, low-frequency response as well as good, high-frequency response.

Figure 7. Effect of a poor low-frequency response on a square wave



(2) The lowest frequency (f_L) that a circuit must pass to reproduce a pulse can be obtained from the formula $f_L = 1/prt$, where prt represents the pulse recurrence time in seconds. Notice that this is the same as saying F_L equals prf since the pulse recurrence time is the reciprocal of the pulse repetition frequency. When the lower frequency limit of the circuit equals the prf, satisfactory reproduction results. A pulse having a repetition frequency of 1 kHz requires that the lower limit of the bandwidth be 1 kHz.

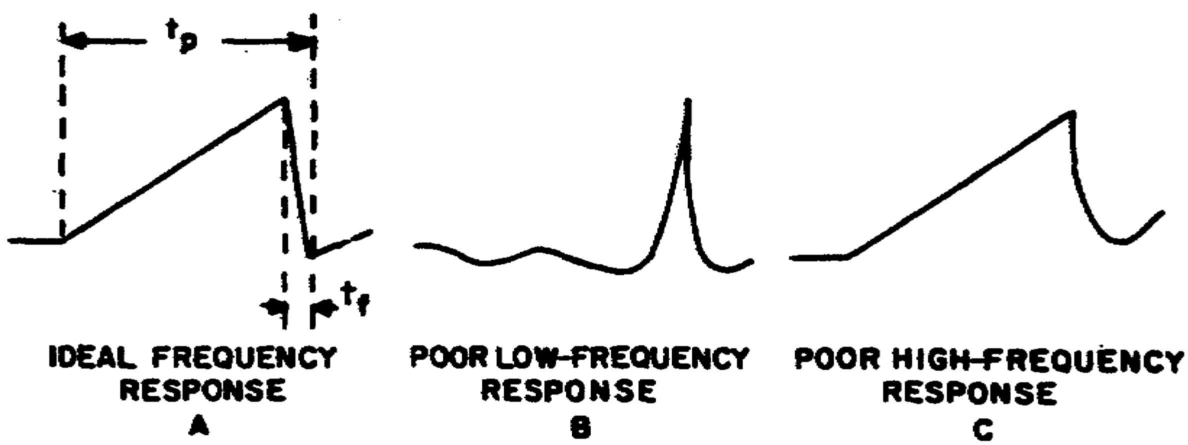
8. BANDWIDTH REQUIREMENTS FOR A SAWTOOTH WAVE.

a. The square-wave principles for high- and low-frequency response can be applied to all nonsinusoidal waveforms. It can be stated that the high-frequency response of a circuit affects any

waveform when the voltage is changing most rapidly (rise and decay times). The low-frequency response affects any waveform when the voltage is constant (pulse duration), or when the voltage change is gradual as in the rise of a sawtooth waveform.

b. These principles may be used, for example, to determine the high- and low-frequency response of a sawtooth waveform (Figure 8). The voltage of this waveform changes gradually during the rise time until the maximum amplitude is reached, and then fails sharply to zero during the decay time. In Figure 8B, a poor low-frequency response causes the omission of the first, second, and third harmonics in the rising portion of the wave. In Figure 8C, a poor high-frequency response causes the voltage to decay more gradually and run into the rise time of the next cycle.

Figure 8. Sawtooth wave frequency response



c. The bandwidth of a circuit must be low enough to pass the fundamental frequency, and sufficiently high to pass a frequency of $1/2t_f$. Consider the bandwidth required to pass a sawtooth voltage with a fundamental frequency of 1000 Hz, and a decay time (t_f) of 5 usec. The low-frequency response limit of the circuit must be 1 kHz, and the high-frequency response must be $1/2t_f$ or $1/10 \times 10^{-6}$ or 100 kHz. For good reproduction of the waveform, the bandwidth of the circuit must be 99 kHz (1 kHz to 100 kHz).

Section V. SUMMARY AND REVIEW

9. SUMMARY.

a. Waveshapes that do not follow the conventional pattern of the sine wave are called nonsinusoidal waves.

b. An aperiodic wave is a wave which appears at irregular intervals or only once.

c. A period wave is a wave that is repeated at constant intervals.

d. Nonsinusoidal waves can be analyzed by either the frequency-response method of analysis or the transient-response method of analysis.

e. A steady state is a period when there is no change in voltage or current.

f. The frequency-response method analyzes a waveform by determining the number, amplitude, and frequency of sine waves required to reproduce it.

g. The rate at which a waveform is repeated is known as repetition frequency, and is equal to the frequency of the fundamental sine wave required to produce it.

h. The second harmonic is equal to twice the frequency and half the amplitude of the fundamental frequency.

i. When forming a waveshape, the maximum number of harmonics that must be included varies inversely with the pulse width.

j. The transient-response method analyzes the response of a circuit to nonsinusoidal voltages.

k. A transient is a brief change in voltage or current.

l. Transient time is the period of time during which the transient occurs.

m. A square wave consists of a fundamental frequency and its odd harmonics.

n. A rectangular wave consists of a fundamental frequency and both its odd and even harmonics. A DC voltage is usually added to establish the desired reference level.

o. A sawtooth wave consists of a fundamental frequency and its even and odd harmonics.

p. Bandwidth represents the range of frequencies that a circuit will pass.

q. A pulse is a sudden rise and fall of voltage or current.

r. A pulse parameter is a characteristic property that describes a pulse.

s. Good reproduction of a pulse during its rise and decay times depends on the high-frequency response of the circuit.

t. High-frequency response is determined by using the formula

$$f_h = \frac{1}{2t_r} \quad \text{or} \quad f_h = \frac{1}{2t_f}$$

u. Good reproduction of a pulse during its duration time depends on the low-frequency response of the circuit.

v. Low-frequency response is determined by the prf of the input pulse.

10. REVIEW QUESTIONS.

a. What is a nonsinusoidal wave? (Paragraph 1b)

b. What is a periodic wave? (Paragraph 1c)

c. Name the two methods of analyzing nonsinusoidal waves. (Paragraph 2)

d. A pulse occurs at a rate of 1000 times per second. What is the frequency of the third harmonic? (Paragraph 3a)

e. What is the difference between a square wave and a sawtooth wave? (Paragraphs 5a and 5b)

f. What is meant by the bandwidth of a circuit? (Paragraph 6a)

g. How does the waveform to be passed determine the upper- and lower-frequency limits of the desired bandwidth? (Paragraph 6b)

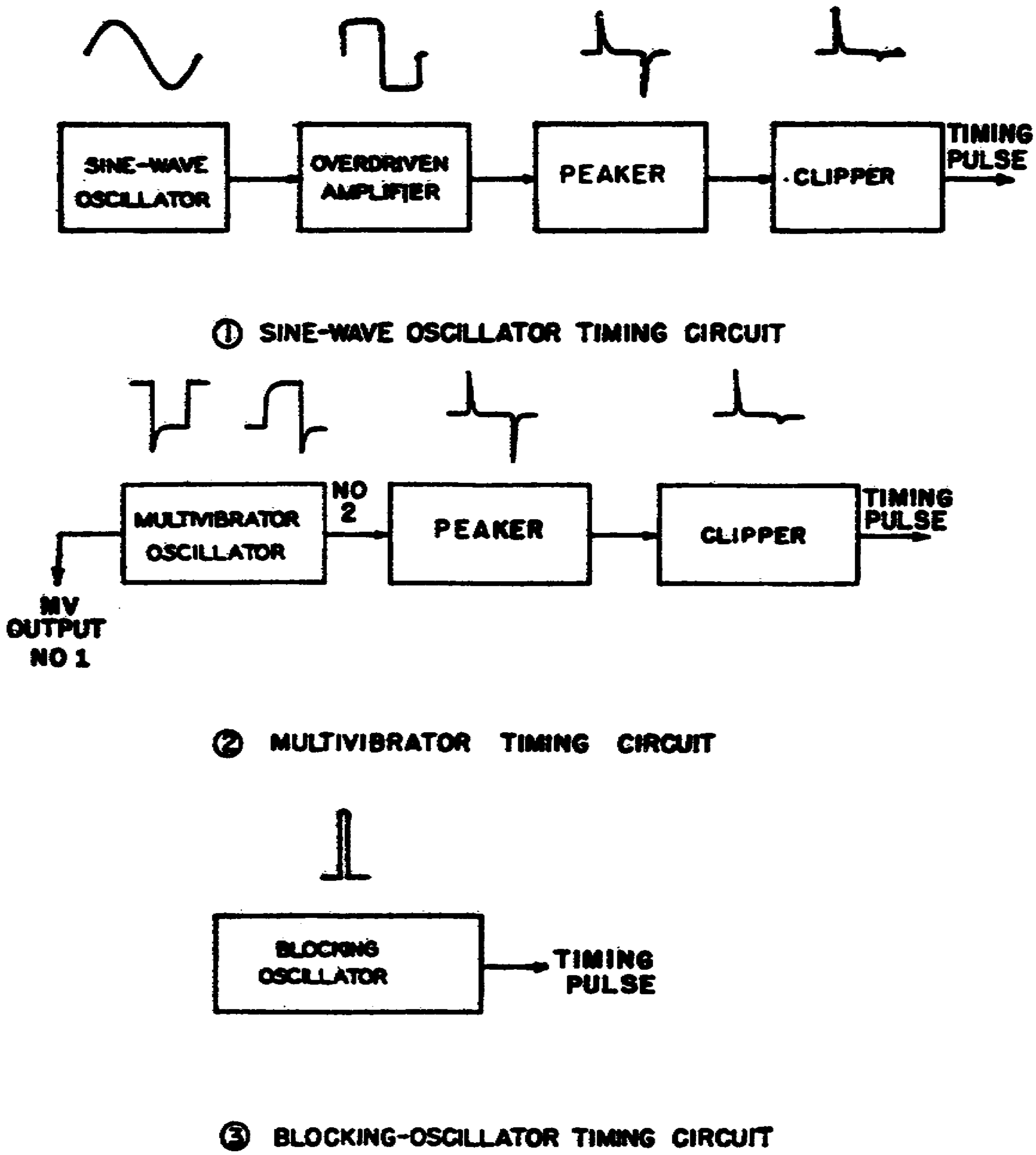
11. TYPES OF TIMERS.

The function of a timer is to ensure that all circuits connected within an electronic system operate in a definite time relationship with each other, and that the interval between pulses is of the proper length. Multiplexers, which are used to increase traffic capability in voice communication, require precise timing;

so does television, both transmitter and receiver. The circuits used to produce the timing pulses are similar to those used in radar or oscilloscopes. The timer is sometimes referred to as the synchronizer or keyer. In general, there are two methods of supplying the timing requirements.

(1) Timing by separate unit. The pulse repetition frequency can be determined by an oscillator of any stable type, such as a sine-wave oscillator, a multivibrator, or a blocking oscillator. The output is then applied to pulse-shaping circuits to produce the required timing pulses. Figure 9 shows typical combinations of circuits which may be used as timers in television, radar, multiplexers, and oscilloscopes.

Figure 9. Representative method of timing radar systems



(2) Internal timing. Electronic equipment with its associated circuits may establish its own pulse width and pulse

repetition frequency and provide the synchronizing pulse for the other components of the system. This may be done by a self-pulsing or blocking oscillator with properly chosen circuit constants. This method of timing eliminates a number of special timing circuits, but the pulse repetition frequency obtained may be less rigidly controlled than that desired for some applications.

12. TIMING PULSES.

The timing pulses required from a timer may depend largely upon the purpose of the electronic equipment.

(1) Oscilloscope and television timing. Typical requirements for oscilloscopes and televisions are illustrated in Figure 10. The diagram does not necessarily apply to any particular oscilloscope or television, but it shows the more common timing pulses that are in general use. In Figure 11, these timing pulses are shown in their proper time relationship.

Figure 10. Typical timing of an oscilloscope

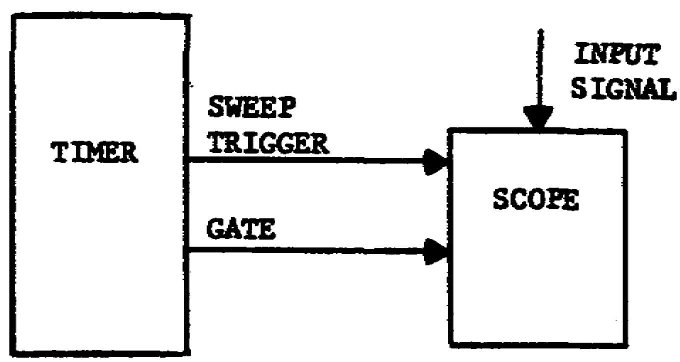
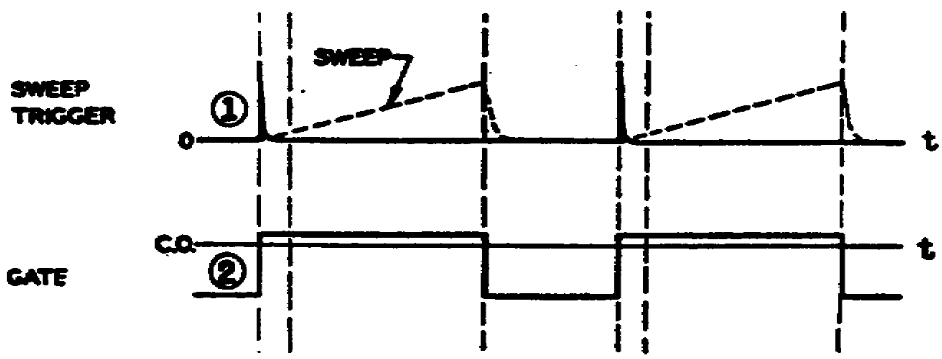


Figure 11. Time relationship of timing pulses



(a) Sweep trigger. The timer starts the sweep in the indicator circuits. The timing pulse is normally in the form of a sweep trigger where it occurs simultaneously with the input signal so that the beginning of the sweep and the beginning of the input signal coincide.

(b) Gate. The gating voltage limits the length of time the sweep appears on the screen. If the sweep were to remain in operation during the period between pulses, input signals might appear on the sweep retrace, and the operator might become confused when interpreting the signals. The negative portion of this waveform is commonly called a blanking pulse. The portion of the waveform below the indicator tube's cutoff (CO) point blanks out the electron beam from the tube's cathode.

(2) Typical radar timer block diagram. The timer performs the functions of establishing the pulse repetition frequency of a radar system and of synchronizing the actions of the other components to the transmitter. The block diagram in Figure 12 shows a combination of circuits that can be used to develop the trigger pulses and the gating voltages required in a radar system. The waveforms produced by the circuits represented in Figure 12 are shown in Figure 13.

