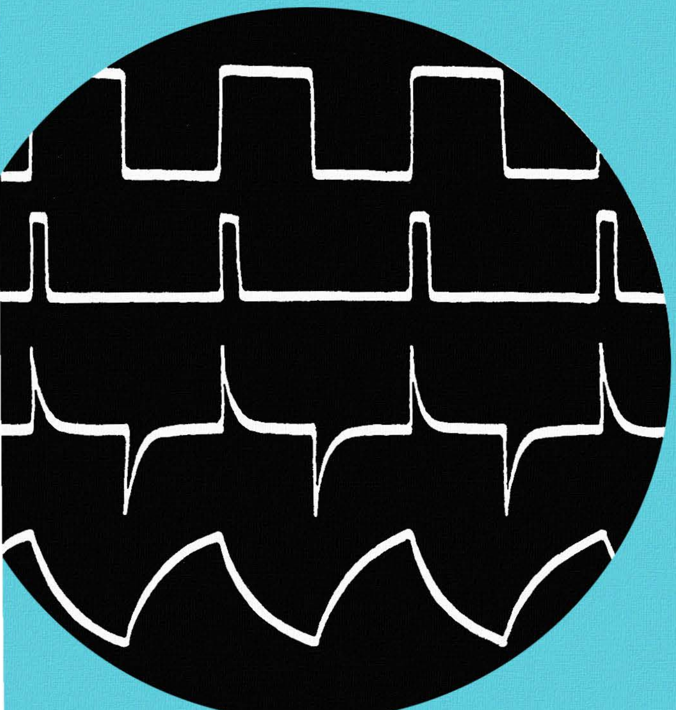
basic pulses

by I. GOTTLIEB



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basic pulses

by Irving Gottlieb, P.E.

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PREFACE

The purpose of this book, which the author hopes will benefit those in most levels of electronic endeavor, is to set forth a practical application of pulse theory. Both hobbyist and specialist have been plagued with misconceptions, and both are susceptible to confused thinking when dealing with pulse phenomena.

Traditional concepts of pulses, or nonsinusoids, have developed from mathematically rigorous equations of *electrical* engineering; the nonsinusoid of electrical power generation and distribution occurs too infrequently, or with too meager consequence, to merit much more than passing attention. Unfortunately, this situation is at odds with conditions generally extant in *electronic* circuits. Such circuits are often dependent upon the unique characteristics of waveshapes *other* than the sinusoid.

If one is to gain insight into the operating principles underlying radar, computers, the various digital techniques, and other modern pulse applications, a new approach to pulses is needed. Specifically, one must treat the nonsinusoid as a respectable electrical parameter; regarding the nonsinusoid as a necessary evil, or an imperfection in the attempt to attain ideal conditions, must be avoided. Accordingly, this book inverts the outmoded convention; it is now the *sine wave* which is recognized as the secondary waveshape.

The author believes that a majority of those engaged in the several departments of electronics will respond favorably to this book. *Technicians,* *servicemen, radio-amateurs,* and *engineers* will benefit according to the particular facets of their interest and background.

Another group which the author feels will find BASIC PULSES very useful is the *student,* whose present knowledge of electronics enables him to construct, operate, and service radios, transmitters, amplifiers, and other equipment. Within the student category are those who have completed basic instruction courses such as those conducted by the services, technical schools, and the pre-engineering school curriculum of colleges and universities.

An important aspect of this book is the relative absence of mathematics. The treatment is primarily based upon *descriptive* narration. Pulse phenomena is explained by analogy, through cause and effect relationship, and in general by means of qualitative rather than quantitative analysis. The author feels that even those who are mathematically inclined will find this descriptive approach helpful in converting symbolic logic into practical electronic circuitry. Of even greater importance, the descriptive treatment in this volume constitutes an excellent prelude for advanced study.

The author is indebted to the staff of the Stanford University Engineering Library, who exhibited cordiality as well as competence in aiding the author locate numerous obscure but important treatises bearing on the subject of pulses. Public acknowledgement is hereby conferred on my wife, Anne Lee Gottlieb, for her assistance in the preparation of manuscripts and in the refinement of the supporting illustrations.