Figure 12. Externally synchronized timer block diagram

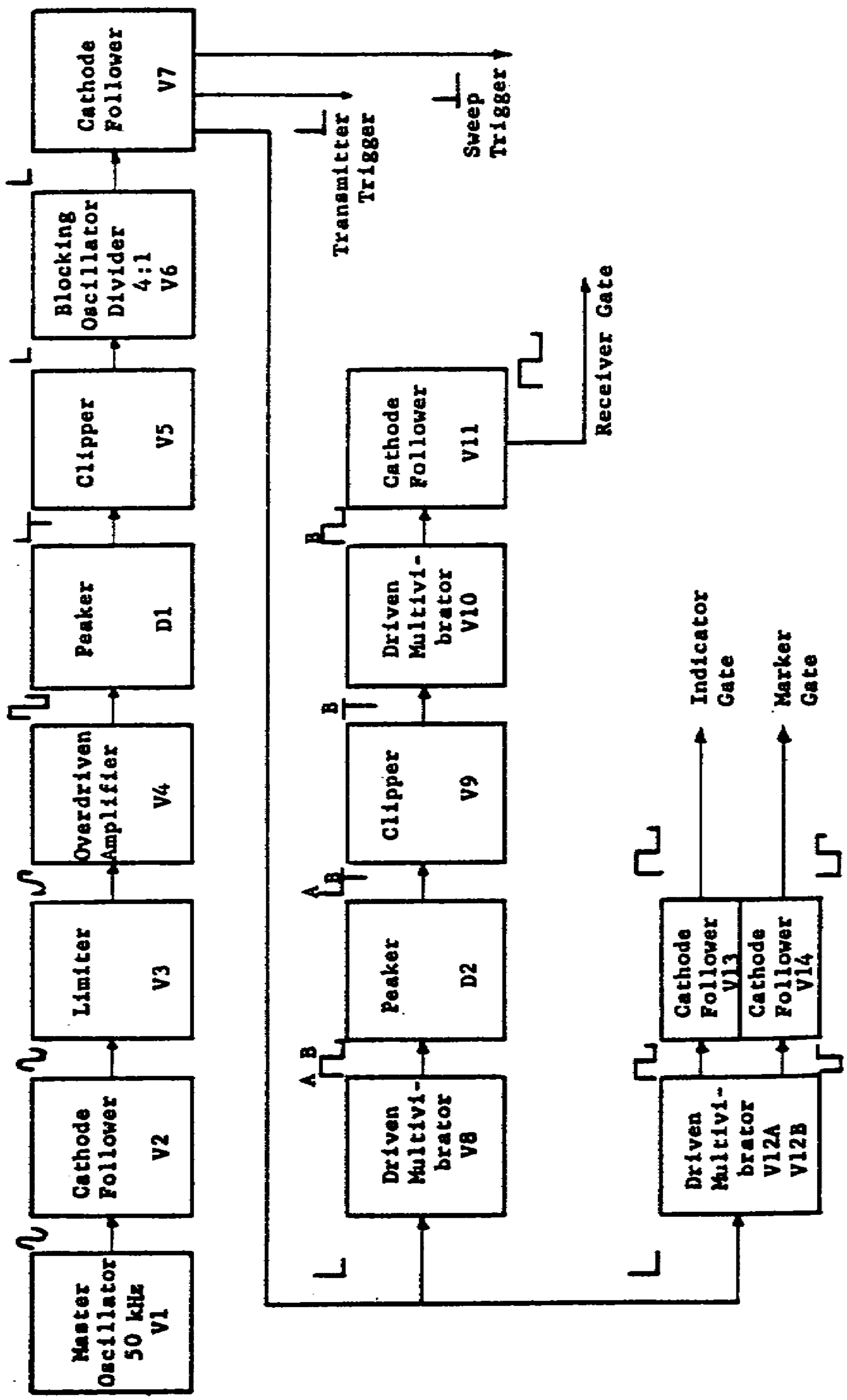


Figure 12a. Externally synchronized timer block diagram

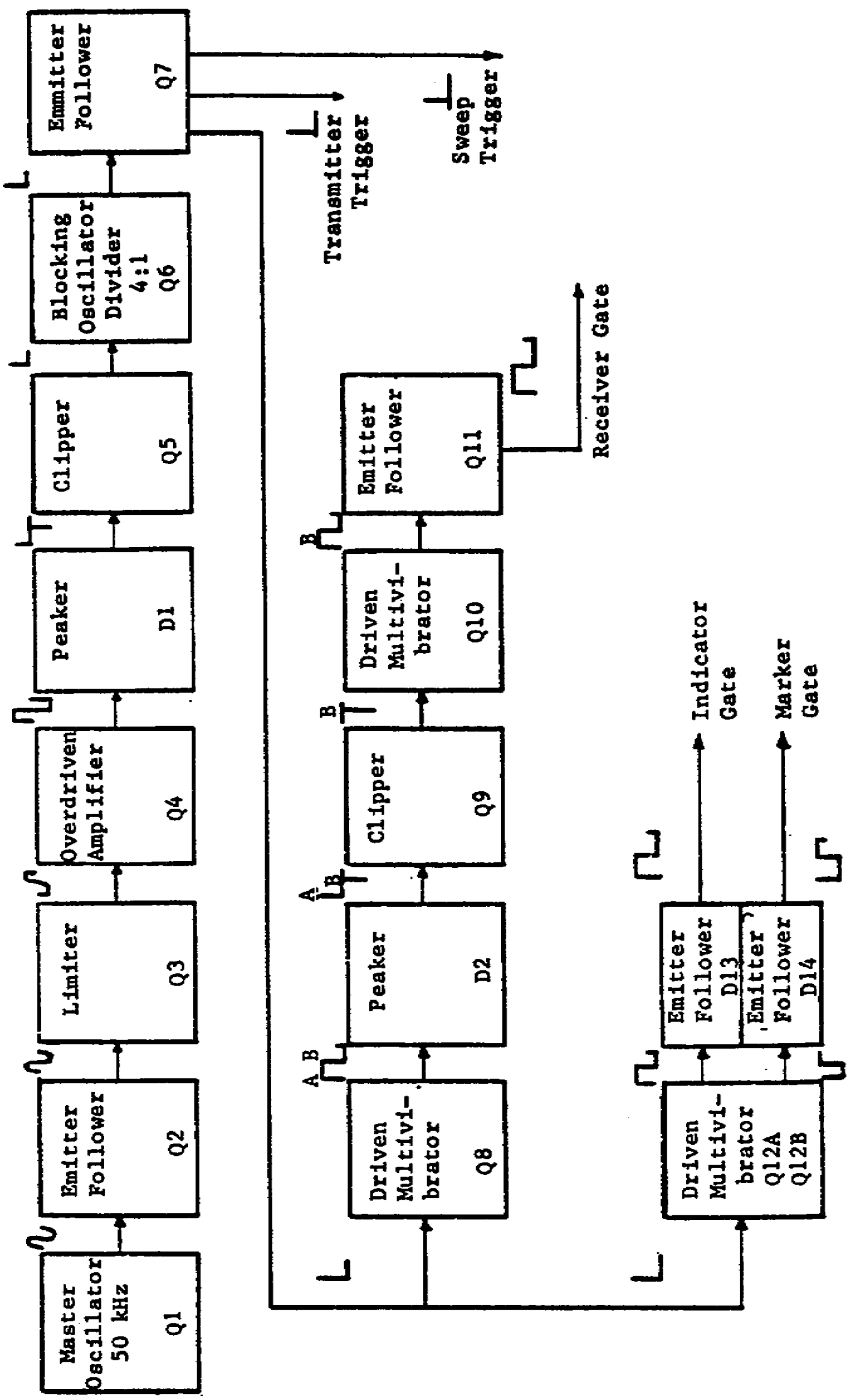
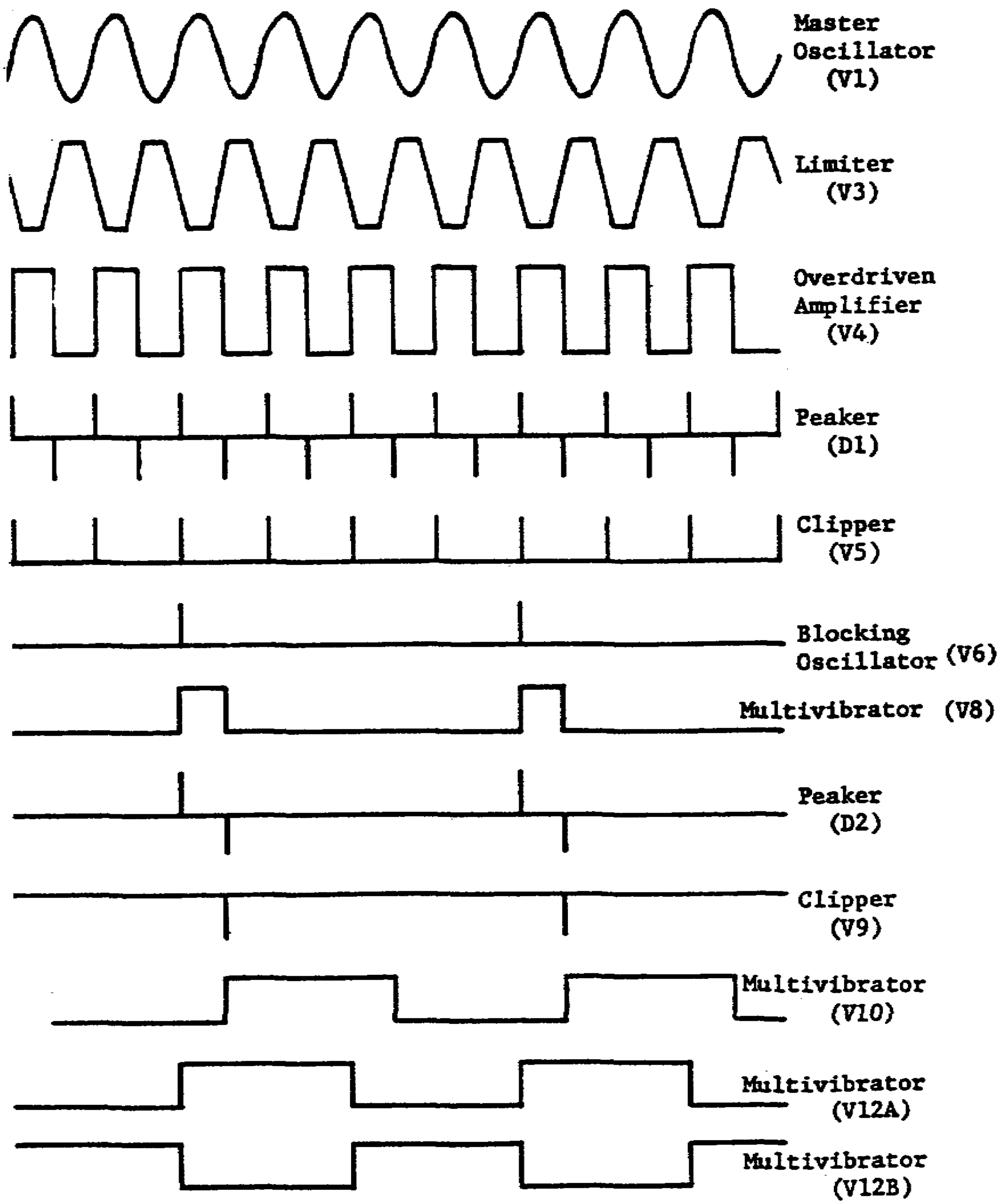


Figure 13. Timer waveforms



(a) Master oscillator (V1). The circuit used to control the pulse repetition frequency is usually a crystal-controlled oscillator. The sine-wave output of the oscillator should have excellent frequency stability.

(b) Cathode follower (V2). To prevent the limiter stage from loading down the master oscillator stage, a cathode follower is used to isolate the two stages from each other. The cathode follower will appear as a constant load to the master oscillator, and as a result, the limiter will not load down the oscillator.

(c) Limiter (V3). The first step in producing trigger pulses from the sine-wave voltages is to convert the sine waves into square waves. To make this conversion, the amplitudes of both the positive and negative alternations of the sine waves must be limited to specific values.

(d) Overdriven amplifier (V4). Although the sine-wave voltages have been squared by the limiter, the sides of the square waves are not as vertical as is desired for the production of sharply peaked pulses. Therefore, the square waves produced by the limiter stage are applied to an overdriven amplifier to steepen the sides of the square waves.

(e) Peakers (D1 and D2). To produce sharp pulses from the square waves, the time constants of the coupling circuits are made very short. By making the time constants short, the high-frequency components of the square waves will be coupled to the following stages and the low frequencies will be rejected. The output waveforms will be sharp positive and negative pulses. The sharp pulses are called triggers.

(f) Clipper (V5). To ensure that the negative pulses do not interfere with the blocking oscillator circuit operation, they are removed by a clipper circuit.

(g) Blocking oscillator (V6). To obtain the desired frequencies for the transmitter and indicators, the master oscillator frequency must be reduced or divided. The blocking oscillator divides the incoming synchronizing triggers by a predetermined amount. Figure 13 shows that the blocking oscillator requires four input triggers to produce one output pulse. In this example, the blocking oscillator divides the incoming frequency by four. A blocking oscillator can be designed to divide by a different amount. A timer may use one or more blocking oscillators as frequency dividers to obtain the desired timing signals.

(h) Cathode followers (V7, V11, V13, and V14). To prevent reflections in the connecting cables and ensure maximum power transfer, the low impedances of the cables are matched to the high impedances of the multivibrators and the blocking oscillator by cathode follower circuits.

(i) Multivibrator (V8). When triggered by a positive pulse, the multivibrator will produce a rectangular wave whose leading edge A coincides with the transmitter pulse. The trailing edge B will coincide with the trailing edge of the transmitter pulse.

(j) Clipper (V9). To ensure that the positive pulses do not interfere with the multivibrator circuit operation, they are removed by a clipper circuit.

(k) Multivibrator (V10). When triggered by a negative pulse, the multivibrator produces a rectangular waveform whose leading edge coincides with the trailing edge of the transmitter pulse. This rectangular waveform, to be used as the receiver gate, has been delayed by a time equal to the width of the transmitted pulse.

(l) Multivibrator (V12A and V12B). A single multivibrator stage consists of two tubes. When the multivibrator is triggered by a positive pulse, each tube will develop a rectangular waveform. The waveforms will be 180° out of phase with each other. The two rectangular waveforms are used as the indicator and marker gates.

(3) Timer requirements. To provide the required timing pulses, a timer must include a circuit capable of establishing the pulse repetition frequency, a means of forming the desired signals with the proper time relationship, and circuits designed to protect one component from the loading effect of another and to deliver pulses to the loads without distortion. The same signals can be made with use of solid state circuits as seen in Figure 12a.

PRACTICE EXERCISES

In each of the following exercises, select the one answer that best completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

1. In the analysis of a nonsinusoidal waveform, the term transient time refers to the

   a. periods of the waveform known as rise time, duration time, and decay time.
   b. time when the waveform is considered to have reached a steady state.
   c. periods of the waveform known as rise time and decay time.
   d. time required to reproduce the waveform.

2. If the fundamental sine-wave frequency in a square wave is 200 Hz and its amplitude is equal to 5 volts, the fifth harmonic will have a frequency and amplitude, respectively, equal to

   a. 320 gigahertz and 25 volts.
   b. 320 gigahertz and 1 volt.
   c. 1 kilohertz and 25 volts.
   d. 1 kilohertz and 1 volt.

3. A waveform that contains only odd harmonics in its composition is a

   a. rectangular wave.
   b. sawtooth wave.
   c. peaked wave.
   d. square wave.

4. A 1000-Hz symmetrical square wave will be reproduced satisfactorily if it contains 10 odd harmonics added to the fundamental frequency. If such a square wave's frequency is changed to 50 Hz, how many odd harmonics must be added to obtain the same quality of reproduction?

   a. 5.
   b. 10.
   c. 20.
   d. 40.

5. Assume that an amplifier circuit is being used to increase the amplitude of a sawtooth waveform. The circuit's bandwidth refers to the

   a. range of frequencies that the circuit will pass.
   b. number of sawtooth waveforms that the circuit will pass.
   c. lowest frequency necessary to pass the sawtooth waveform and still afford good reproduction.
   d. highest frequency necessary to pass the sawtooth waveform and still afford good reproduction.

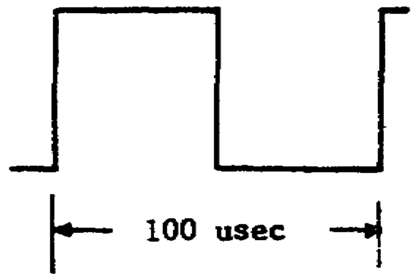
6. Assume that a square wave is being applied to an amplifier circuit. How will the square wave be affected if the high-frequency response of the circuit is decreased?

   a. The pulse repetition frequency will increase.
   b. The rise time of the output pulse will decrease.
   c. The decay time of the output pulse will decrease.
   d. The duration period of the output pulse will decrease.

7. If a circuit is designed to produce the square wave shown in Figure 14, the fundamental sine-wave frequency used must be

   a. 100 Hz.
   b. 1000 Hz.
   c. 10,000 Hz.
   d. 100,000 Hz.

Figure 14. Square wave



8. Assume that a sawtooth waveform with a fundamental frequency of 50 kHz, a rise time of 8 microseconds, and a decay time of 2 microseconds is applied to a circuit. To reproduce the sawtooth waveform, the upper bandwidth limit of the circuit should be equal to

   a. 25 kHz.
   b. 50 kHz.
   c. 100 kHz.
   d. 250 kHz.

9. Since the voltage used for timing an electronic circuit must be a sharp pulse, the output of a sine-wave master oscillator timer is shaped or distorted by using

   a. a clipper, a cathode follower, and a rectifier.
   b. an overdriven amplifier, a peaker, and a clipper.
   c. a buffer amplifier, a multivibrator, and a peaker.
   d. an isolation amplifier, a blocking oscillator, and a Class A amplifier.

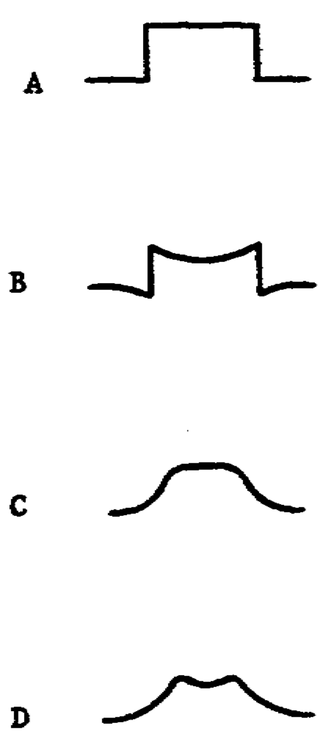
10. Assume that a waveform appearing on an oscilloscope is analyzed and found to contain a fundamental frequency and the first 10 harmonics of the fundamental frequency. The waveform observed would be classified as a

a. sine wave.
b. square wave.
c. sawtooth wave.
d. trapezoidal wave.

11. If a square wave is applied to a circuit having good high-frequency response but poor low-frequency response, the output waveform will resemble the one shown in Figure 15 in sketch

a. A.
b. B.
c. C.
d. D.

Figure 15. Effect of poor low-frequency response



12. The duration of the sweep presentation on the screen of an oscilloscope is controlled by the

    a. gate voltage.
    b. sweep trigger.
    c. duration of the information signal.
    d. frequency of the information signal.

13. Assume that the nonsinusoidal voltage shown in B of Figure 44 (page 86) is applied to a filter circuit. The filter's high-frequency response has the greatest influence on the waveform during the time period between

    a. 0 and 10 microseconds.
    b. 10 and 40 microseconds.
    c. 20 and 50 microseconds.
    d. 40 and 60 microseconds.

14. Which circuits can be eliminated in the timer shown in Figure 12 if the crystal-controlled master oscillator is replaced by a multivibrator?

    a. Limiter and clipper.
    b. Cathode follower and peaker.
    c. Overdriven amplifier and peaker.
    d. Limiter and overdriven amplifier.

15. To obtain precise timing of electronic components, the square waves produced in timing circuits must be converted into triggers. What type of circuit converts square waves into triggers?

    a. Peaker.
    b. Limiter.
    c. Clipper.
    d. Cathode follower.

16. Assume that the output of a blocking oscillator is composed of the desired positive trigger and an undesired negative trigger. What circuit could be added to the timer to eliminate the negative triggers?

    a. Peaker.
    b. Clipper.
    c. Buffer amplifier.
    d. Overdriven amplifier.

SITUATION.

Assume that the timer shown in Figure 12 is being used to establish the pulse repetition frequency and develop the gating voltages of a ground-controlled approach (GCA) radar set.

Exercises 17 through 19 are based on the above situation.

17. The blocking oscillator (V6) shown in Figure 12 is used to develop the transmitter trigger. If the blocking oscillator is adjusted to produce a pulse repetition frequency of 10,000 Hz, it will operate in a manner that is best described as

    a. dividing the incoming frequency by three.
    b. reducing the master oscillator frequency by one half.
    c. producing two output triggers for each input trigger.
    d. requiring five input triggers to produce one output trigger.

18. Cathode followers are used to reduce the loading effects of components and to

    a. increase the amplitude of the output pulses.
    b. decrease the rise time of the trigger pulse.
    c. provide a low-impedance output to match cable impedances.
    d. invert or change the polarity of the timer output pulse.

19. The function of multivibrator V8, peaker D2, and clipper V9 is to

    a. develop the receiver gate.
    b. delay the starting time of the receiver gate.
    c. determine the duration time of the receiver gate.
    d. match the output impedance of cathode follower V7 to the input impedance of multivibrator V10.

20. Besides forming the desired signals with the proper time relationship and protecting components from the loading effects of other components, the timer must be capable of establishing the

    a. pulse repetition frequency.
    b. intermediate frequency.
    c. carrier frequency.
    d. pulse width.

Check your answers with lesson solutions.

ANSWERS TO PRACTICE EXERCISES

MM5000 ....Timing Circuits

Lesson 1.....................................Introduction to Timers

1. c--paragraph 4a, 7b
2. d--paragraph 5a(2)
3. d--paragraph 5a(2)
4. b--paragraph 5a(2)
5. a--paragraph 6a
6. d--paragraph 7c(2), Figure 6
7. c--paragraph 7d

   f = 1/pulse repetition period

   f = 1/100 usec

   f = 10,000 Hz
8. d--paragraph 8c

   High frequency response = 1/(2 x decay time)

   = 1/(2 x 2 microseconds)

   = $1/(4 \times 10^{-6}$ seconds)

   = 250,000 Hz

   = 250 kHz

9. b--paragraph 11a; Figure 9

a. A clipper will remove a specific portion of a signal, a cathode follower does not distort a signal, and a rectifier removes half of the waveform.

b. An overdriven amplifier will square the waveform, the peaker will produce sharp pulses from the square wave, and the clipper will remove the undesired half cycle.

c. A buffer amplifier has no effect on a waveform, a multivibrator is a square wave generator, and the peaker will peak the input waveform.

d. An isolation amplifier and Class A amplifier have no effect on the waveform. A blocking oscillator is a pulse generator.

10. c--paragraph 5b

11. b--paragraph 7c, d

12. a--paragraph 12a(2)

13. a--paragraph 8a

14. d--paragraph 12b(3), (4)

The limiter and overdriven amplifier circuits convert the sine waves into square waves. A multivibrator generates square waves. Therefore, the limiter and overdriven amplifier can be eliminated. The cathode follower must still be used to prevent overloading the multivibrator.

15. a--paragraph 12b(5)

16. b--paragraph 12b(6)

17. d--paragraph 12b(7); Figure 12

18. c--paragraph 12b(8)

19. b--paragraph 12b(9), (10), (11)

20. a--paragraph 12c

LESSON 2

APPLICATIONS OF RC AND RL CIRCUITS

SCOPE............................	Response of RC and RL circuits to nonsinusoidal waveforms; function of RC and RL filter circuits; applications of RC and RL differentiating and integrating circuits.
TEXT ASSIGNMENT....................	Pages 33 through 91
MATERIALS REQUIRED.................	None

LESSON OBJECTIVES

When you have completed this lesson, you will be able to:

a. Use time constants to determine the outputs, at any specified time, of various RC and RL circuits.

b. Analyze the input and output waveforms of RC and RL circuits to determine the type of filtering action taking place.

c. Distinguish between differentiating and integrating circuits.

d. Select the component across which the differentiated and integrated waveforms appear when given the circuit time constant.

1. WAVEFORMS.

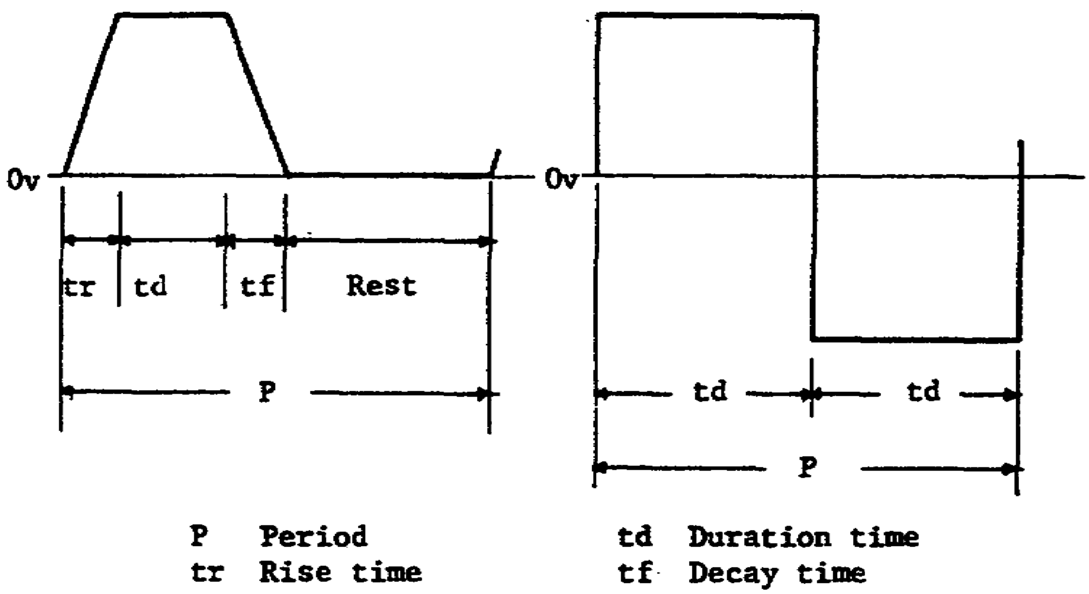
a. Types. A waveform can be described as any rise or fall of voltage or current over a finite period of time. Waveforms that do not follow the conventional pattern of the sine wave are called nonsinusoidal waveforms. Various nonsinusoidal waveforms are produced in electronic circuits.

(1) Aperiodic. A nonsinusoidal waveform that appears at irregular intervals.

(2) Periodic. A periodic waveform is any waveform that is repeated at constant intervals. Unless specifically referred to as aperiodic, all waveforms discussed will be periodic waveforms.

b. Reference periods. In many RC and RL circuits, the response of a circuit to a waveform depends on the relationship of the time constant (TC) of the circuit to the reference periods of the waveform. The rise, duration, and decay times are the reference periods of a pulse. The reference periods of two waveforms are shown in Figure 16.

Figure 16. Pulse reference periods



(1) Period. The period (P) of any waveform is the time required to completed one full cycle of operation. The period of a waveform has the same meaning as the pulse repetition period (PRP). The formula for the period of a waveform is the same as the formula used in determining the PRP. (Frequency is given in pulses per second or hertz.)

PRP (seconds) = 1/PRF

PRP (microseconds) = 10^6/PRF

Period (seconds) = 1/Frequency

Period (microseconds) = 10^6/Frequency

(2) Rise. A pulse's rise time (tr) is the time required for the pulse to rise from zero to maximum. In practical use, a pulse's rise time is the time required for the pulse to rise from 10 percent to 90 percent of its maximum value.

(3) Duration. The time that a pulse remains at its maximum amplitude is the duration time (td) of the pulse. If the waveform is symmetrical and has zero rise and decay times, the pulse will have two equal duration times. The time duration of a symmetrical waveform is

Time duration (td) = Period/2

or

Time duration (td) = 1/(2 x Frequency)

(4) Decay. The decay time (tf) of a pulse is the time required for the pulse to return to zero from its maximum amplitude. In practical applications, we use 90 percent to 10 percent.

(5) Rest. The time between pulses is the rest time of a waveform.

Section I. SERIES RL CIRCUIT RESPONSE

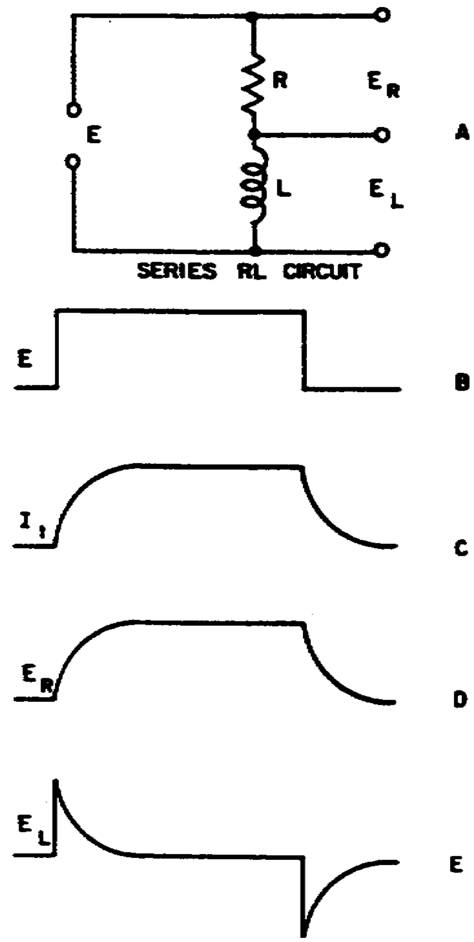
2. GENERAL.

The response of any circuit to a step voltage can be determined by using Kirchoff's law, which states that the sum of the voltage drops in any closed circuit is equal to the applied voltage. In Figure 17, a voltage E is applied to a series RL circuit. The voltage drop across the resistor E_R added to the voltage drop across the inductor E_L must, at all times, be equal to the applied voltage E. The applied voltage is a rectangular pulse (Figure 17B), consisting of both a positive and a negative voltage.

3. POSITIVE STEP VOLTAGE.

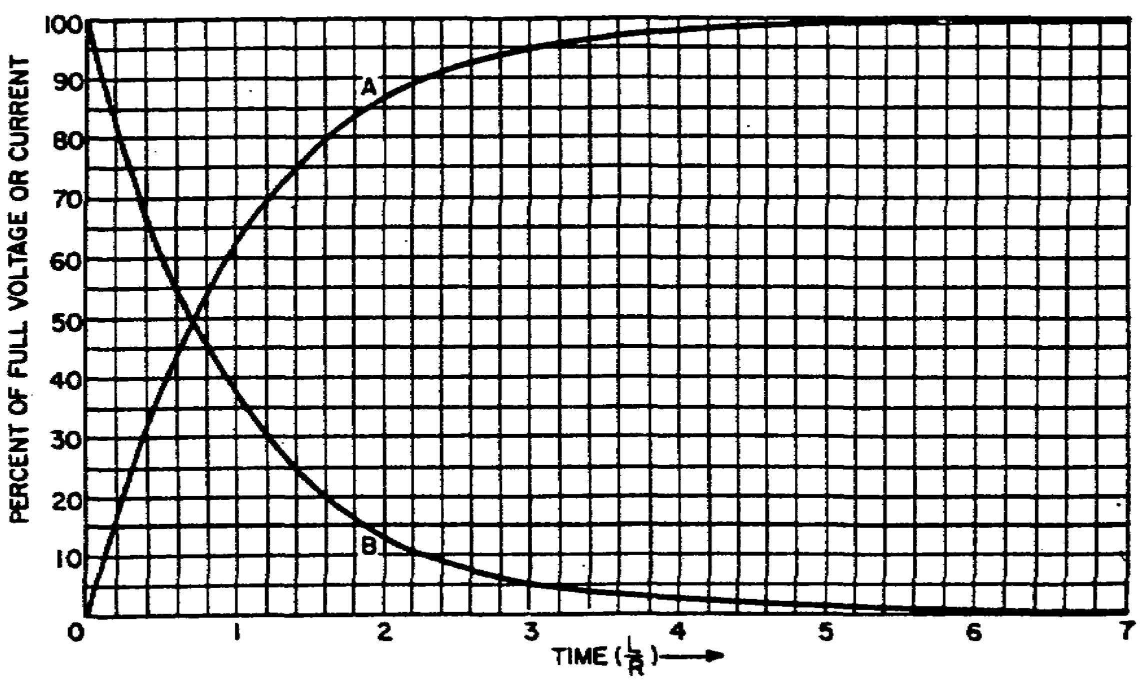
a. When the positive step voltage (Figure 17B) is applied to the series RL circuit, the inductor opposes the flow of current by building up an instantaneous back or counter emf equal to the applied voltage. Consequently, at the instant the voltage is applied to the circuit, there is no current flowing in the circuit (Figure 17C). At this time, all the voltage is impressed across L (Figure 17E), and there is no voltage drop across the resistor (Figure 17D). As the counter emf starts to decrease, current starts to flow and a voltage E_R is developed across the resistor. This voltage represents the difference between the applied voltage and the voltage drop E_L across the inductor at that instant. As the voltage drop across the inductor decreases, the rate of current change decreases causing a less rapid increase in the magnitude of the voltage across the resistor. When the entire applied voltage appears across the resistor, the steady state has been reached and E_R is equal to E. The current is then at its maximum value and is equal to E/R. Since the resistance of the inductor is negligible, E_L is equal to zero when the steady state is reached.

Figure 17. RL circuit response to a step voltage



b. The voltage, current, and rate of current change during the transient periods should be more closely examined to see how these characteristics change with time. From the instantaneous current Curve A in Figure 18, which is an enlargement of the first portion of Figure 17C, it can be seen that the current starts from zero and increases rapidly at first and then tapers off to practically a zero rate of increase at the end of five time constants. (RL time constants are discussed in Section II.) Since the instantaneous values of the voltage across the resistor are directly proportional to the current flowing through it, the E_R curve is identical to the I_t curve. The inductor voltage is represented by Curve B in Figure 18. If the polarity of the E_L curve is reversed, it may be considered to represent the counter emf-in the inductor. (The polarity of the counter emf is always opposite to that of the applied voltage.)

Figure 18. Universal time constant chart for series RL circuit



c. Theoretically, the current never stops increasing, because it never reaches 100 percent of its maximum value. In actual practice, when the current is equal to approximately 99.9 percent of its maximum value, it is considered to be equal to the maximum value and E_L is considered to be equal to zero.

4. NEGATIVE STEP VOLTAGE.

a. When the negative step voltage is applied to the series RL circuit, E (Figure 17B) drops instantly to zero. The magnetic field about the inductor collapses, and in the process, induces a

counter emf in the inductor which acts as the source of voltage in the circuit. E_L is now equal to E_R (Figure 17D), but opposite in polarity. Since the counter emf of the inductor opposes any change in current flow in the circuit, current continues to flow in the same direction as it did when the applied voltage was present.

b. At the instant the applied voltage falls to zero, E_L becomes equal to its maximum value but opposite in polarity (Figure 17E). The current and, therefore, E_R are at their maximum values. As the counter emf of the inductor gradually decreases to zero, the current and the voltage across the resistor decrease in exactly the same manner. This decrease is rapid at first, but gradually declines until, at the end of five time constants, the rate of decrease is practically zero.

Section II. RL TIME CONSTANTS

5. THEORY OF RL TIME CONSTANTS.

a. An RL time constant can be defined as the time requited for the current flowing through an RL circuit to increase to 63.2 percent of its maximum value. The formula for an RL time constant is TC = L/R, where TC represents the time constant in seconds, L represents the inductance in henries, and R represents the resistance in ohms. The ratio L/R also represents the time required for the voltage across the resistor to rise to 63.2 percent of the applied voltage, and the time required for the voltage across the inductor to fall to 36.8 percent of the applied voltage. (These values are determined by detailed mathematical calculations. However, since these calculations do not necessarily increase one's understanding of practical RL circuit response, they are not included in this text.) For example, if L is equal to 10 mH and R is equal to .1,000 ohms, the TC is equal to $10 \times 10^{-3}/10^3$ or 10 usec. If the applied voltage is 10 volts, then the maximum current in the circuit is equal to 10 volts/1,000 ohms or 10 mA. 10 usec (1 time constant) after the voltage is applied to the circuit, I_t is equal to 6.32 mA, E_R is equal to 6.32 volts, and E_L is equal to 3.68 volts. At the end of 20 usec (two time constants), I_t will have increased to 63.2 percent of the remaining 3.68 mA (10 mA - 6.32 mA) or a total of 8.64 mA. E_R will have increased to 8.64 volts, and E_L will have decreased to 36.8 percent of the

remaining 3.68 volts or 1.36 volts. Using this same method, the value of I_t at the end of 30 usec (three time constants) is found to be 9.5 mA, E_R is 9.5 volts, and E_L is 0.5 volts. This process may be repeated for any number of time constants.

b. The period of time required for the current in any RL circuit to rise to 99.9 percent of the steady-state value is found to be equal to 7 time constants. If the time constant is 10 usec, 99.9 percent of the steady-state value is reached in 70 usec or 7 time constants later. If the time constant is 50 usec, 99.9 percent of the steady-state value is reached in 350 usec, again 7 time constants later. Regardless of the value of the time constant, 7 time constants will always represent the time required for the current to reach 99.9 percent of the steady-state value. When the time constant is short, the current rises rapidly to its steady-state value. When the time constant is long, the current rises slowly to its steady-state value.

6. EFFECT ON TIME CONSTANT OF VARYING L AND R.

a. Varying L only. Inductance in a circuit prevents the current from rising immediately to its steady-state value. The larger the inductance, the greater the opposition to a change in current, and the longer the period of time required to reach the steady-state value. Increasing the value of L, therefore, increases the time constant. Decreasing the value of L decreases the time constant.

b. Varying R only. If the value of the resistance is increased without varying the inductance, the steady-state is reached in a shorter period of time. Increasing the value of R decreases the maximum value of current in the circuit. Since the rate of current increase remains the same, the steady state will be reached in a shorter period of time, thus decreasing the time constant of the circuit. Decreasing the value of R increases the time constant.

c. Effect of varying R and L proportionately. Circuits with the same time constants require the same period of time to reach the steady-state condition. For example, if L is equal to 10 mH and R is equal to 1,000 ohms, the time constant is equal to 10 usec. If the values of L and R are doubled so that the values increase to 20 mH and 2,000 ohms respectively, the time constant remains 10 usec. In both cases, 70 usec or 7 time constants are required to reach the steady-state condition.

7. UNIVERSAL TIME CONSTANT CHART.

a. When a step voltage is applied to a series RL circuit, it is possible to determine the values of I_t, E_R, and E_L through the use of the universal time constant chart (Figure 27). The horizontal axis is plotted in terms of time constants. The vertical axis is plotted in terms of relative voltage or current where 100 percent corresponds to the applied voltage or current. With a positive step voltage, the rising Curve A represents either the current I_t or the voltage E_R across the resistor. Curve B represents the voltage E_L across the inductor. For negative step voltages, Curve B represents I_t, E_R, and E_L. However, E_L is opposite in polarity to E_R and I_t. The same TC chart is used to analyze I and E in RC and RL circuits.

b. The following discussion illustrates how the time constant chart can be used. In a series RL circuit, if L is equal to 10 mH, R is equal to 1,000 ohms, and the applied voltage is equal to 1 volt, then 1 time constant is equal to 10 usec. The current will reach 63.2 percent of its final value at the end of this time (Figure 27). At the instant E is applied, I_t and E_R are equal to zero and E_L is equal to 100 percent of the applied voltage, or 1 volt. After 1 usec, one-tenth of the time constant period has elapsed. At this time, E_L is equal to 90 percent of the applied voltage or 0.9 volt, E_R is equal to 10 percent of the applied voltage or 0.1 volt, and I_t is equal to 10 percent of its maximum value or 0.1 mA. The values of E_L, E_R, and I_t in Table I are obtained from the universal time constant chart.

Table I. Voltage and current values when a positive step voltage is applied to a series RL circuit

Time Elapsed (in usec)	I_t (mA)	E_R (volt)	E_L (volt)
2	0.18	0.18	0.82
4	0.33	0.33	0.67
6	0.45	0.45	0.55
8	0.55	0.55	0.45
10	0.64	0.64	0.36
20	0.86	0.86	0.14
40	0.98	0.98	0.02
70	1.00	1.00	0.00

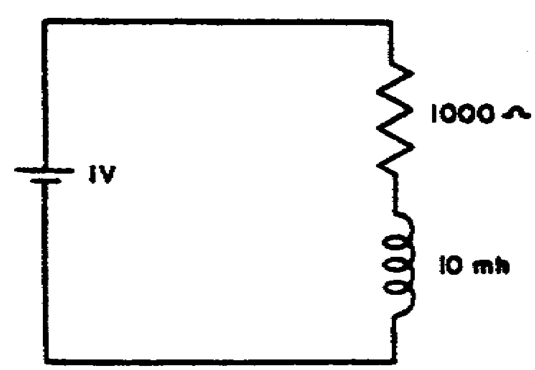
c. After 70 usec, 7 time constants have elapsed. E_L is then equal to zero, and E_R and I_t are equal to 100 percent of their maximum value or 1 volt and 1 mA, respectively. The current and voltages of any series RL circuit can be determined by substituting the appropriate values of E, R, and L.

8. STEP-BY-STEP PROCEDURE FOR DETERMINING TRANSIENT RESPONSE.

a. When a universal time constant chart is not available, the response curve can be approximated by using the equation for finding the rate of change of current through an inductor. This equation states that the rate of current change is equal to the instantaneous voltage E_L, divided by the inductance L. The following step-by-step procedure can be used to provide an approximate response of an RL circuit to any waveform.

b. In this procedure, it is assumed the current does not increase continuously, but in small steps. At the instant that the voltage in Figure 19 is applied to the circuit, the current is zero and the applied voltage appears across L. The initial rate of current increase is equal to E_L/L or $1/10 \times 10^{-3}$, which is equal to 100 amperes per second, or 0.1 mA per usec. After 1 usec, the current is considered to have increased from zero to 0.1 mA. With a current of 0.1 mA flowing in the circuit, $E_R = 0.1 \times 10^{-3} \times 10^3$ or 0.1 volt. E_L then equals 0.9 volts and the rate of current change is reduced to $0.9/10 \times 10^{-3}$ or 0.09 mA per usec. The current still is increasing, and at the end of 2 usec, it becomes 0.1 + 0.09 = 0.19 mA.

Figure 19. Series RL circuit



c. In a similar way, all values of current can be determined until the steady-state condition is reached. The voltages and currents at the end of each usec, for the problem just discussed, are shown in Table II. Check these values with those given for the same period of time in Table I. The values obtained using the step-by-step procedure are slightly higher, but very close to the actual values. The response of a series RL circuit to any type of input voltage waveform can be determined by using these same time constant and voltage equations.

Table II. Voltage and current values when positive step voltage is applied to a series RL circuit

Time Elapsed (in usec)	I_t (mA)	E_R (volt)	E_L (volt)
1	0.10	0.10	0.90
2	0.19	0.19	0.81
3	0.27	0.27	0.73
4	0.34	0.34	0.66
5	0.41	0.41	0.59
6	0.47	0.47	0.53
7	0.52	0.52	0.48
8	0.57	0.57	0.43
9	0.61	0.61	0.39
10	0.64	0.64	0.36

Section III. RC CIRCUIT RESPONSE AND VOLTAGE DROPS

9. GENERAL.

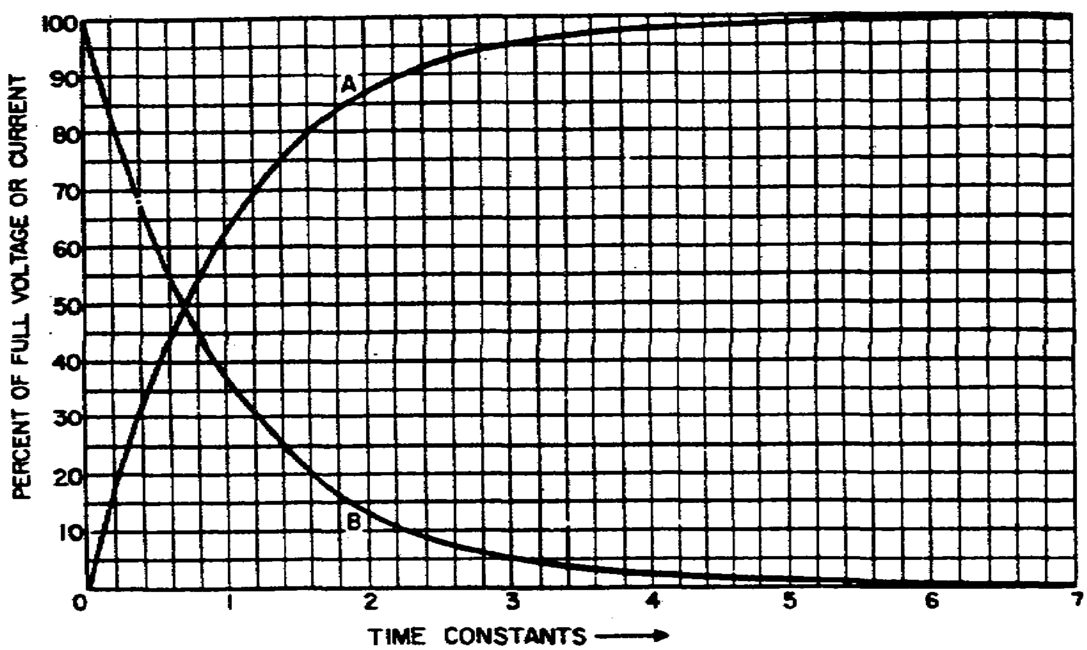
In the following discussion, the voltage, current, rate of charge, and rate of discharge of an RC circuit are examined at a number of intervals during the transient period following the application of positive and negative step voltages.

10. TRANSIENT RESPONSES.

a. Positive step voltage. The curves in Figure 20 represent the current and voltage waveforms of a series RC circuit. At the instant that E is applied to the circuit, E_C is equal to zero, E_R is equal to E, and the current in the circuit is at maximum. At the end of 1 time constant (RC time constants are discussed in Section IV of this chapter), the current (Curve B) has rapidly decreased to 36.8 percent of its maximum value. E_R (also Curve B) is directly proportional to I_t and is, therefore, also equal to

36.8 percent of its maximum value. The capacitor voltage (Curve A) $E-E_R$) is then equal to 63.2 percent of the applied voltage. At the end of two time constants, I_t and E_R are equal to 12.9 percent of their maximum values, while E_C is equal to 87.1 percent of its maximum value. The rate of current change decreases rapidly until at the end of five time constants there is little change in current flow. Thus, the capacitor charges, and the current and resistor voltage decrease at a gradual rate. Theoretically, the capacitor never becomes fully charged, it is normally considered fully charged at the end of 7 time constants, when it has obtained a charge equal to 99.9 percent of the applied voltage.

Figure 20. Universal time constant for a series RC circuit



b. Negative step voltage. When the negative step voltage is applied, E drops instantly to zero, and the voltage drop across the resistor is equal to the voltage drop across the capacitor, but is of opposite polarity. The current is equal to its maximum value, but is now flowing in the opposite direction. The instantaneous values of E_C are represented by Curve B in Figure 20.

The curves for E_R and I_t are identical to Curve B, but opposite in polarity. At the end of 1 time constant, the capacitor voltage has decreased to 36.8 percent of its maximum value, while E_R (which is the negative value of E_C) has decreased the same amount and I_t has decreased proportionately. The reduced current flow causes less charge to be drawn from the capacitor and the rate of discharge decreases. After five time constants, the rate of change of E_C, E_R, and I_t is small. It can be seen that the E_C, E_R, and I_t curves change gradually as they did when the positive step was applied.

Section IV. TIME CONSTANTS

11. THEORY OF RC TIME CONSTANTS.

a. An RC time constant is the time required for the capacitor voltage, in a series RC circuit, to reach 63.2 percent of the applied or steady-state voltage. 1 time constant, in addition to representing the time required for the capacitor to charge to 63.2 percent of the applied voltage, also represents the time required for the voltage across the resistor and the current in the circuit to fall to 36.8 percent of their maximum values. During the second time constant, the capacitor voltage will increase to 63.2 percent of the remaining 36.8 percent (100 percent - 63.2 percent) or 86.4 percent of its maximum value, and the voltage across the resistor and the current in the circuit will fall to 36.8 percent of their remaining 36.8 percent, or 13.6 percent of their maximum values. During each succeeding time, constant E_C will increase to 63.2 percent of its remaining value, while E_R and I_t will decrease to 36.8 percent of their remaining values. The formula for computing an RC time constant is TC = RC, where R is in ohms, C is in farads, and the time constant is in seconds. For example, if C is equal to 1,000 uuf and R is equal to 10,000 ohms, the time constant is equal to $0.001 \times 10^{-6} \times 10^{4}$ or 10 usec. When the time constant is short, the capacitor charges rapidly to its steady-state value. When the time constant is long, the capacitor charges slowly to its steady-state value.

b. Figure 20 indicates that, after 7 time constants, the capacitor has charged to 99.9 percent of its maximum value. The period of time required for any capacitor in a series RC circuit to charge to 99.9 percent of the steady-state value can be expressed in terms of the time constant. If the time constant of a circuit

is 20 usec, 99.9 percent of the steady-state value is reached in 140 usec or 7 time constants. If the time constant is 50 usec, 99.9 percent of the steady-state value is reached in 350 usec. At the end of 7 time constants, the voltage across the capacitor always equals 99.9 percent of the steady-state value, regardless of the value of the time constant.

12. EFFECT OF VARYING R AND C.

a. The larger the capacitance, the larger is the amount of charge necessary for the voltage drop across the capacitor to reach the applied voltage. Increasing the capacitance increases the time required to reach a steady-state condition, thereby increasing the time constant. Decreasing the capacitance decreases the time constant.

b. Since the capacitor must charge through the resistor, increasing the value of the resistance decreases the charging current in the circuit, and, therefore, increases the time required for the capacitor to charge. Increasing the value of R, therefore, increases the time constant. Decreasing the value of R increases the charging current in the circuit, and, therefore, decreases the time required for the capacitor to charge. Decreasing the value of R, therefore, decreases the time constant.

c. Circuits with the same time constants require the same period of time to reach the steady-state condition. For example, if C is equal to 0.001 uf and R is equal to 10,000 ohms, the time constant is equal to 10 usec. If the capacitance is decreased to 0.0001 uf and the resistance is increased to 100,000 ohms, the time constant is still 10 usec. In both cases, 7 time constants or 70 usec are required to reach the steady-state condition.