Sunnyvale, California IRVING M. GOTTLIEB

August, 1958

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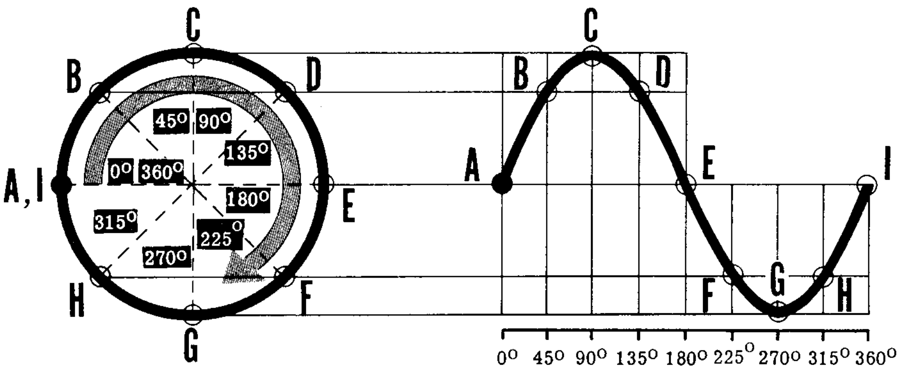
THE PULSE WAVE DEFINED

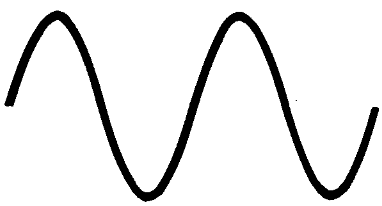
Defining the Pulse

It is both interesting and instructive to begin our acquaintance with pulses by considering the one exception to all waveforms which can never qualify as a pulse waveform. This unique exception among waveforms is the *sinusoid* or *sine wave*. The shape of a sine wave is given by a graph, which shows the vertical displacement a point on a circle makes with respect to its angular progresses around the circle.

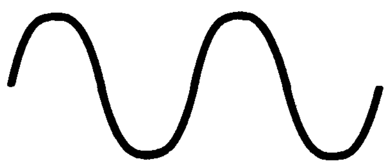
We see a continuous sequence of identical sine waves. This is typical of the sinusoidal waveform displayed on the screen of an oscilloscope. Whether a sinusoidal waveform contains one sine wave or many identical sine waves, the waveform displays no pulse properties.



The Sine Wave, the Only Waveshape Which Cannot be a Pulse



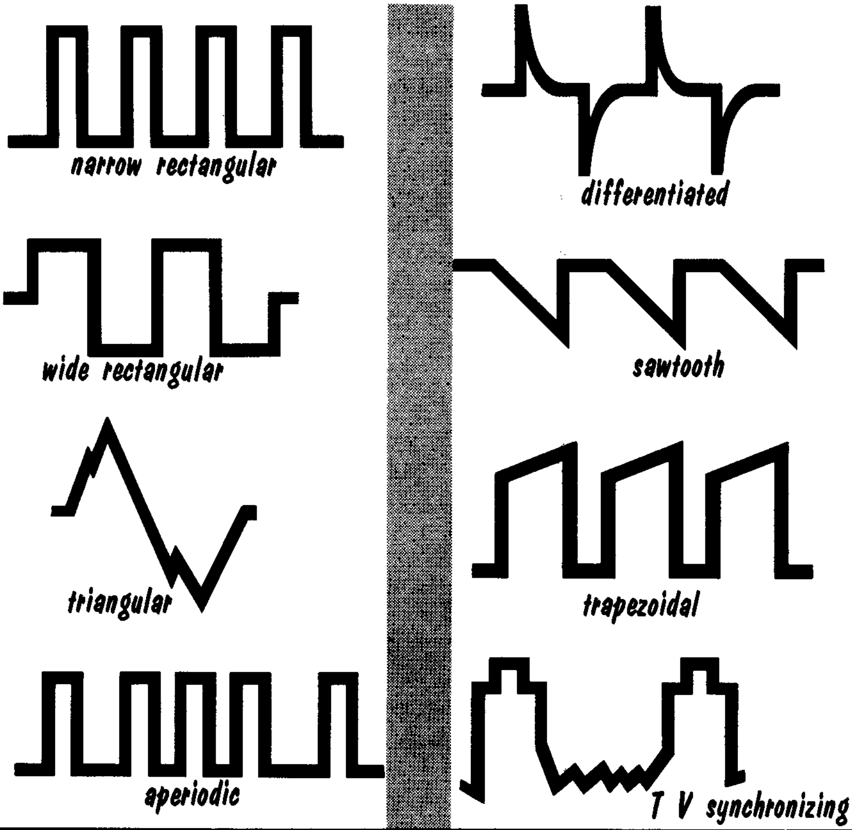
A Wavetrain of Identical Sinusoids



A Smooth Waveform Which Can Exhibit Pulse Properties

It is important to keep this in mind: although many waveforms are composed of smoothly curved segments, such waves are not exempted from classification as pulses, as are true sine waves. For example, the waveform made up of half circles can, under conditions discussed later, be considered a pulse waveform. It is a pulse waveform because a frequency-selective circuit can alter the waveshape and make its pulse characteristics evident. Of all imaginable waveshapes, only the sine wave is undistorted by frequency discrimination.