UNIVERSAL RC TIME CONSTANT CHART

a. When a positive step voltage is applied to a series RC circuit, it is possible to determine the values of I_t, E_R, and E_C through the use of the universal time constant chart (Figure 20). The horizontal axis is plotted in time constants. The vertical axis is plotted in terms of relative voltage or current, where 100 percent corresponds to the applied voltage or maximum attainable current. The rising Curve A represents the charging of the capacitor. Curve B represents the current flowing in the circuit and voltage appearing across the resistor.

b. The following discussion illustrates how the time constant chart can be used. In a series RC circuit, if C is equal to 1000 uuf, R is equal to 10,000 ohms, and the applied voltage is equal to 1 volt, 1 time constant is equal to 10 usec, and the voltage drop across the capacitor will reach 63.2 percent of the

applied voltage at the end of this time. At the instant E is applied, t and E_C are equal to zero; current and E_R equal 100 percent of their maximum values. When t is 1 usec, one-tenth of 1 time constant has elapsed. At this time, E_C is equal to 10 percent of the applied voltage or 0.1 volt, E_R, is equal to 90 percent of the applied voltage or 0.9 volt, and I_t is equal to 90 percent of its maximum value or 0.09 mA. The values of E_C, E_R, and I_t in Table III are obtained from the universal time constant chart.

Table III. Voltage and current values when a positive DC is applied to a series RC circuit

Time Elapsed (in usec)	E_c (volt)	E_R (volt)	I_t (mA)
1	0.10	0.90	0.09
2	0.19	0.81	0.081
5	0.40	0.60	0.06
10	0.63	0.37	0.038
20	0.87	0.13	0.013
30	0.95	0.05	0.005

c. After 70 usec, 7 time constants have elapsed. E_C then is equal to 1 volt, and E_R and I_t are equal to zero. The approximate current flowing in any series RC circuit and the voltage across the components in the circuit can be determined by substituting the appropriate values of E, R, and C in the circuit.

13. STEP-BY-STEP PROCEDURE FOR DETERMINING TRANSIENT RESPONSE

a. When a universal time constant chart is unavailable, the response curve of any RC circuit can be approximated by using the basic voltage equation $E = I_tR + Q/c$. Since $Q/C = E_C$, the formula may be expressed as $E = I_t R + E_C$. The following step-by-step procedure is used to provide an approximate response of a series RC circuit to any waveform.

b. In this procedure, assume that the current does not decrease continuously, but rather, in small steps. In a series RC circuit, let E equal 1 volt, C equal 1,000 uuf, and R equal 10,000

ohms. At the instant that E is applied to the circuit, the current is 0.1 mA and the applied voltage E appears across R. Since one coulomb is the quantity of electrons required to pass a given point in the circuit during one second of time in order to produce a current flow of one ampere, the initial rate of charge must be 0.0001 coulomb per second (this is determined on the basis that the initial current is 0.1 mA) or 0.0001×10^{-6} coulomb per usec. After 1 usec, the voltage across C is equal to 0.0001×10^{-6} (charge in coulombs) divided by 10^{-9} (capacitance in farads) or 0.1 volt. The voltage across R, therefore, is equal to 0.9 volt and I_t is equal to 0.09 mA. Since I_t now is equal to 0.09 mA, the rate of charge has decreased to 0.00009 coulomb per second or 0.00009×10^{-6} coulomb per usec. After 2 usec, Q is equal to $0.00001 \times 10^{-6} + 0.00009 \times 10^{-6}$ or 0.00019×10^{-6} coulomb. E_C then is equal to $0.00019 \times 10^{-6}/10^{-9}$ or 0.19 volt. The rate of voltage change is now 0.09 volt per usec. E_R, at this time, is equal to 0.81 volt and the current is equal to 0.081 mA. In a similar way, all values of I_t, E_R, and E_C, and the charging rate can be determined until the steady-state condition is reached.

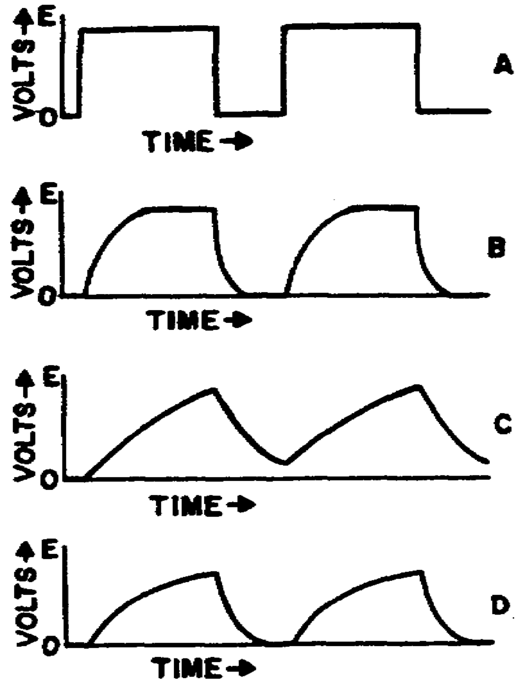
PRACTICAL APPLICATIONS OF RC AND RL CIRCUITS

Section I. RELATIONSHIP BETWEEN TIME CONSTANTS AND PULSE DURATIONS

14. TIME CONSTANT CHARACTERISTICS.

a. In the series RC and RL circuits discussed previously, the time required for the output current or voltages to reach a steady-state condition depended on the time constant of the circuit. Time constants were used in describing pulse characteristics during the rise time, duration period, or decay time of the output pulse. Time constants are a factor in determining the amplitude of the output pulse since it can prohibit the amplitude from reaching a value equal to the applied voltage (Figure 21D). Time constants are also a factor in determining the value to which the output pulse decays since it can prohibit the pulse from decaying to zero before the next input pulse is applied (Figure 21C).

Figure 21. Response of a series RL circuit to an ideal rectangular pulse



b. In Figure 21A, the rectangular pulse represents the input voltage to a series RC or RL circuit. The output waveforms in Figure 21B, C, and D are taken across C in an RC circuit and across R in an RL circuit. In Figure 21B, the output voltage reaches a value equal to E a short time after the input pulse is applied, and decays to zero after the input pulse is removed. This is the result of a short-time constant in relation to the width of the input pulse and the rest time between the pulses. In Figure 21C, the output voltage reaches a value equal to E more slowly and does not decay to zero before the next input pulse is applied. This is the result of a long-time constant in relation to the rest time between pulses. In Figure 21D, the output voltage does not reach a value equal to E but does decay to zero before the next input pulse is applied. This is the result of a long-time constant in relation to the width of the pulse.

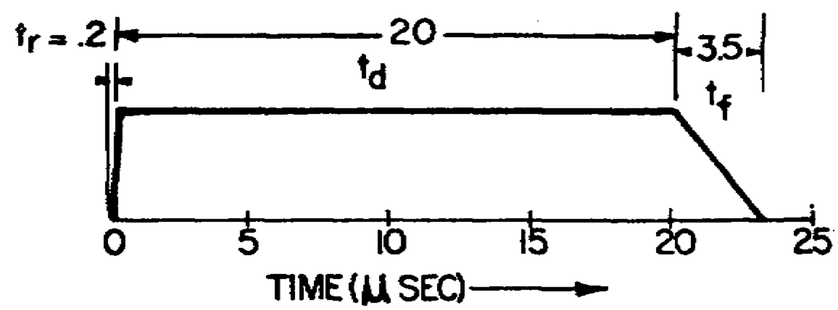
Section II. CHARACTERISTICS OF RC AND RL TIME CONSTANTS

15. GENERAL.

a. In a series RC or RL circuit, the time constant depends upon the value of the component parts since the time constant formula is TC = RC for an RC circuit, and TC = L/R for an RL

circuit. Whether a time constant is long, short, or medium, however, depends upon the reference periods. The rise time, duration time, and decay time (Figure 22) of the input pulse determine the reference periods. If a time constant is less than one-seventh the time of the reference period, the time constant is considered to be short. If the time constant is greater than 7 times the time of the reference period, the time constant is considered to be long. If the time constant is greater than one-seventh but less than 7 times that of the reference period, the time constant is considered to be medium.

Figure 22. Pulse with finite rise and decay times

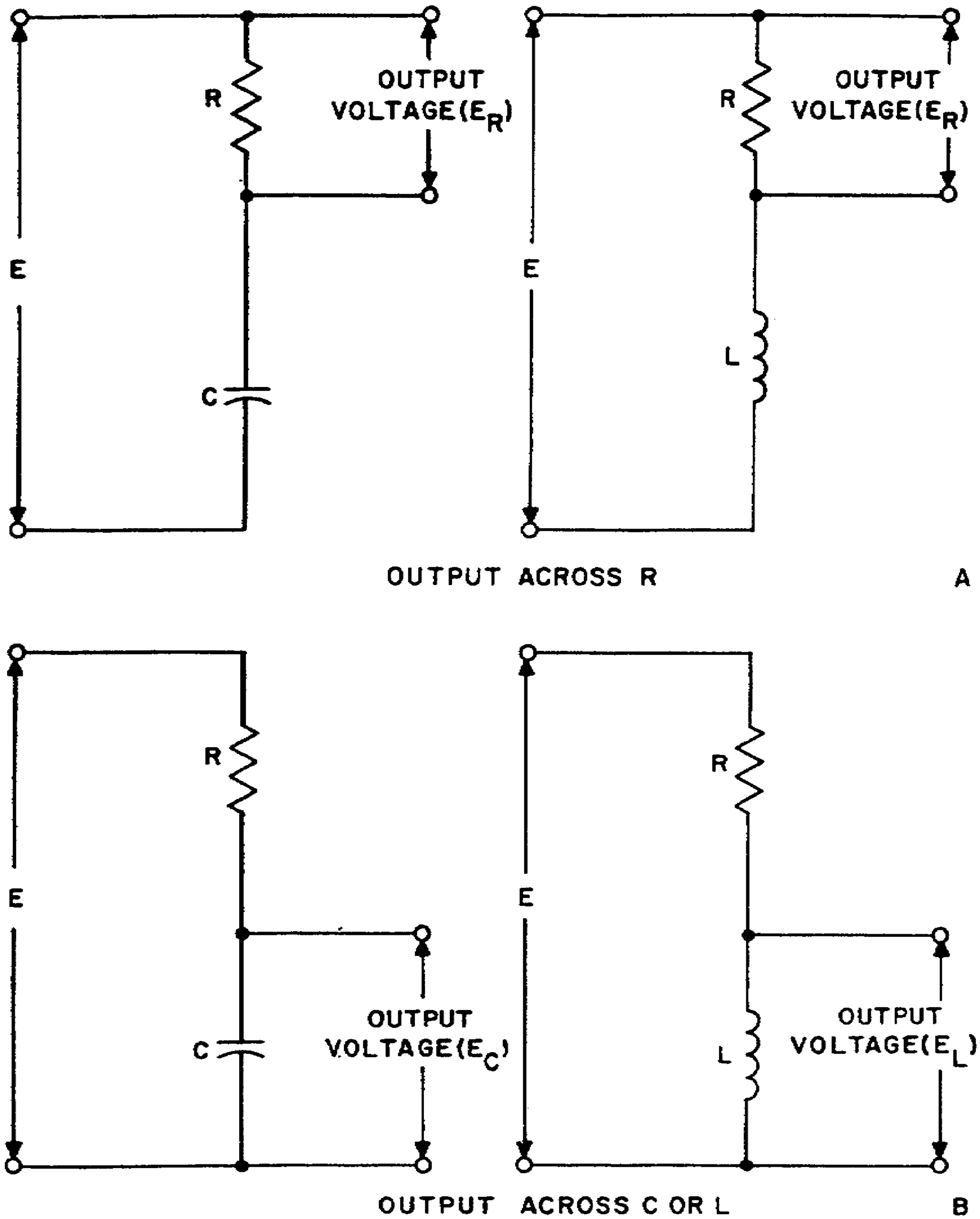


b. For example, if the pulse shown in Figure 22 is applied to a series RC or RL circuit having a time constant of 1.5 usec, the circuit is considered to have a long-time constant in relation to the rise time of the pulse, a short-time constant in relation to duration time of the pulse, and medium-time constant in relation to the pulse's decay time.

16. EFFECT OF TIME CONSTANT ON A SQUARE WAVE.

a. General. There are two sources of output voltage available from either an RC or an RL circuit (Figure 23). When taken across the resistor, the output voltage is proportional to the current flowing in the circuit; when taken across the capacitor, the output voltage is proportional to the charge on the capacitor, and when taken across the inductor, the output voltage is proportional to the rate of change of current.

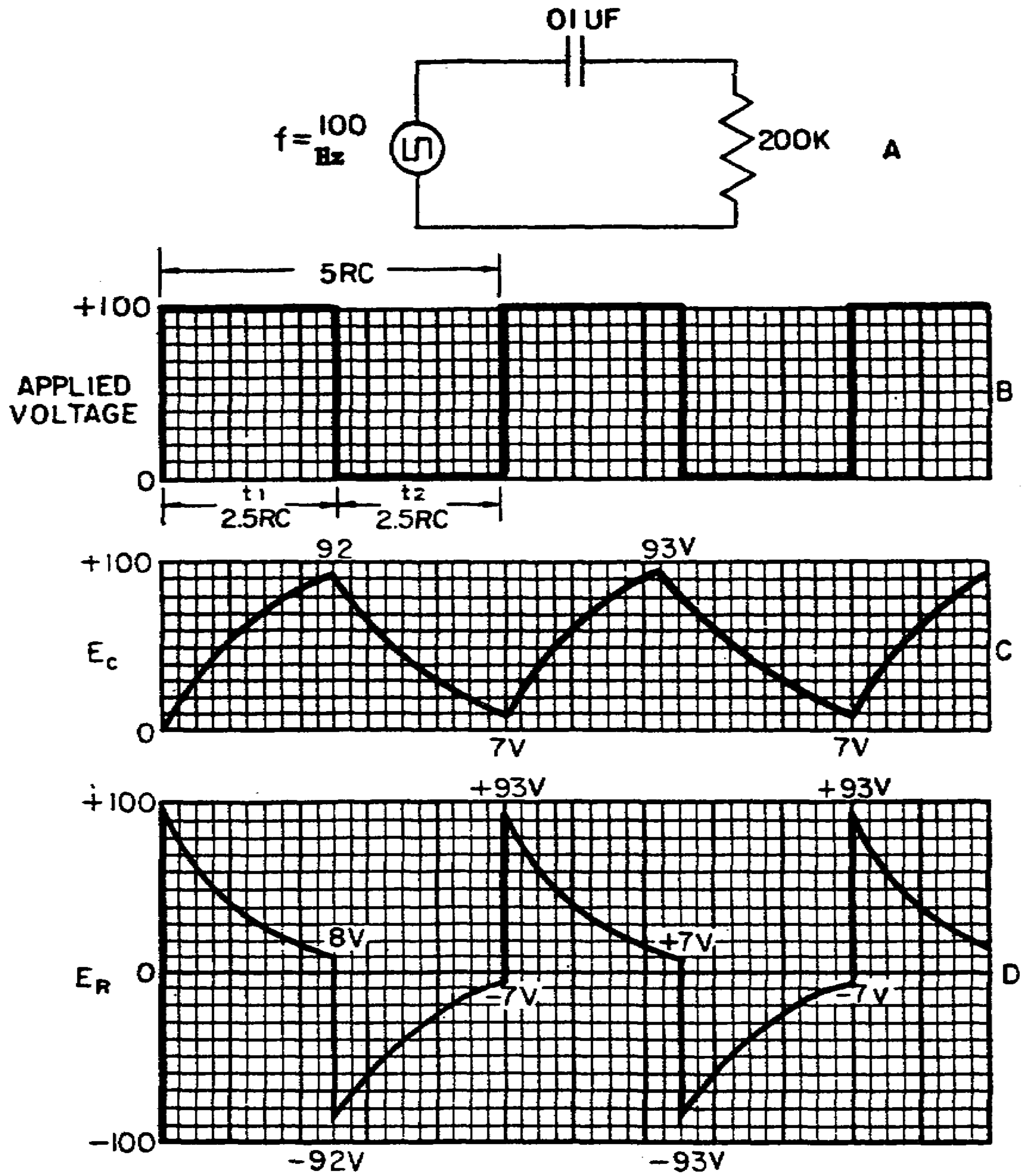
Figure 23. Output voltage sources in RC and RL circuits



b. Response of an RC circuit.

(1) Figure 24 shows the effect of a time constant on an RC circuit when the period of the square wave (one complete cycle) is equal to five time constants. Since the pulse rise and decay times are considered to be zero, the duration time is considered to be equal to the entire width of the pulse or one-half the time of a complete cycle. The duration time, therefore, is equal to 2.5 time constants. During the second half of the square wave (t_2), or the zero voltage period, the capacitor discharge current flows through the generator. The resistance encountered in the generator is considered to be zero.

Figure 24. Effect of medium-time constant square-wave input

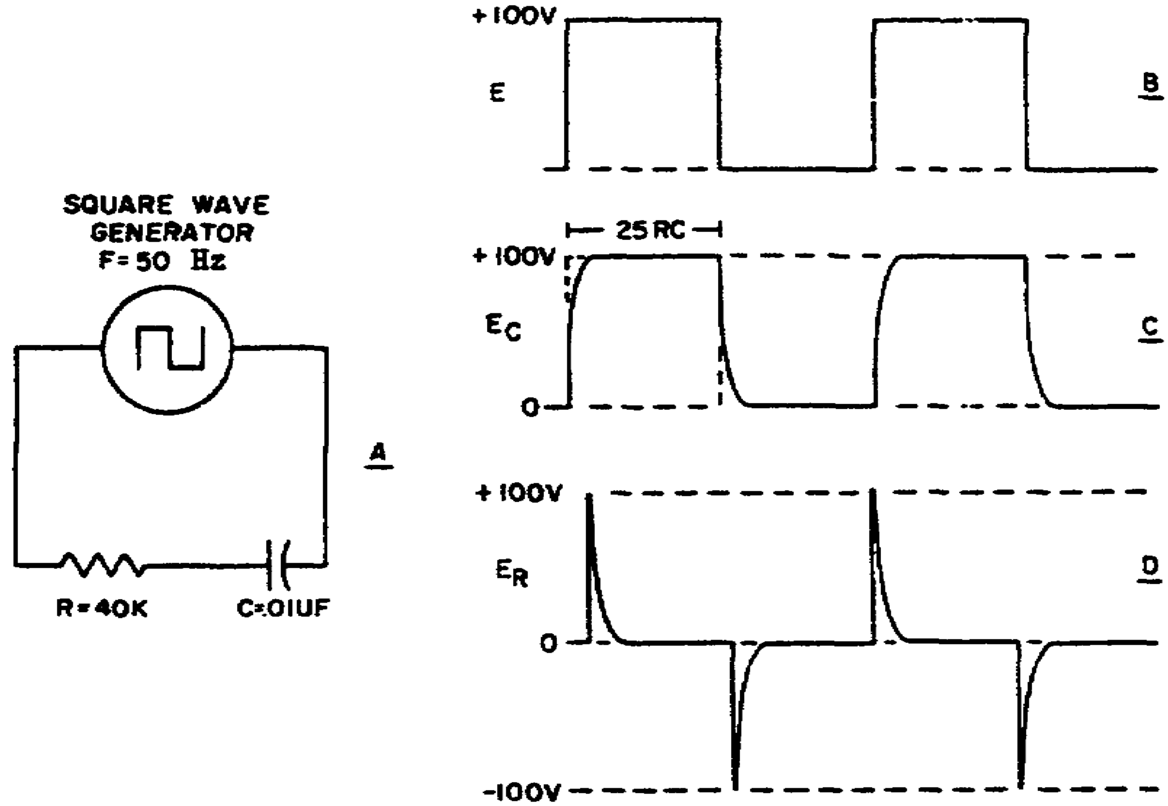


(2) When the pulse is first applied to the circuit, the full input voltage appears across R, since the capacitor has no charge. At this time, E_R is equal to E and E_C is equal to zero. The capacitor begins to charge exponentially to a value determined by the universal time constant chart (Figure 20). As the voltage

across the capacitor increases, the voltage across the resistor decreases. At the end of two and a half time constants, the capacitor voltage, as determined by the universal time constant chart, is equal to approximately 92 percent of the applied voltage, while the resistor voltage has decreased to approximately 8 percent of the applied voltage. At this time, the applied voltage falls to zero, and the capacitor starts to discharge through the resistor. This causes a negative voltage to be developed across R equal to 92 percent of the maximum applied voltage. The discharge curve is slightly more gradual than the charge curve for the first pulse. The reason for this difference is that the capacitor charges from zero toward E during the pulse duration time (t_1), and discharges from 92 percent of E toward zero during the pulse rest time (t_2). At the end of five time constants E_C is equal to approximately 7 percent of the maximum value of E, while E_R is equal to approximately 7 percent of -E. At this time, another positive pulse is applied, and the process is repeated.

(3) Now consider the output waveshapes when a square wave is applied to an RC circuit with a comparatively short-time constant (Figure 25). In this case, the time constant is equal to 0.02 of a frequency cycle. Thus, in 20 percent of a half cycle (duration time), five time constants occur. As a result, the capacitor charges very quickly to the maximum applied voltage. The early rise of E_C to the full, applied voltage and its rapid decrease to zero when E falls to zero cause the voltage waveform across the capacitor to resemble the square-wave input. The short duration of the high charging and discharging currents affect the resistor voltage quite differently. The rapid rise and drop of E_R cause the voltage waveform across the resistor to be peaked at each square-wave changeover (change from maximum voltage to zero or from zero to maximum). The amplitude of each curve, at any instant of time, can be readily determined from the universal time constant chart (Figure 20).

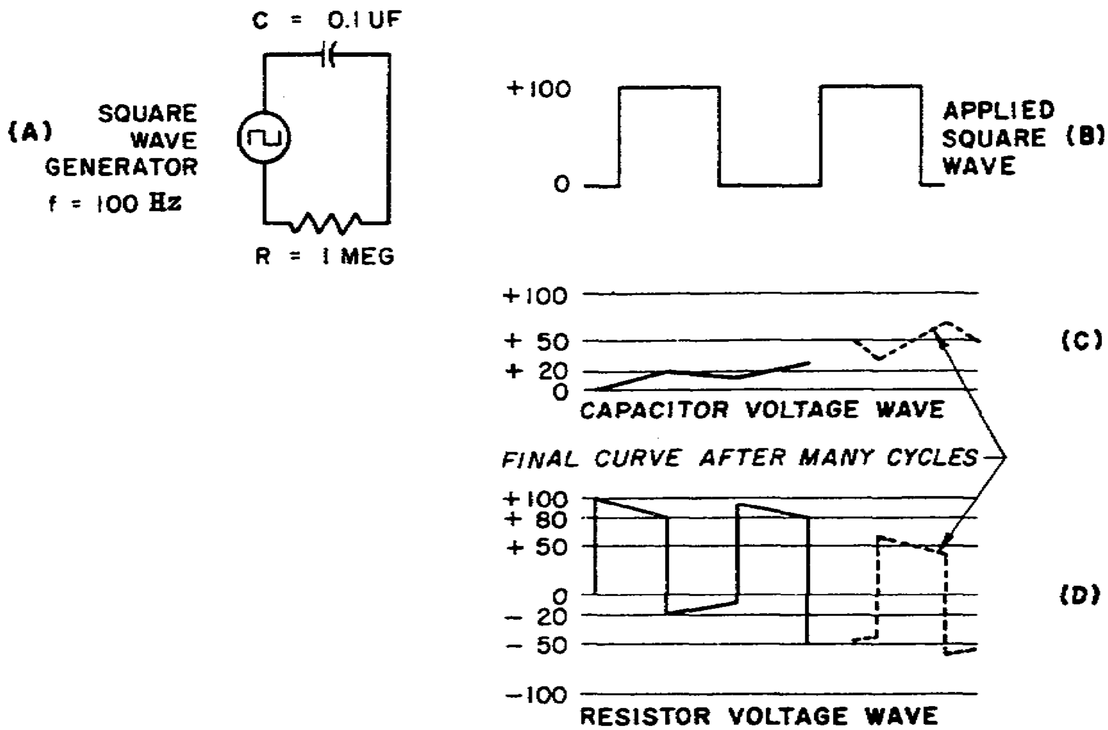
Figure 25. Waveshapes for short-time constant RC circuit.



(4) The output waveforms produced by applying a square wave to an RC circuit having a comparatively long-time constant are illustrated in Figure 26. Here the time constant is 10 times as long as the duration of one complete cycle of input voltage of 20 times the pulse duration time. Referring to the universal time constant chart (Figure 20), it can be seen that the capacitor in the circuit will charge almost linearly for about 20 percent of the first-time constant. This causes the waveforms of the capacitor voltage (Figure 26C) and the resistor voltage (Figure 26D) to be linear during the entire half cycle. This also holds true during the second half of the cycle when the capacitor is discharging from 20 percent of the maximum value of E towards zero, and the resistor voltage is decreasing from minus 20 volts towards zero. On each succeeding half-cycle, the capacitor charges and then discharges from a slightly higher value of voltage. Eventually, a point is reached where E_C varies equally above and below the average value of E, while E_R varies equally

above and below the zero voltage axis. The waveforms for E_C and E_R, at this time, are illustrated by the dotted lines in Figures 26C and 26D.

Figure 26. Waveshapes for long-time constant RC circuit

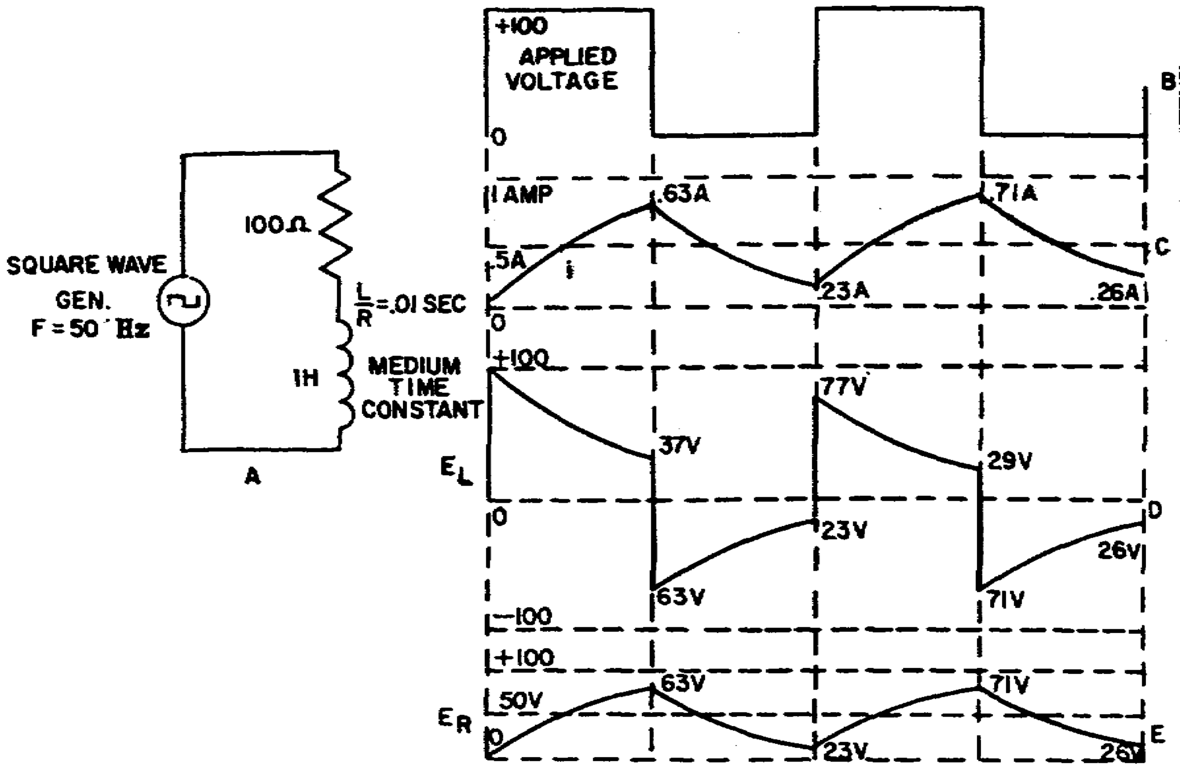


c. Response of RL circuit.

(1) In a series RL circuit, the current and, therefore, the resistor voltage varies in exactly the same manner as the capacitor voltage in a series RC circuit. The inductor voltage waveform is the same as the current and resistor voltage waveforms in an RC circuit. In Figure 27A, a square wave is applied to an RL circuit in which the time constant is equal to one-half the duration of one complete cycle (duration time). At the first instant the square wave is applied, a back emf equal to E is developed across the inductor, and no current flows. Current then begins to flow in the circuit at a rate determined by the universal time constant chart (Figure 18). At the end of 1 time constant, the current (Figure 27C) has increased to approximately 63 percent of its steady-state value E/R. The voltage across the resistor, therefore, is equal to approximately 63 percent of E applied (Figure 27E), and E_L has decreased to approximately 37 percent of

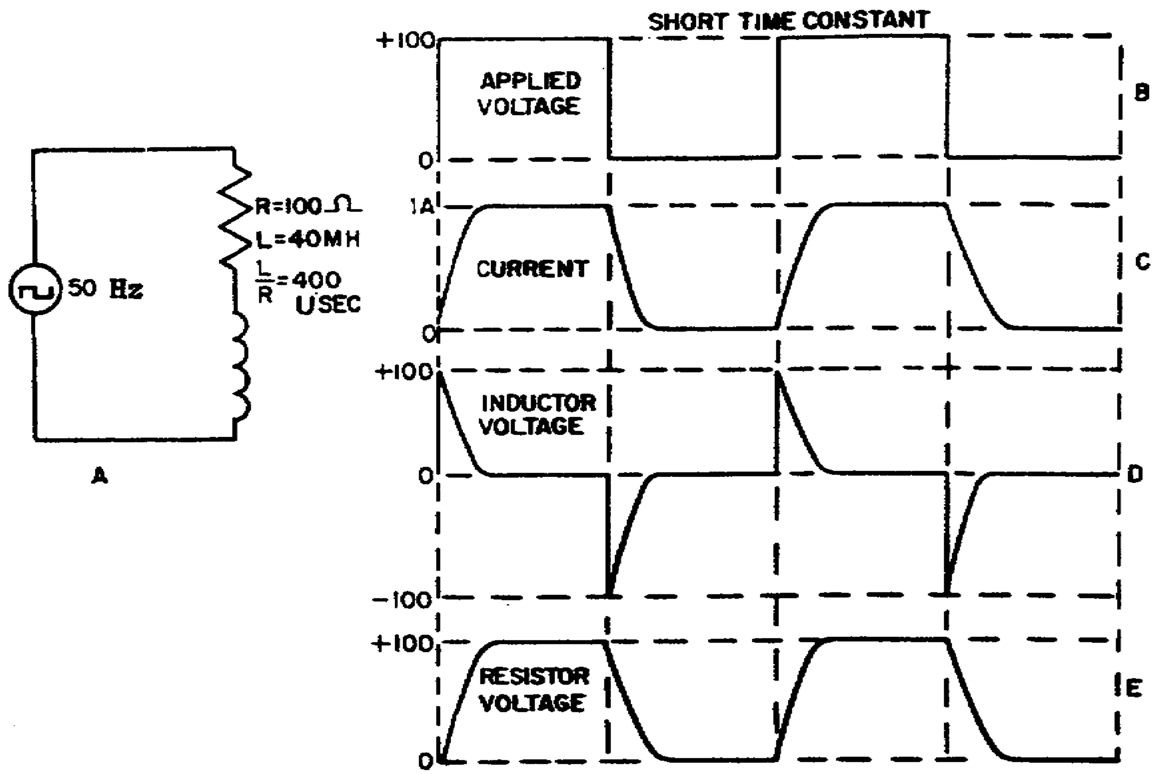
the applied voltage (Figure 27D). At this time, the input pulse decays to zero and a back emf is developed across the inductor. This voltage is equal and opposite to E_R, or 63 percent of -E. The current and the resistor voltage now decrease towards zero at a rate determined by the universal time constant chart. After 1 time constant, the current and E_R are both equal to 37 percent of the values from which they started to decrease, or approximately 23 percent of their steady-state values. At the same time, E_L is decreasing to approximately 23 percent of -E. During the next half-cycle, the current and the resistor voltage start increasing from a value equal to approximately 23 percent of their steady-state values and, therefore, reach a higher value than they did during the first half-cycle when they started increasing from zero. During each succeeding cycle, the current and the resistor voltage reach a slightly higher value than they did during the previous cycle, until a point is reached where E_R varies equally above and below the average value of the applied voltage (50 volts in the circuit illustrated), and the current varies equally above and below an average value of 50 volts divided by 100 ohms (value of R) or 0.5 amperes. The inductor voltage at this time varies equally above and below the zero volt axis.

Figure 27. Effect of medium RL time constant



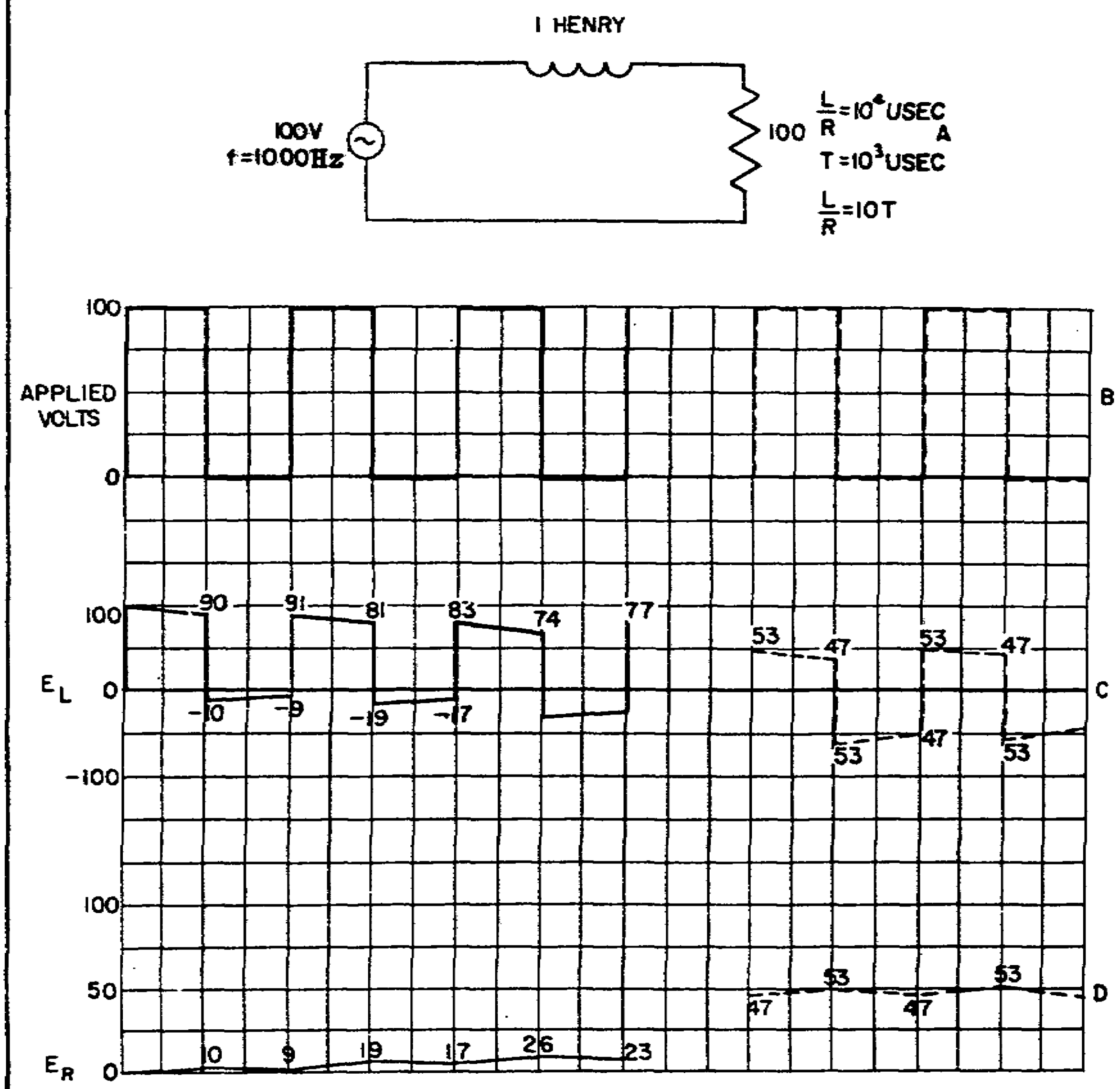
(2) If the same square wave is applied to an RL circuit having a short-time constant in respect to its duration time (Figure 28A), E_R (Figure 28E) rises quickly to a value equal to E when the pulse is applied, and falls rapidly to zero when the pulse decays to zero. On the other hand, the voltage waveform across the inductor (Figure 28D) assumes the form of alternate positive and negative triggers having peak values equal to E and -E.

Figure 28. Effect of short RL time constant



(3) The waveshapes illustrated in Figure 29 are those produced when a square wave is applied to an RL circuit having a long-time constant in respect to its duration time. The time constant used in this circuit is 10 times the period of one complete input cycle, or 20 times the duration time. Since each half-cycle represents only 5 percent of 1 time constant, the current, resistor voltage (Figure 29D), and the inductor voltage (Figure 29C) changes are practically linear. The resistor voltage starts each cycle at a slightly higher value, and the inductor voltage starts at a slightly lower value, until a point is reached where E_R varies equally above and below the average value of the applied voltage, and E_L varies equally above and below zero. These waveforms are illustrated by the dotted lines in Figure 29.

Figure 29. Effect of long RL time constant



17. TRIANGULAR WAVEFORMS IN RC AND RL CIRCUITS.

a. General. Waveforms having gradual rise and decay times are required in many of the circuits contained in a radar system. A triangular waveform is shown in Figure 30A. Notice that the waveform starts at zero and continues to increase at a constant rate (rise time). When the maximum amplitude has been reached, the waveform immediately starts decreasing at a constant rate

(decay time). Since the waveform does not level off at a constant value, the duration time is zero. The triangular waveform thus is different from the square wave in which the voltage rises quickly and then levels off. Likewise, the response of RC and RL circuits to a triangular wave is different from their response to a square wave.

b. Response of an RC circuit. The response of an RC circuit to a triangular wave input is illustrated in Figure 30. Figure 30C shows the voltage waveforms enlarged several times for easier study. When a square wave is applied, the capacitor charges gradually towards the value at which the square wave levels off; with the application of a triangular wave, the voltage continues to increase as the capacitor charges toward it, and the capacitor must continuously charge toward a new, higher value. Initially, when the voltage E is applied to the circuit, the current rises with the voltage because the capacitor is uncharged. The current charges the capacitor to a voltage that opposes the applied voltage. This action should decrease the circuit current, but since the input voltage is continuously increasing, the opposing voltage across the capacitor is more than overcome by the applied voltage, and the current actually increases, but at a slower rate than it did initially. As the current continues to increase, the capacitor becomes charged to a higher voltage and the rate of current increase is reduced further until, finally, the current is high enough to raise the capacitor voltage at the same rate as the increase in the input waveform. At this point, the current becomes constant, and the capacitor voltage slope is essentially the same as the input voltage slope.

(1) The current curve is the same as the curve E_R. At the end of 1 time constant, the resistor voltage is equal to approximately 63.2 percent of the voltage applied at that time, and the current is equal to 63.2 percent of the voltage applied at that time divided by the value of the resistance in the circuit. After 7 time constants, E_R will level off at a value equal to the voltage applied at the end of the first-time constant, and the current will be equal to this voltage divided by the resistance. The capacitor continues to charge at the same rate as the rise in input voltage, until the rise of input voltage ceases. As the applied voltage abruptly starts decreasing during the second half of the cycle, the charging rate of the capacitor decreases, until the applied voltage drops to the same value as the capacitor voltage (Figure 31B). At this point, the current in the circuit is zero. As the applied voltage continues to decrease, it falls below the capacitor voltage, and the capacitor starts to discharge.

This action reverses the current flow and causes a negative voltage to be developed across the resistor. Again, the change-over cannot occur any faster than the capacitor can discharge; therefore, the current change and, consequently, the resistor voltage change, follows a gradual curve.

Figure 30. Response of RC circuit to triangular wave input

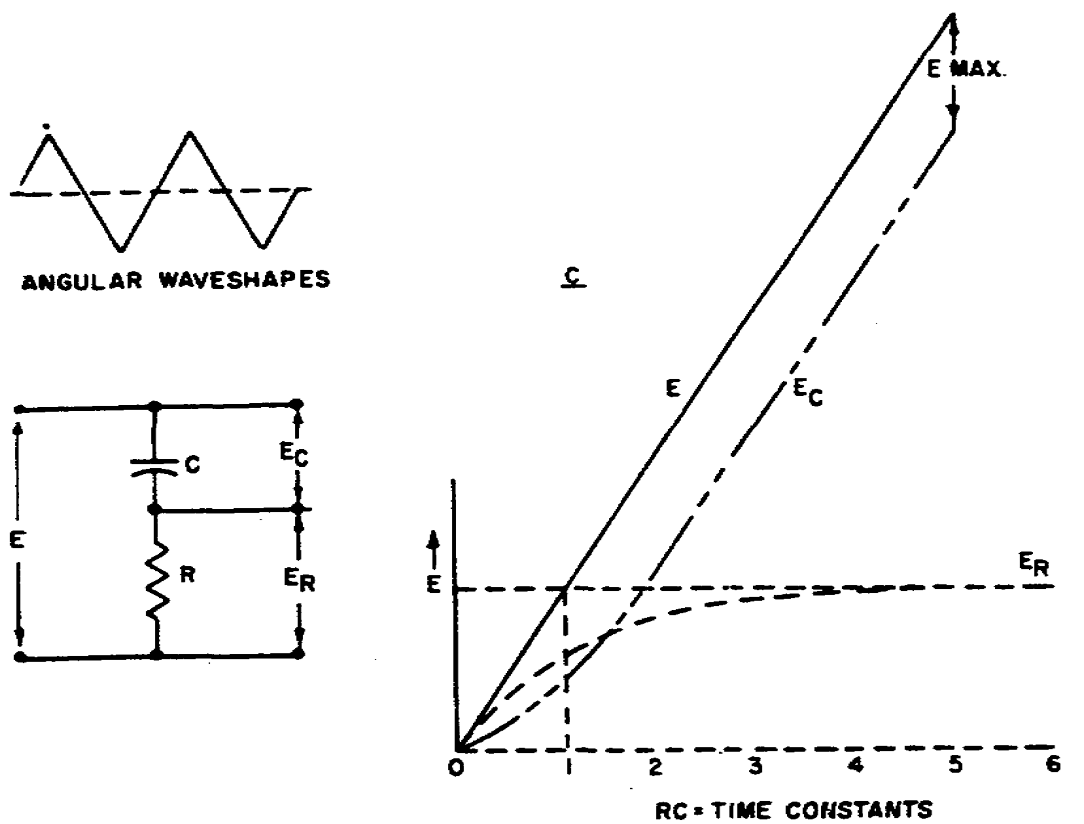
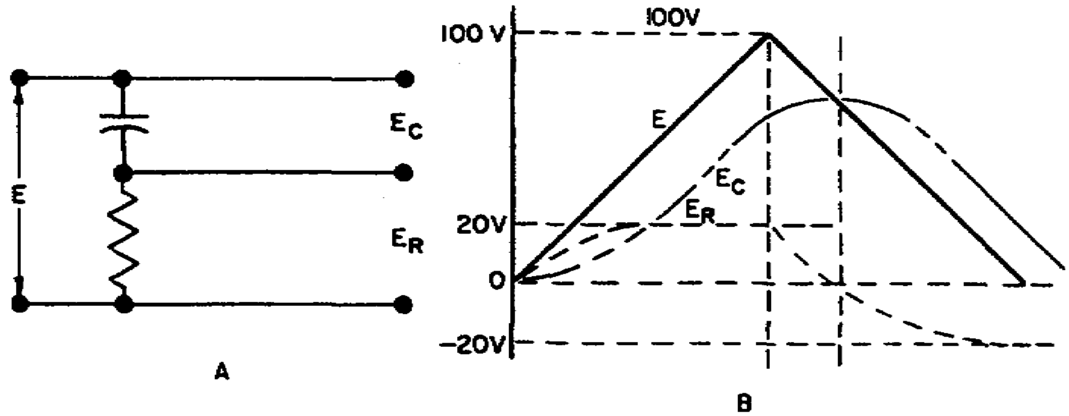
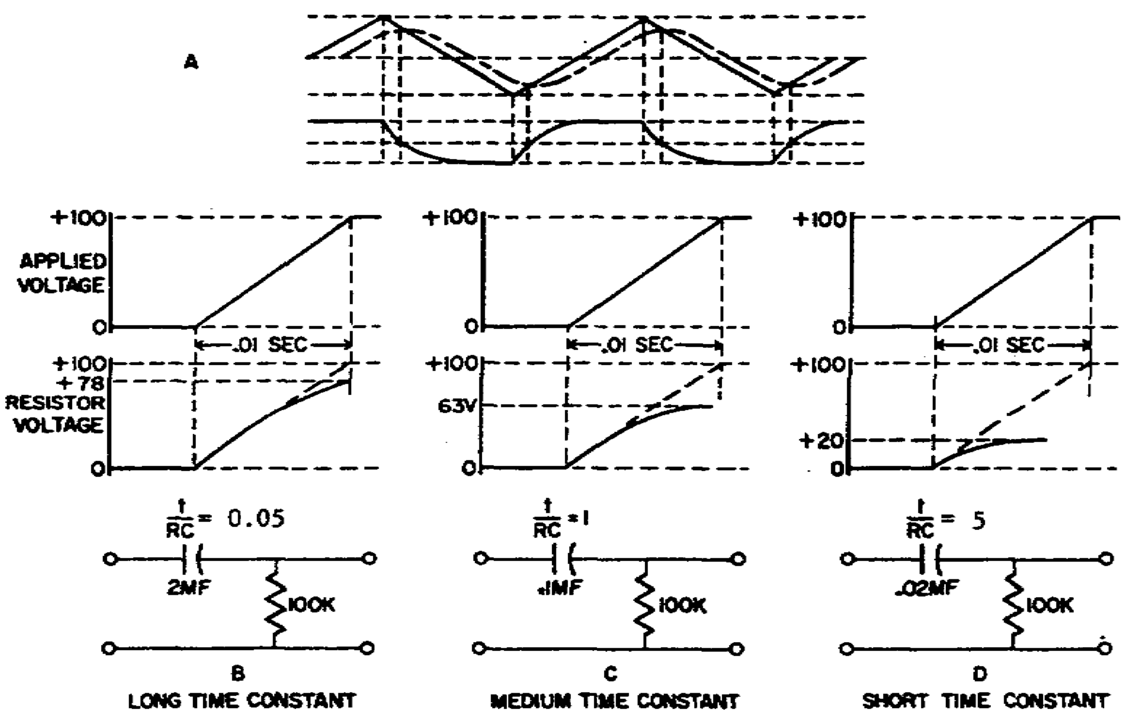