Pulse Waveforms in Electronics



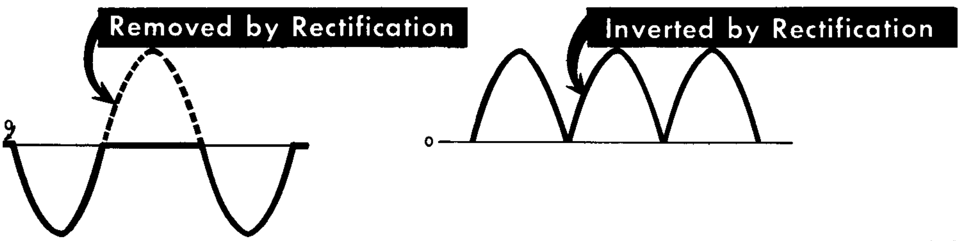
TYPICAL PULSE WAVEFORMS

ENCOUNTERED IN ELECTRONIC DEVICES

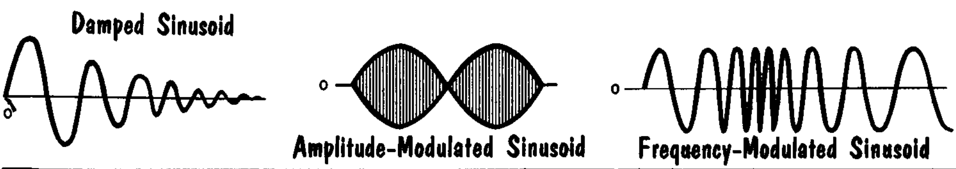
From common experience, the term "pulse" might be associated with "abrupt," "sudden," "brief," and similar words which signify rapid transition, or the short persistance of an event. It is indeed helpful to carry such words into the study of pulses. For the purposes of practical electronics we may define pulse as follows: *any rapid change in voltage or current which does not represent a whole number of sine waves is a pulse, or a series of pulses.*

Pulse Properties of Partial Sine Waves

The waveforms illustrated are typical of the pulse waveforms encountered in electronic devices. It will be shown that the qualifying term "rapid" has an exact meaning when the definition (page 2) is applied to practical circuits. First we shall investigate certain waveforms which may be construed to be sine waves, but which, unlike true sine waves, exhibit properties of the pulse. The waveforms depicted represent the rectified current monitored at the output of a half-wave and full-wave rectifier, respectively. These waveforms are sinusoidal variations, but cannot be referred to as sinusoids or sine waves according to accepted usage in electrical practice. A partial or incomplete sine wave does not possess the immunity from pulse behavior that a complete sine wave does. Indeed, in a power supply, the design of the filter which follows the rectifier is facilitated by taking into account the pulse nature of such "semi" sine waves.