Figure 31. Capacitor and resistor voltages with triangular wave input



(2) Figure 32A illustrates two complete cycles of the triangular wave input, E_C (dotted curve), and E_R. To illustrate the effect of varying the time constant of the circuit, the input rise time, and the E_R curve during this time, are enlarged and illustrated for different values of time constants in Figures 32B, 32C, and 32D. The time constant of the RC circuit in Figure 32B is equal to 20 times the rise time of the input waveform, and the resistor voltage very closely follows the input waveform. When RC is equal to the rise time of the input waveform, the resistor voltage reaches approximately 63 percent of the maximum applied voltage after 1 time constant (Figure 32C). In Figure 32D, the time constant is equal to one-fifth of the rise time of the applied voltage, and, therefore, E_R only reaches a value of approximately 20 percent of the maximum applied voltage.

Figure 32. Varying the time constant with triangular wave input



c. Response of an RL circuit. An RL circuit has the same effect on triangular waveforms as an RC circuit if certain changes are observed. The resistor voltage waveform of an RC circuit occurs across the inductor in an RL circuit, and the capacitor voltage waveform occurs across the resistor. The time constant, of course, is equal to L/R instead of R x C. Also, when a triangular voltage waveform is applied to an RL circuit, the current increases at a constant rate. This constant rate of current increase, in turn, causes the inductor voltage to become constant after 7 time constants.

Section III. HIGH-PASS RC CIRCUIT

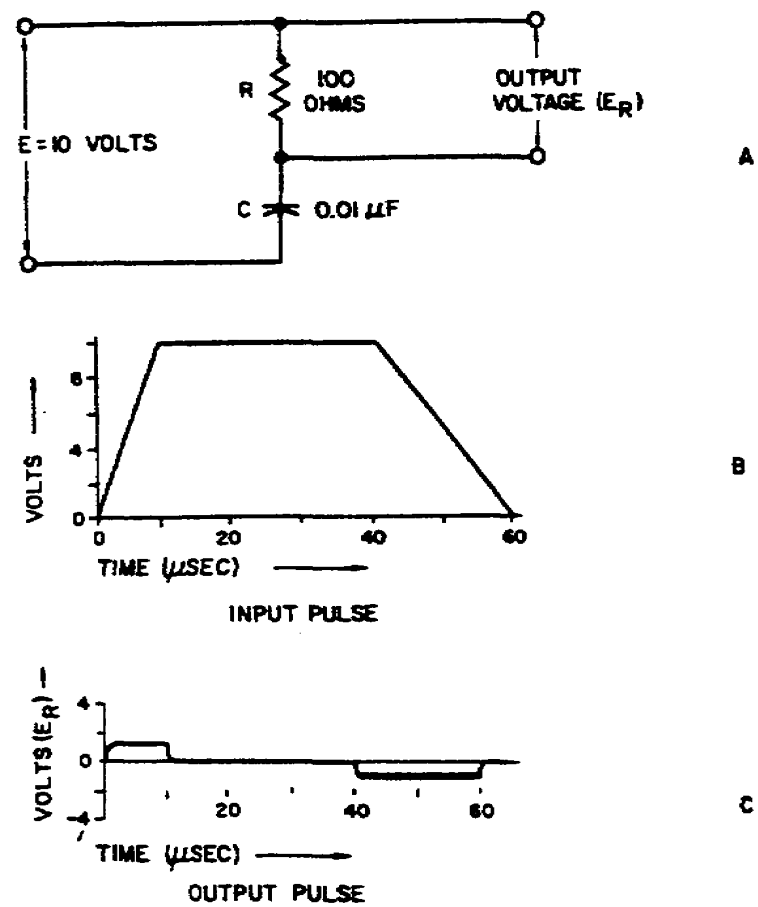
18. GENERAL.

When E_R is taken as the output voltage, the RC circuit is known as a high-pass filter. A high-pass filter attenuates all frequencies below a certain determined value, while passing frequencies above this value.

19. SHORT-TIME CONSTANT.

a. The pulse shown in Figure 33B is applied to the high-pass RC filter in Figure 33A. The time constant of the circuit is 1 usec, which is short compared to the rise (10 usec), duration (30 usec), and decay (20 usec) times of the pulse. Since the time constant of this circuit is short when compared with the pulse rise time, the capacitor charging rate quickly reaches the rate of increase of the applied voltage. This causes the current and, therefore, the output voltage across the resistor to level off at a very low value.

Figure 33. Input and output pulses for a high-pass, short-time-constant, series RC circuit



b. At 10 usec, the applied voltage reaches the maximum value of 10 volts and remains constant for the next 30 usec. Since there is only a small difference between E and E_C, the capacitor quickly charges to 10 volts. This increase in E_C to a value equal to E causes the output voltage and current to decrease to zero and to remain at zero during the remainder of the duration period of the input pulse.

c. At 40 usec, the applied voltage begins to decay. Current begins to flow in a direction opposite to the original current flow. This results in a negative output voltage across the resistor. Again, because of the short-time constant, the rate of discharge of the capacitor quickly reaches the rate of decrease of the applied voltage causing the current and the negative output voltage across R to level off at a low value.

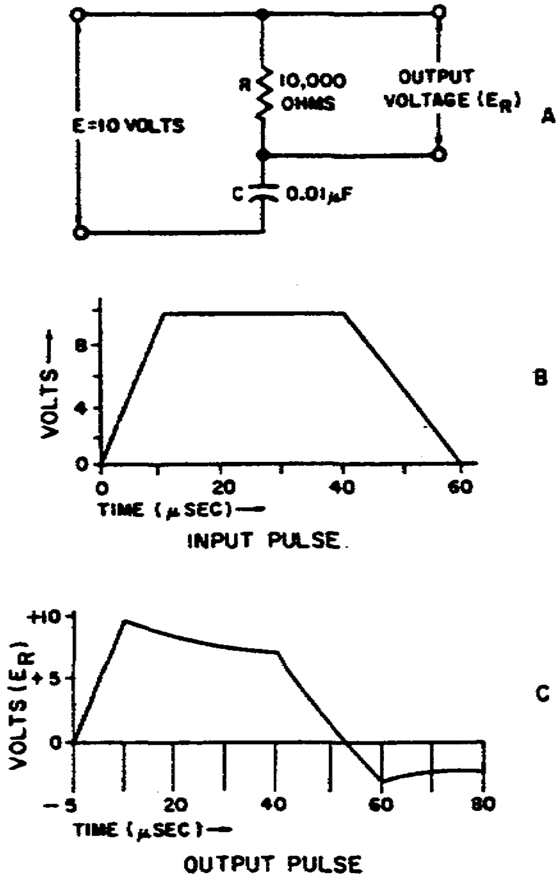
d. At 60 usec, the applied voltage is equal to zero and E_C is equal to E_R. The capacitor continues to discharge at the same rate; and after 61 usec, E_C is considered to be zero. The current and output voltage are also zero at this time.

20. LONG-TIME CONSTANT.

a. When the time constant is long compared with the pulse rise, duration, and decay times, the capacitor charges to only a small fraction of the total applied voltage. Most of the applied voltage appears across R, and the output waveform closely resembles the input waveform.

b. The pulse shown in Figure 34B is applied to the high-pass RC filter in Figure 34A. The time constant of the circuit is equal to 100 usec. Since the rise time of the pulse (10 usec) represents only 10 percent of 1 time constant, the capacitor charges only slightly, and the resistor voltage closely follows the rise of the input pulse.

Figure 34. Input and output pulses for a high-pass, long-time-constant, series RC circuit



c. After 10 usec, the applied voltage remains at 10 volts for 30 usec and the capacitor charges slowly toward the applied voltage at a rate determined by the universal time constant chart. During this time, the output voltage E_R decreases at the same rate.

d. After 40 usec, the applied voltage starts to decay. The capacitor voltage remains constant until the applied voltage has decayed to a value equal to E_C. During this time, the output voltage E_R decreases rapidly as the applied voltage. When the applied voltage is equal to E_C, the output voltage E_R is equal to the difference between E_C and E, or zero. As E decreases toward zero, E_C also decreases, but follows a more gradual decay curve.

Since E - E_C = E_R , then E_R is increasing during this time but in a negative direction. At 60 usec, E is equal to zero, and the output voltage E_R is equal to E_C, but is opposite in polarity. The capacitor continues to discharge until, at the end of 7 time constants (700 usec later), E_C and the output voltage E_R are both equal to zero.

Section IV. LOW-PASS RC CIRCUIT

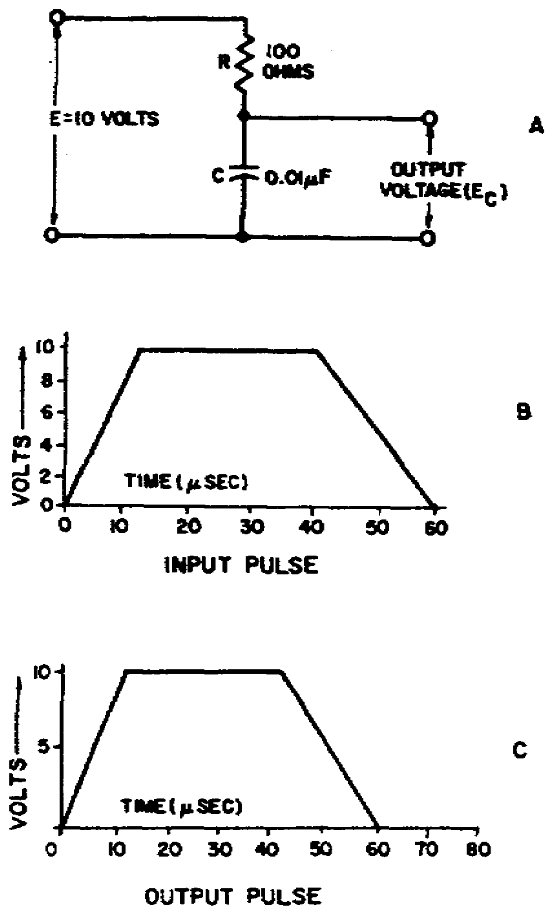
21. GENERAL.

The output of a low-pass RC filter is taken across the capacitor. The effect of the time constant on the output waveform differs entirely from that of a high-pass RC filter. When the time constant of a low-pass RC filter is short compared with the reference period, the output waveform closely resembles the input waveform. When the time constant of a low-pass RC filter is long compared with the reference period, the output waveform does not resemble the input waveform.

22. SHORT-TIME CONSTANT.

a. The pulse shown in Figure 35B is applied to the low-pass RC filter in Figure 35A. The time constant of the circuit is equal to 1 usec, which is short compared to the pulse rise (10 usec), duration (30 usec), and decay (20 usec) times. Since the time constant of this circuit is short compared with the pulse ripe time, the charging rate of the capacitor quickly reaches the rate of increase of the applied voltage. As a result, the output voltage E_C (Figure 35C) closely follows the rise of the pulse. During this time, the current and E_R level off at a low value.

Figure 35. Input and output pulses for a low-pass, short-time-constant, series RC circuit



b. At 10 usec, the applied voltage is equal to 10 volts. Since there is only a small difference between E and E_C at this time, the capacitor quickly charges to 10 volts while the current and E_R decrease to zero. E_C then remains at 10 volts during the remainder of the duration period of the input pulse.

c. At 40 usec, the applied voltage begins to decay. Current begins to flow in a direction opposite to that of the original current flow, and causes a small negative voltage to be developed across the resistor. The rate of discharge of the capacitor quickly reaches the rate of decrease of the applied voltage, and E_C closely follows the decay of the pulse.

d. At 60 usec, the applied voltage is equal to zero and the output voltage E_C is equal to E_R but is opposite in polarity. E_C continues to discharge at the same rate; and at 67 usec, E_C and E_R are equal to zero.

23. LONG-TIME CONSTANT.

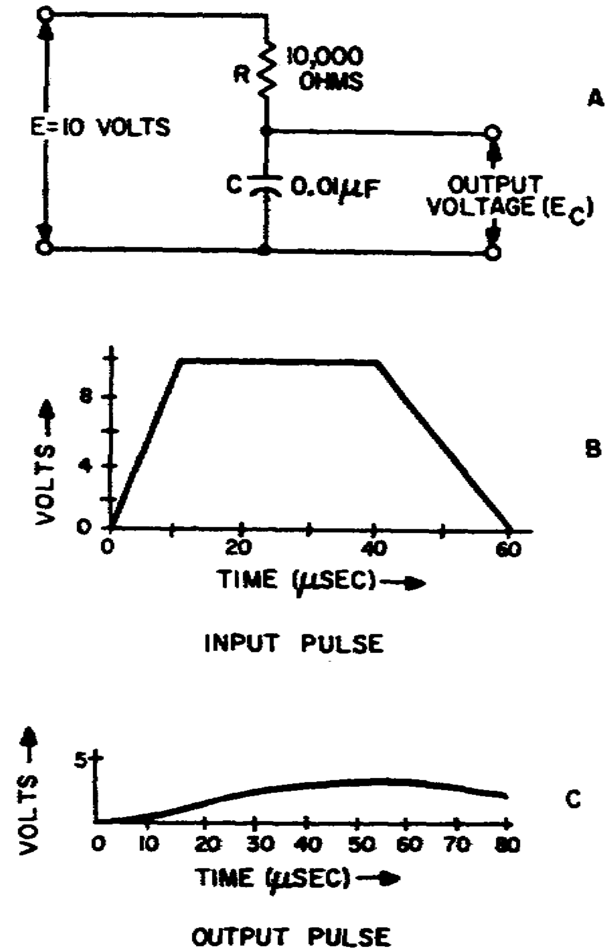
a. When the time constant is long compared with the pulse rise, duration, and decay times, the capacitor charges to only a small fraction of the total applied voltage. Most of the voltage appears across R, therefore, the output voltage E_C does not resemble the input waveform.

b. The pulse shown in Figure 36B is applied to the low-pass RC filter in Figure 36A. The time constant of the circuit is equal to 100 usec. Since the rise time of the input pulse represents only 10 percent of 1 time constant, the capacitor charges only slightly during this time, while the current and E_R closely follow the rise of the input pulse.

c. After 10 usec, the applied voltage remains at 10 volts for 30 usec and the capacitor charges slowly toward the applied voltage, at a rate determined by the universal time constant chart. During this time the current and E_R are decreasing at the same rate.

d. After 40 usec, the applied voltage starts to decay. The output voltage continues to rise at a reduced rate until E decays to a value equal to E_C, When E is equal to E_C, the current and E_R are equal to zero. As E decreases toward zero, E_C also decreases, but follows a more gradual decay curve. After the applied voltage reaches zero, E_C continues to decay following the capacitor discharge curve of the universal time constant chart. After 7 time constants have elapsed, that is, after 760 usec, the output voltage E_C is equal to zero.

Figure 36. Input and output pulses for a low-pass, long-time-constant, series RC circuit.



Section V. HIGH-PASS RL CIRCUIT

24. GENERAL.

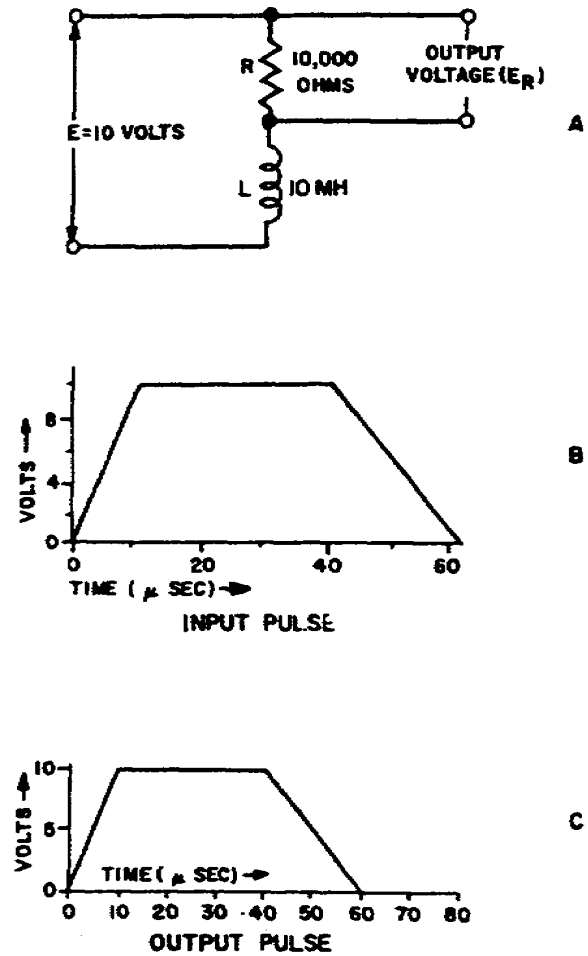
When E_L is taken as the output voltage, the series RL circuit is known as a high-pass filter. A high-pass filter attenuates all frequencies below a certain determined value, while passing frequencies above this value.

25. SHORT-TIME CONSTANT.

a. The pulse shown in Figure 37B is applied to the high-pass RL filter in Figure 37A. The time constant is equal to 1 usec, which is short compared to the pulse rise (10 usec), duration (30 usec), and decay (20 usec) times. Since the time constant of this circuit is short compared to the pulse rise time, the output voltage across the inductor (Figure 37C) will increase to only a fraction of the input voltage.

b. When the voltage is first applied to the circuit, current attempts to flow. During the first microsecond, the inductor develops a back emf which is considered to be equal to the applied voltage. As the applied voltage continues to increase, the rate of current increase becomes proportional to the rate of increase of E. As a result, the output voltage E_L remains constant, while E_R closely follows the rise of the input pulse. At 10 usec, the output voltage E_L is still at this low value and E_R is equal to $E - E_L$.

Figure 37. Input and output pulses for a high-pass, short-time-constant, series RL circuit



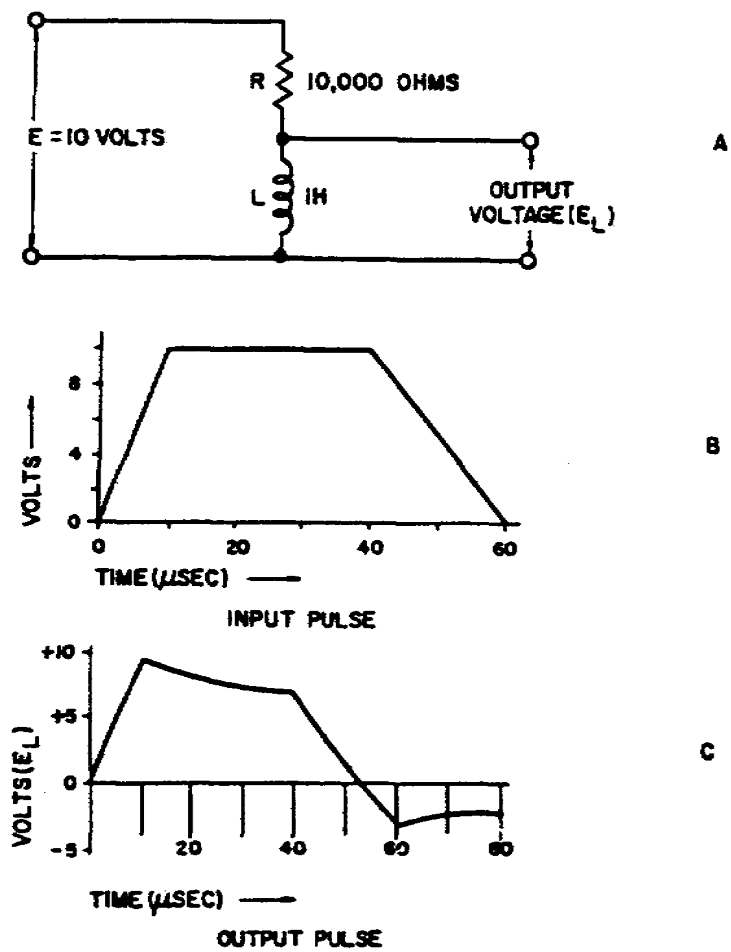
c. At 10 usec, the applied voltage reaches the maximum value of 10 volts and remains constant for 30 usec. The rate of current change remains the same until E_R is equal to E. E_R is considered to be equal to E after 11 usec. The output voltage E_L decreases to zero and remains at zero during the remainder of the input pulse duration period.

d. At 40 usec, the applied voltage begins to decay and the inductor opposes any change in current flow. At 41 usec, the applied voltage has decreased to 9.5 volts and the voltage drop across the coil is considered to be equal to the amount of decrease in the applied voltage (0.5 volt) but is opposite in polarity.

The voltage drop across the resistor is still equal to 10 volts. Since the rate of current decrease now becomes proportional to the rate of decrease of E, the output voltage E_L remains constant while E_R decreases at a rate equal to the rate of decrease of the applied voltage.

e. After 60 usec, the applied voltage is equal to zero. E_L has remained constant is equal to -0.5 volt. E_R is now equal to E_L but is opposite in polarity. The rate of current change is considered to remain the same. After 61 usec, therefore, no current is flowing in the circuit and E_L and E_R are equal to zero.

Figure 38. Input and output pulses for a long-time-constant series RL circuit



26. LONG-TIME CONSTANT.

a. When the time constant is long compared to the pulse rise, duration, and decay times, the voltage drop across the resistor is a small fraction of the applied voltage. Most of the applied voltage appears across the inductor, and the output waveform closely resembles the input waveform.

b. The pulse in Figure 38B is applied to the high-pass RL filter in Figure 38A. The time constant is 100 usec. Since the pulse rise time (10 usec) represents only 10 percent of 1 time constant, the current and E_R reach only a low value during this time. The output voltage E_L very closely follows the rise of the input pulse.

c. After 10 usec, the applied voltage remains constant for 30 usec. During this time, the inductor continues to oppose any change in current flow. However, the current and the voltage drop across the resistor continue to increase at a rate determined by the universal time constant chart. As E_R increases, E_L decreases; and at 40 usec, approximately 70 percent of the applied voltage appears across the inductor and 30 percent is developed across the resistor.

d. After 40 usec, the applied voltage starts to decay and the inductor opposes any change in current flow. As E decreases, E_L decreases proportionally until 60 usec, when the applied voltage is equal to zero, E_R and the output voltage E_L are equal to approximately 3 volts (30 percent of the applied voltage), but are opposite in polarity. After this time, ER and EL decay to zero at a rate determined by the universal time constant chart.

Section VI. LOW-PASS RL CIRCUIT

27. GENERAL.

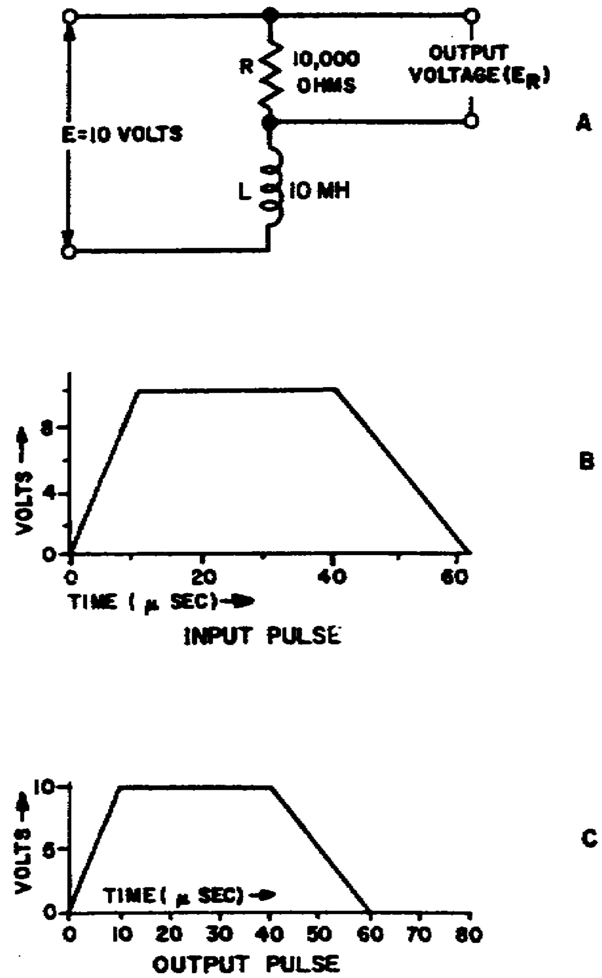
The output of a low-pass RL filter is taken across the resistor. The effect of the time constant on the output waveform differs entirely from that of a high-pass RL filter. When the time constant of a low-pass RL filter is short compared with the reference period, the output waveform closely resembles the input waveform. When the time constant of a low-pass RL filter is long compared to the reference period, the output waveform is only a fraction of the input waveform.

28. SHORT-TIME CONSTANT.

a. The pulse shown in Figure 39B is applied to the low-pass RL filter in Figure 39A. The time constant is equal to 1 usec, which is short compared to the pulse rise (10 usec), duration (30 usec), and decay (20 usec) times. Since the time constant of this circuit is short compared with the pulse rise time, the current and, therefore, the output voltage across the resistor can increase almost as rapidly as the input voltage increases, while E_L levels off at a low value.

b. At 10 usec, the applied voltage reaches the maximum value of 20 volts and remains constant for 30 usec. The rate of current increase remains the same until the output voltage E_R is equal to E. E_R is considered to be equal to E after 11 usec. E_L

Figure 39. Input and output pulses for low-pass, short-time-constant, series RL circuit.



during this use decreases to zero. E_R remains at 10 volts during the remainder of the duration period.

c. At 40 usec, the applied voltage starts to decay and the inductor opposes any change in current flow. At 41 usec, the applied voltage has decayed to 9.5 volts. The voltage drop across the coil is considered to be equal to the amount of decrease in applied voltage (0.5 volt) but is opposite in polarity. The output voltage E_R, therefore, remains equal to 10 volts. The rate of current change now becomes proportional to the rate of decrease of the applied voltage, and the output voltage E_R decreases at a rate that is equal to the rate of decay of the applied voltage.

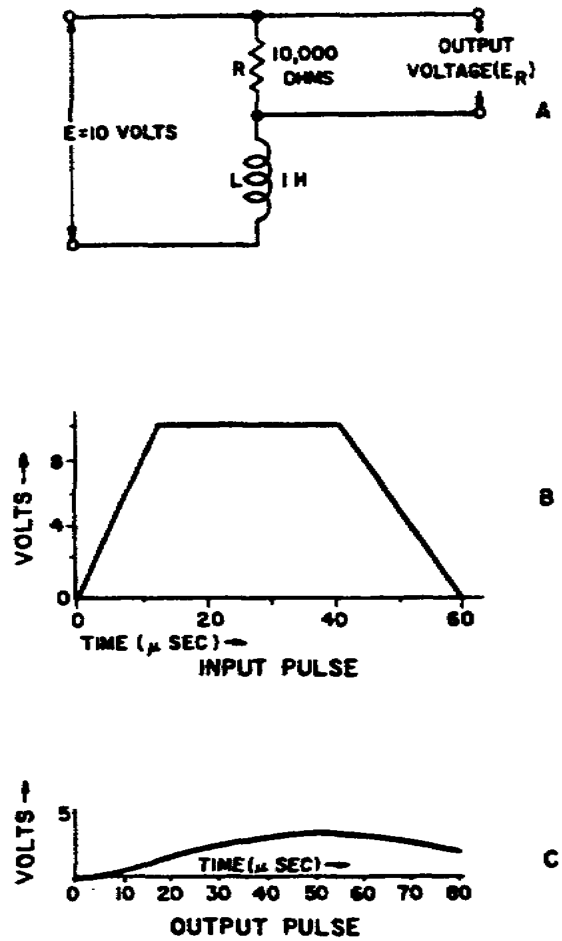
d. At 60 usec, the applied voltage is zero. E_L has remained constant and is equal to -0.5 volt. The output voltage E_R is now equal to E_L but is opposite in polarity. The rate of current change is considered to remain the same; and at 61 usec, there is no current flow in the circuit and E_L and the output E_R are equal to zero.

29. LONG-TIME CONSTANT.

a. When the time constant is long compared to the pulse rise, duration, and decay times, the voltage drop across the resistor is a small fraction of the applied voltage. Most of the applied voltage appears across the inductor and the output waveform differs greatly from the input waveform.

b. The pulse shown in Figure 40B is applied to the low-pass RL filter in Figure 40A. The time constant is equal to 100 usec. Since the pulse rise time (10 usec) represents only 10 percent of 1 time constant, the current and the output voltage E_R only reach a very low value during this time.

Figure 40. Input and output pulses for a low-pass, long-time-constant, series RL circuit



c. After 10 usec, the applied voltage remains constant for 30 usec. During this time, the inductor continues to oppose any change in current flow. However, the current and the output voltage E_R continue to increase at a rate determined by the universal time constant chart. At 40 usec, approximately 30 percent of the applied voltage appears across the resistor.

d. After 40 usec, the applied voltage starts to decay and the inductor opposes any change in current flow. As the applied voltage decreases, E_L decreases proportionally and the output voltage remains constant. At 60 usec, the applied voltage is equal to zero, and E_L and E_R are equal but opposite in polarity. After this time, E_R and E_L decay to zero at a rate determined by the universal time constant chart.

Section VII. RC PULSE-SHAPING CIRCUITS

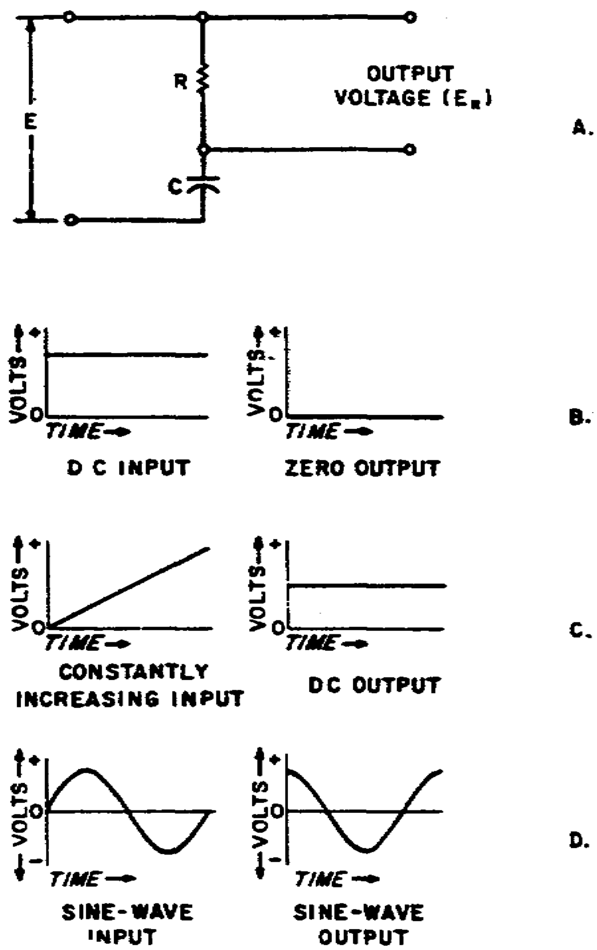
30. GENERAL.

In radar systems, it is often necessary to change or reshape an input waveform. Sawtooth and triangular waveforms are required for deflection circuits, and sharp pulses are required to trigger the modulating and transmitting circuits. As seen previously, RC and RL circuits may be used to obtain various output waveforms from different inputs by varying the circuits' time constant and taking the output waveforms from different components. Differentiators and integrators are the two most common types of RC and RL shaping circuits. Each shapes the waveform in a different way.

31. DIFFERENTIATION.

a. A waveform is differentiated when the amplitude of the output waveform is proportional to the rate of change of voltage in the input waveform. Any high-pass RC or RL circuit with a short-time constant, as compared to the reference periods of the applied waveform, acts as a differentiator. In a series RL circuit, the differentiated output is always taken across the inductor; while in a series RC circuit, it is always taken across the resistor. The RC differentiator (Figure 41A) is the most widely used.

Figure 41. Differentiator circuit input and output pulses

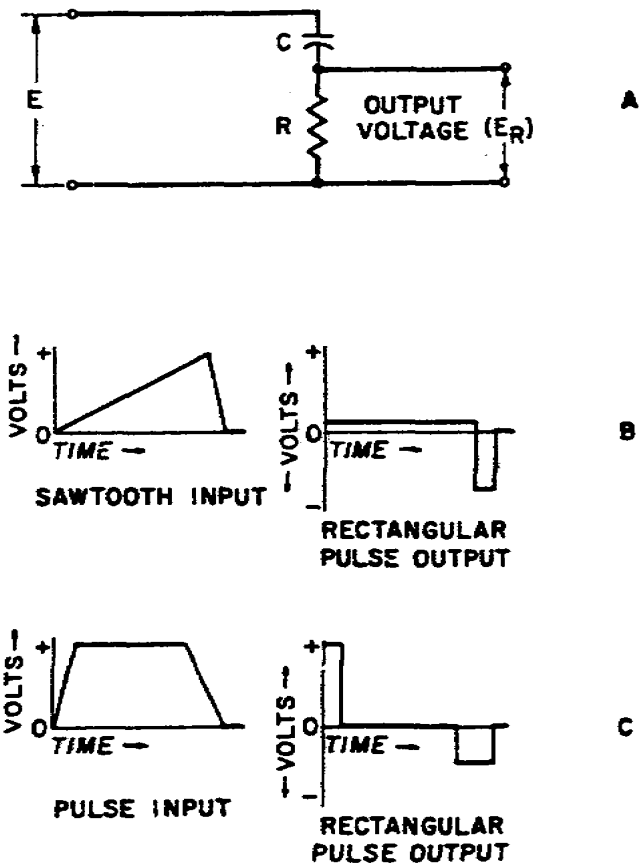


b. The DC voltage indicated in Figure 41B is applied to the RC differentiator circuit of Figure 41A. After the circuit has reached its steady-state condition, the rate of change in voltage is zero, and the differentiated output is zero. The input voltage in Figure 41C has a constant, positive rate of increase. When this voltage is applied to the differentiator circuit shown in Figure 41A, a constant DC voltage is obtained at the output. The amplitude of the output voltage depends on the input voltage rate of change and the time constant of the circuit. The higher the voltage rate of change, the greater the DC voltage output. The longer the RC time constant, the greater the DC output.

c. In Figure 41D, the input to the differentiator circuit of Figure 41A is a sine wave. When the input voltage is zero, its rate of change is maximum, and the differentiated output voltage is maximum. When the input voltage is maximum, the rate of change of current is zero, and the differentiated output voltage is zero. As a result, the differentiated output voltage is a sine wave that is 90 degrees out of phase with the input sine wave.

d. In Figure 42B, the input to the differentiator circuit is a sawtooth wave. Since the voltage rises at a constant rate to some maximum amplitude, the input voltage rate of change remains constant. The differentiated output voltage during this time is a positive DC voltage whose amplitude is proportional to the voltage rate of change and the time constant. When the maximum value of the input voltage is reached, the input voltage begins to decay toward zero. The input voltage rate of decrease is constant, and the differentiated output during this time is a negative DC voltage. Since the input voltage rate of change is greater during the decay time, the amplitude of the negative DC differentiated output voltage is greater.

Figure 42. Differentiator circuit output for common waveforms



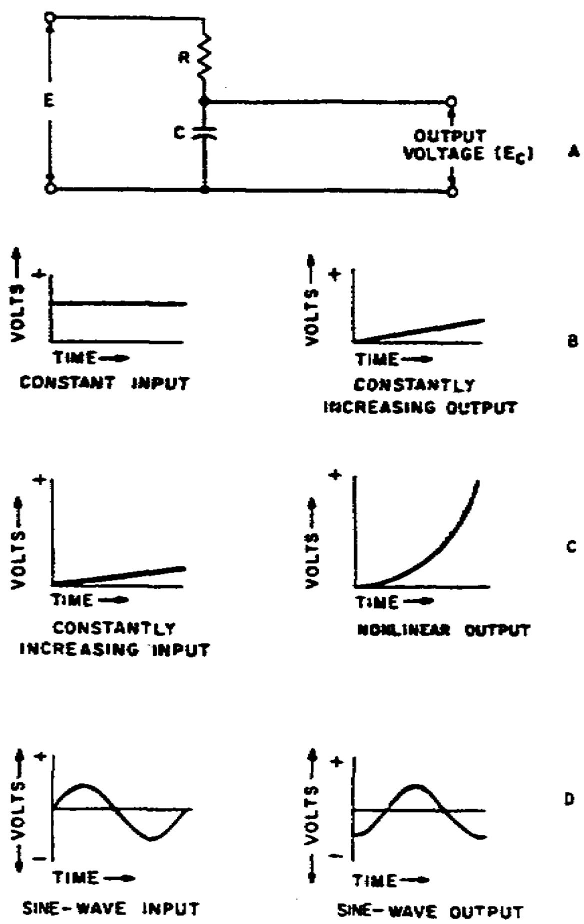
e. In Figure 42C, the input to the differentiator circuit is a rectangular pulse with finite rise and decay times. Since the voltage rises at a constant rate to some maximum value, the input voltage rate of change is constant. After the differentiated output voltage reaches a steady state, it becomes a positive DC voltage whose amplitude is proportional to the voltage rate of change and the time constant. When the maximum value of the input voltage is reached, the differentiated output voltage drops instantaneously to zero since the input voltage rate of change is zero. The output voltage remains at zero during the input voltage duration period. During the input voltage decay period, the rate of input voltage decrease is constant and the differentiated output voltage during this time is a negative DC voltage. Since the input voltage rate of change is greater during the rise time than it is during the decay time, the amplitude of the positive DC differentiated output voltage is greater than the negative pulse.

32. INTEGRATION.

a. An integrating circuit is often referred to as a storage circuit, since the output voltage is proportional to the total amount of energy stored. Any low-pass RC or RL circuit which has a long-time constant as compared to the reference periods of the applied waveform acts as an integrator. In a series RC circuit, the integrated output is always taken across the capacitor; while in a series RL circuit, it is always taken across the resistor.

b. The output voltage E_C of an RC integrator circuit is proportional to the total charge of the capacitor. The greater the charge, the greater the amount of energy stored and the higher the output voltage across the capacitor. When a constant DC voltage is applied to an integrating circuit (Figure 43B), the output voltage increases at a constant rate. When a constantly increasing voltage is applied to an integrator circuit (Figure 43C), the rate of increase of the output voltage increases at a rate that is proportional to the increase in applied voltage and the length of time that the voltage is applied to the circuit. The resultant voltage has a parabolic waveform. When a sine wave is applied to an RC integrator circuit (Figure 43D), the output waveform varies sinusoidally but lags the input voltage by 90 degrees.

Figure 43. Integrator circuit input and output pulses



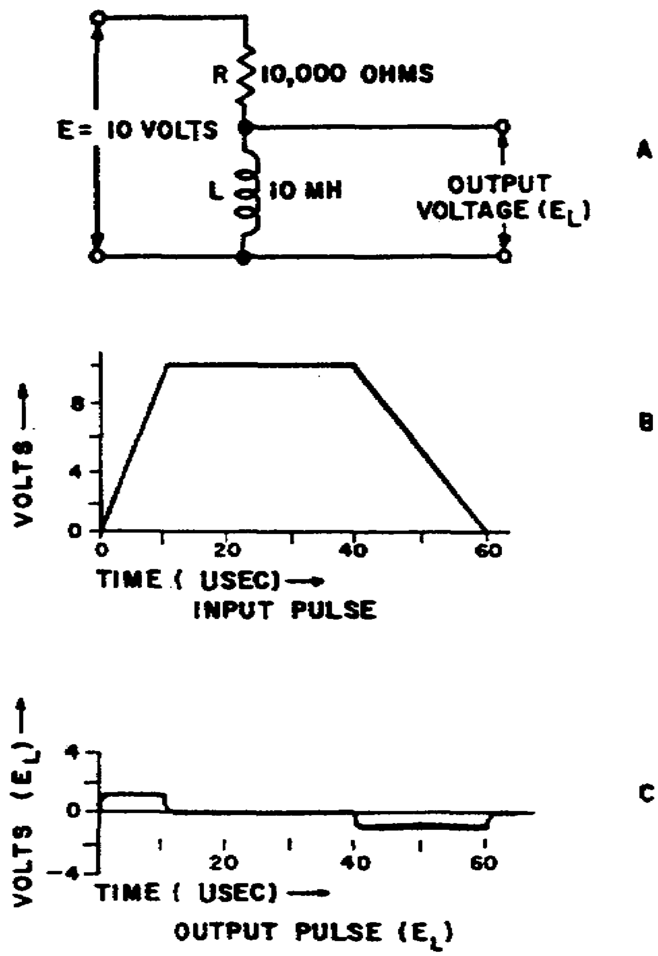
c. When a rectangular pulse is applied to an integrator circuit, the output is a sawtooth waveform. During the input pulse duration period, the output voltage increases at a constant or linear rate. When the input pulse decays to zero, the output voltage then decreases, again at a linear rate.

Section VIII. RL PULSE-SHAPING CIRCUITS

33. DIFFERENTIATOR.

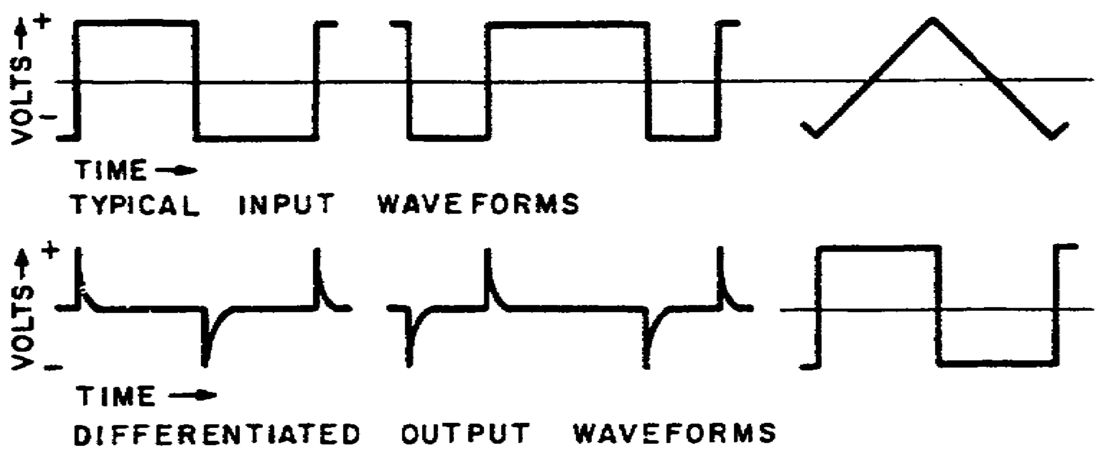
a. The short-time-constant, high-pass, RL circuit shown in Figure 44A is a differentiator since the output voltage E_L is proportional to the rate of change of the applied voltage.

Figure 44. Differentiator circuit input and output pulses



b. From Figure 44, it is evident that when the input voltage is applied, E_L increases almost instantaneously to a small positive value, and then remains constant at that value during the remaining rise time. During the pulse-duration period, E_L is equal to zero. When the applied voltage starts to decay, E_L increases in a negative direction and then remains constant during the decay time. When the applied voltage is equal to zero, E_L decays to zero and remains constant until the next pulse is applied. Outputs of other waveforms are shown in Figure 45. In each case, an output is developed only when there is a change in the rate of current flow in the circuit.

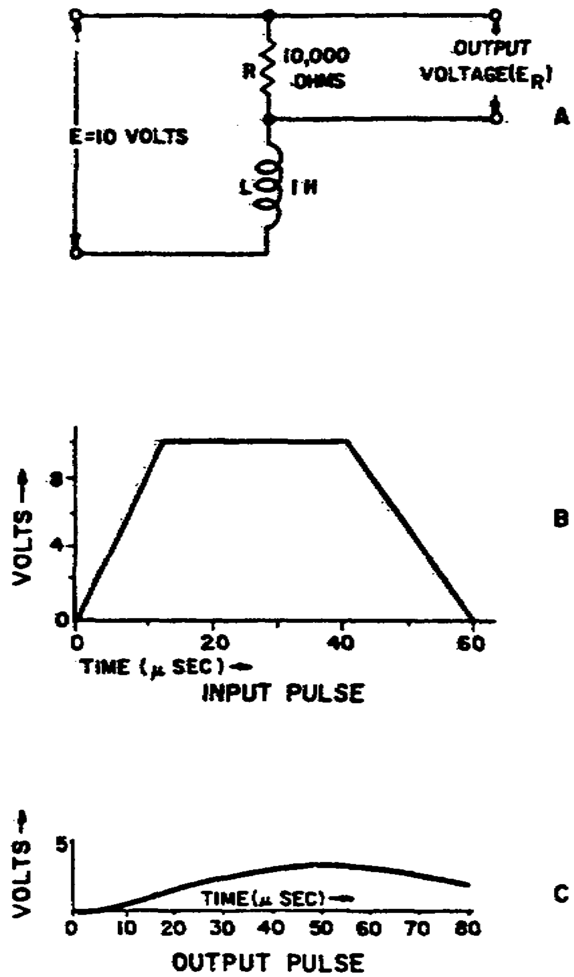
Figure 45. Typical input waveforms and differentiated output waveforms



34. INTEGRATOR.

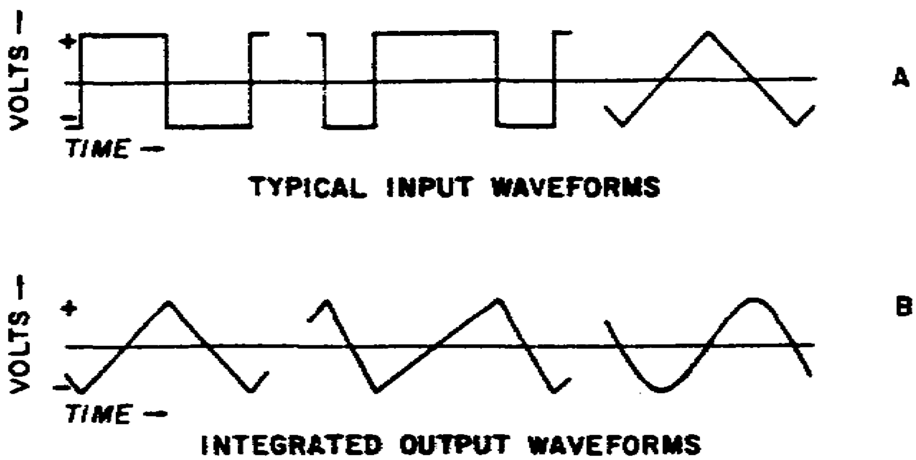
a. The long-time-constant, low-pass RL circuit shown in Figure 46A is an integrator. The gradually increasing amplitude of output voltage E_R (Figure 46C) is proportional to the length of time the applied voltage is present. The action of the inductor in the long-time-constant circuit opposes any change in current flow and, therefore, opposes current flow when a voltage is applied to the circuit. The smaller the current flow, the smaller is the voltage drop across the resistor. E_R increases as the current increases, which is a factor of the length of time that the input voltage is applied.

Figure 46. Integrator circuit input and output pulses



b. In Figure 46C, it can be seen that, upon application of the input pulse to the integrator, E_R increases gradually in a positive direction. This voltage rise across the resistor continues until the applied pulse begins to decay. At that time, the output voltage decays gradually until the next pulse is applied. Outputs of typical input waveforms are shown in Figure 47. In each case, the output voltage increases or decreases, and the amplitude is proportional to the length of time that the pulse is applied or the length of time between pulses.

Figure 47. Typical input waveforms and the integrated output waveforms



Section IX. SUMMARY AND REVIEW

35. SUMMARY.

a. The time constant indicates how rapidly current or voltage in a circuit can change. The time constant is also a factor in determining the amplitude and shape of the output pulse. (Paragraph 35a)

b. The pulse reference periods are the rise time, duration time, and decay time. (Figure 25)

c. A short-time constant can be defined as less than one-seventh of the value of a given reference period. (Paragraph 35h)

d. A long-time constant can be defined as more than 7 times the value of a given reference period. (Paragraph 35i)

e. An equivalent time constant is less than 7 times but more than one-seventh of the value of a given reference period. (Paragraph 31a)

f. A series RC circuit is called a high-pass filter when the output is taken across the resistor. A series RC circuit is called a low-pass filter when the output is taken across the capacitor. (Paragraph 31b)

g. A series RL circuit is called a high-pass filter when the output is taken across the inductor. A series RL circuit is called a low-pass filter when the output is taken across the resistor. (Paragraph 31e)

h. The longer the time constant in a high-pass filter, the more closely the original waveshape is reproduced. (Paragraph 32a)

i. The shorter the time constant in a low-pass filter, the more closely the original waveshape is reproduced. (Paragraph 32a)

j. A differentiator is a circuit whose output voltage is proportional to the rate of change of the input voltage. (Paragraph 32c)

k. A short-time-constant, high-pass, series RC or R1 circuit is known as a differentiator.

l. An integrator is a storage circuit in which the output voltage is proportional to the total amount of energy stored.

m. A long-time-constant, low-pass, series RC or RL circuit is known as an integrator.

36. REVIEW QUESTIONS.

a. What does the time constant indicate with reference to a pulse voltage?

b. What is the output waveform from a short-time-constant, high-pass, circuit with a rectangular pulse voltage input?

c. How does increasing the time constant of a high-pass filter affect the pulse waveform?

d. What time constant provides the best pulse reproduction in a low-pass filter?

e. Describe a differentiated waveform.

f. What is the effect of increasing the time constant in a differentiator circuit?

g. Describe the output of an RC differentiator when a rectangular waveform is applied.

h. What is an integrating circuit?

i. What is the relative time constant of an integrator circuit?

j. Describe the output of an integrator circuit when a rectangular waveform is applied.

PRACTICE EXERCISE

In each of the following exercises, select the one answer that best completes the statement or answers the question. Indicate your solution by circling the letter opposite the correct answer in the subcourse booklet.

SITUATION.

Assume that a DC voltage of 15 volts is applied to a series RL circuit. The total resistance in the circuit is equal to 1,000 ohms and the total inductance is equal to 1 millihenry.

Exercises 1 and 2 are based on the above situation.

1. After the steady state has been reached, the voltage across the inductor and the total current will be equal to

a. 15 volts and 15 milliamperes (mA), respectively.
b. 15 volts and 0 mA, respectively.
c. 0 volt and 15 mA, respectively.
d. 0 volt and 0 mA, respectively.

2. The steady-state condition of the circuit described in the situation will be reached after

a. 0.5 microsecond.
b. 1.0 microsecond.
c. 3.5 microseconds.
d. 7.0 microseconds.

SITUATION.

Assume that a DC voltage of 10 volts is applied to a series RC circuit. The resistance of the circuit is equal to 2,000 ohms and the capacitance is equal to 0.005 microfarad.

Exercise 3 and 4 are based on the above situation.

3. The instant the voltage is applied to the circuit, the voltage across the capacitor and the total current are equal to

   a. 0 volt and 5 mA, respectively.
   b. 0 volt and 0 mA, respectively.
   c. 10 volts and 5 mA, respectively.
   d. 10 volts and 0 mA, respectively.

4. The steady-state condition of this circuit will be reached after

   a. 10.0 microseconds.
   b. 17.5 microseconds.
   c. 25.0 microseconds.
   d. 70.0 microseconds.

5. To completely analyze the effect that a series RC circuit will have on a specific input pulse, you must compare the time constant of the circuit with the reference periods. These reference periods are identified as

   a. rest, duration, and decay times.
   b. duration, rise, and decay times.
   c. rise, duration, and rest times.
   d. decay, rest, and rise times.

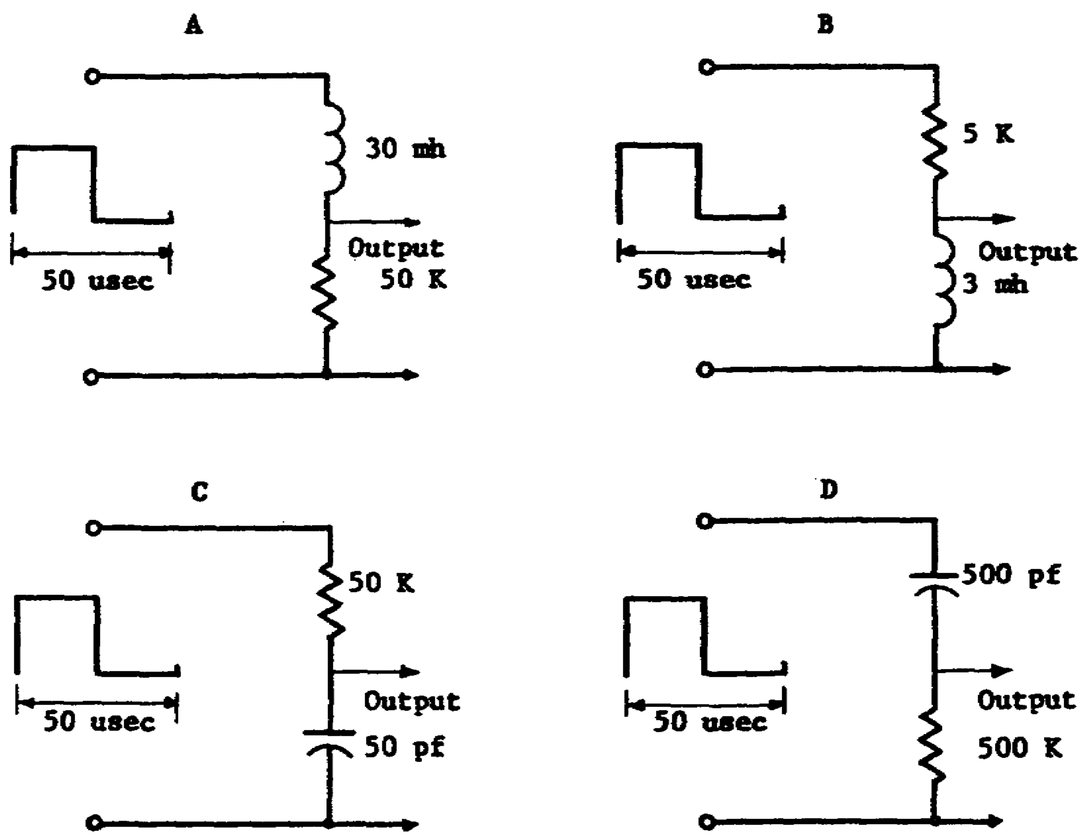
6. Assume that a square wave with a period of 12 microseconds is applied to a series RC circuit in a time-division multiplexing unit. If the capacitance is 100 picofarads (micromicrofarads) and the resistance is 1,000 ohms, the output voltage across the resistor will resemble a

   a. triangular wave.
   b. peaked wave.
   c. square wave.
   d. sine wave.

7. If a series of positive and negative triggers is required to synchronize the indicators in a radar set, the circuit that will change the square wave into triggers is shown in Figure 48 in sketch

a. A.
b. B.
c. C.
d. D.

Figure 48. Waveshaping circuits



NOTE: (pf) = picofarad = 10^{-12} farad

8. Assume that a square wave with a time duration of 5,000 microseconds is applied to a series RC circuit in an oscilloscope. If the capacitance of the circuit is 0.1 microfrarad, the resistance is equal to 1,000,000 ohms, and the output voltage resembles a triangular wave, the circuit will be classified as a

   a. long-time-constant, low-pass filter.
   b. long-time-constant, high-pass filter.
   c. short-time-constant, low-pass filter.
   d. short-time-constant, high-pass filter.

9. Assume that a 10,000-Hz square wave varying between 0 and 10 volts is applied to a series RL circuit in a microwave transmitter. If the resistance of the circuit equals 100 ohms and the inductance equals 100 millihenries, the voltage waveform that appears across the inductor will resemble a

   a. sine wave.
   b. square wave.
   c. peaked wave.
   d. triangular wave.

10. If a triangular waveform is applied to a long-time-constant LR circuit in a special type of cathode-ray-tube indicator, the voltage that appears across the inductor will resemble a

   a. peaked wave.
   b. square wave.
   c. triangular wave.
   d. rectangular wave.

11. What type of RC coupling circuit would be used in a synchronizer to couple square waves from one stage to another with minimum distortion?

   a. Short-time-constant, high-pass filter.
   b. Long-time-constant, high-pass filter.
   c. Differentiator.
   d. Integrator.

12. If the output voltage across the inductor in a synthesizer's series RL circuit reaches only a fraction of the input voltage, the circuit will be classified as a

    a. short-time-constant, high-pass circuit.
    b. long-time-constant, high-pass circuit.
    c. short-time-constant, low-pass circuit.
    d. long-time-constant, low-pass circuit.

13. If a high-pass series RL circuit's time constant is changed from short to long by changing the values of inductance, the maximum values of the output voltage and the current in the RL circuit for a given input voltage will be

    a. lower.
    b. higher.
    c. lower and higher, respectively.
    d. higher and lower, respectively.

14. If a high-pass RL circuit does not act as a differentiator, the reason may be that the

    a. rate of change of current is too great.
    b. current flow is too great.
    c. inductance is too small.
    d. inductance is too large.

15. Multiplexers and communication receivers use integrating circuits to restore distorted waveforms to their original shapes. A waveform is considered to be integrated when the amplitude of the output voltage is proportional to the

    a. rate of change of the applied voltage.
    b. amplitude of the applied voltage.
    c. energy stored in the circuit.
    d. rate of change of current.

16. To produce an output waveform that increases at a constant rate, an integrator circuit may be used with an input voltage that

a. increases gradually and nonlinearly.
b. increases gradually and constantly.
c. increases rapidly and constantly.
d. remains at a constant value.

17. Both RC and RL circuits act as differentiators if the circuit has a specific time constant and if the output is removed from the correct component. A series RL circuit acts as a differentiator if the time constant is

a. short, and the output is taken across R.
b. short, and the output is taken across L.
c. long, and the output is taken across R.
d. long, and the output is taken across L.

18. What type of circuit and input waveform can be used to obtain a series of positive and negative triggers?

a. Low-pass, long-time-constant circuit with a square wave input.
b. Low-pass, long-time-constant circuit with a triangular wave input.
c. High-pass, short-time-constant circuit with a square wave input.
d. High-pass, short-time-constant circuit with a triangular wave input.

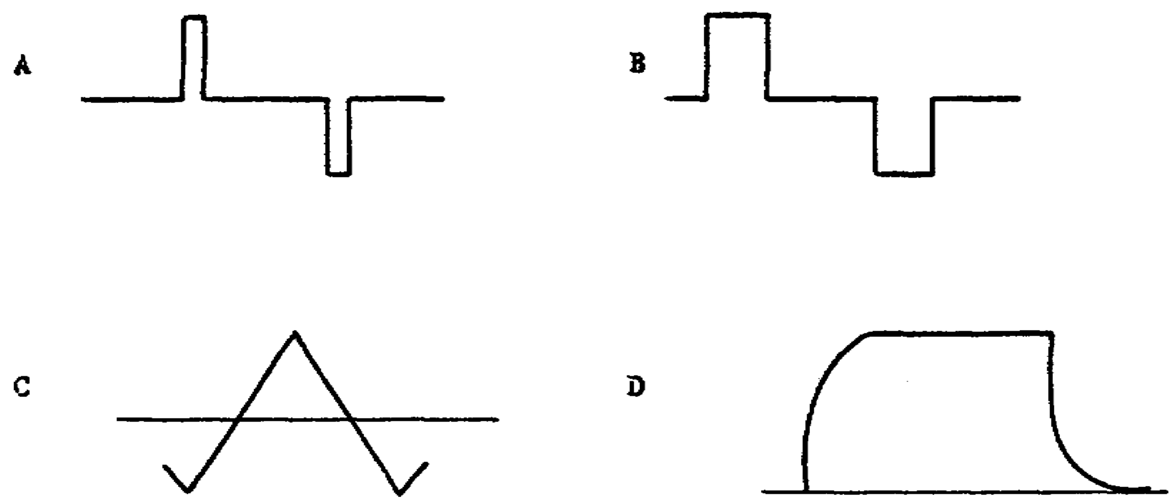
19. A series RL circuit may be used as an integrator if the output is taken from across the resistor. This circuit may also be classified as a

a. low-pass filter with a long-time constant.
b. low-pass filter with a short-time constant.
c. high-pass filter with a long-time constant.
d. high-pass filter with a short-time constant.

20. If a square wave is applied to a series RL circuit that is used as a long-time-constant, low-pass filter, the output across the resistor will resemble the one shown in Figure 49, sketch

a. A.
b. B.
c. C.
d. D.

Figure 49. Waveform



Check your answers with solutions.

ANSWERS TO PRACTICE EXERCISES

MM5000 ....Timing Circuits

Lesson 2...........................Applications of RC and RL Circuits

1. c--paragraph 3a, page 31

   Current = Voltage/Resistance

   It = 15 volts/1,000 ohms

   It = 15 mA

2. d--paragraph 5, page 34

   Time Constant = L/R

   TC = 1 mH/1,000 ohms

   TC = .001 h/1,000 ohms = 1 usec

   Steady State is reached at 7 TC, or 7 microseconds

3. a--paragraph 10a, page 37

   Current = Voltage/Resistance

   It = 10 volts/2,000 ohms

   It = 5 mA

4. d--paragraph 10a, page 37, paragraph 34, page 39

   Time Constant = R x C

   TC = 2,000 ohms x .005 microfarad

   TC = 10 microseconds

   Steady State is reached at 7 TC, or 70.0 microseconds

5. b--paragraph 14a, page 41

6. b--paragraph 15a, 16b(3), pages 43-46; paragraph 1b(3), page 30

Time Constant = R x C

TC = 1,000 ohms x 100 picofarads

TC = 0.1 microsecond

Time duration = Period/2 = 12 microseconds/2

Time duration = 6 microseconds

Since the time constant is short with respect to the time duration, the output voltage will be a peaked wave.

7. b--paragraph 15a, 16c(2), pages 43, 48; paragraph 1b(3), page 30

Time Constant = L/R = 3 mH//5,000 ohms

TC = .003 h/5,000 ohms = .6 usec

Circuit B has a short-time constant, therefore, its output will be the desired triggers.

8. a--paragraph 16b(4), page 46; paragraph 21, page 56; Figure 26, page 47.

Time Constant = R x C

TC = 1,000,000 ohms x 0.1 microfarad

TC = 0.1 second

Time duration = 5,000 microseconds

This is a long-time-constant circuit. A low-pass filter with a long-time constant produces a triangular output.

9. b--paragraph 16c(3), page 48; Figure 29, page 50; paragraph 1b(30), page 30

Time Constant = L/R = 100 mH/100 ohms

TC = 1,000 microseconds

Time duration = 1/2 x Frequency = 1/2 x 10,000 Hz

Time duration = .00005 sec or 50 usec

The voltage across the inductor in a long-time-constant circuit is the same as the input square wave.

10. c--paragraph 17b, c; 26a, pages 49, 52, 61

11. b--paragraph 20a, page 54

12. a--paragraph 24, 25a, page 59

13. d--paragraph 25, 26, pages 59-61

14. d--paragraph 31a, page 65

A differentiator circuit must have a short-time constant compared to the reference periods of the pulse. Since TC = L/R, if L is too large, the time constant may not be short enough.

15. c--paragraph 32a, page 67

16. d--paragraph 32b, Figure 43, page 67

17. b--paragraph 33a, Figure 44, page 69

18. c--paragraph 33b, Figure 45, page 70

19. a--paragraph 34a, page 71

20. c--paragraph 34a, b, Figure 47, page 71