The Half-Sine Wave... Pulse Waveform in Disguise

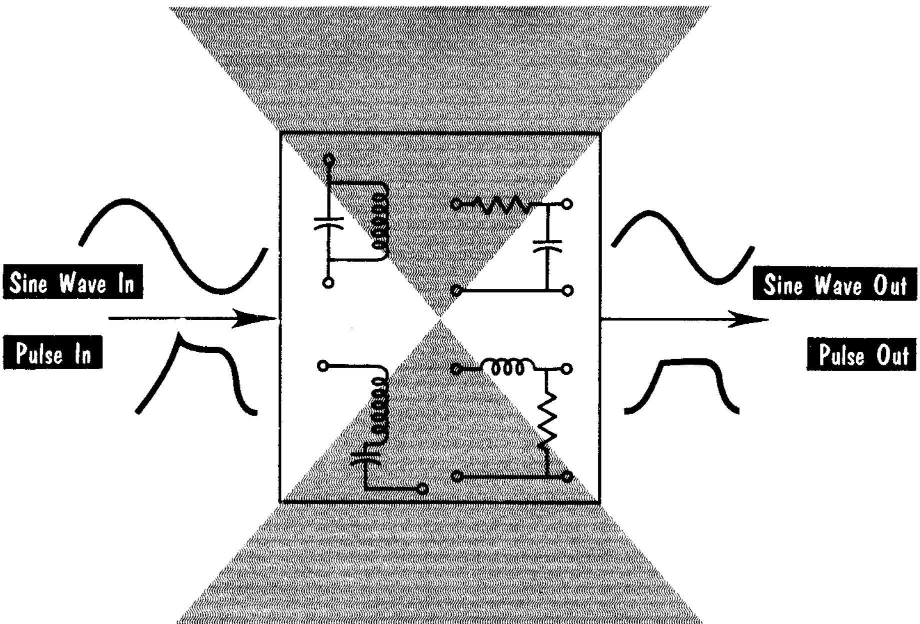


Pulse Waveforms Containing Sine-Wave Cycles

Other interesting partial or near-sinusoids, more difficult to recognize as acting pulses than are the rectified sine waves, are shown. They are, nevertheless, pulses *if* their frequencies or modulations are rapid enough to significantly effect the circuit under consideration. Even a modulated carrier is not, from our point of view, a sine wave. Consequently it can display pulse properties. This viewpoint is not arbitrary, but is formulated upon the following discussion: Can the waveshape be altered by a frequency selective circuit? If the decision is affirmative, we are dealing with a pulse waveform, not a sine wave. For example, if we pass an AM sinusoid waveform through a sharply tuned bandpass filter, the modulation envelope will be removed.

Linearity and Time

The test made with a frequency-selective circuit is valid only if such a circuit does not contain nonlinear elements. A frequency-selective circuit made up of resistors, capacitors, and air-core inductors will be, for practical purposes, a linear frequency-selective network. If the inductors contain iron cores, it is possible that nonlinearity will be introduced, and the shape of an applied sine wave distorted.

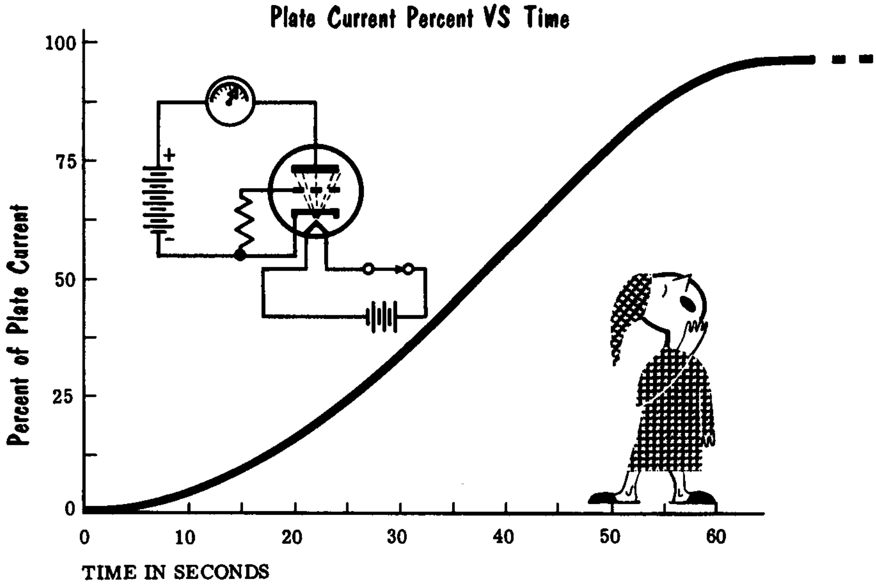


FREQUENCY-SELECTIVE CIRCUITS ALTER PULSE SHAPES BUT DO NOT ALTER THE SHAPE OF A SINE WAVE

In terms of our definition of the properties of a pulse, we now ask: "How rapid is *rapid?*" Generally, pulses found in electronic equipment will complete their cycles in microseconds or milliseconds. Waveshapes which endure for longer times, say seconds or minutes, also manifest pulse properties if their rate of change in amplitude is high. Thus, a square wave which is *off* for 1 minute, then *on* for 1 minute, would generally be classed as a pulse waveform if the transition between states occurs in a time conveniently measured in microseconds or milliseconds. If the transition required a number of seconds, or an even greater time, the waveshape would not generally be considered a pulse. There are, however, exceptions to this rule-of-thumb approach.

Nonsinusoids Which Are Not Pulses

The plate-current increase in an audio-amplifier, as the tube heaters are attaining operating emissivity, is a function of time. We see that almost a minute is required for the transition to complete its cycle. The plate-current-increase waveform is not considered a pulse because its change is too gradual to merit special attention of frequency-selective circuits within the amplifier. For example, the interstage coupling capacitors are not designed to provide easy passage to this waveform, since this would not gain any desirable operating characteristic. The plate-current increase waveform is not relevant to this part of the amplifier circuitry. However, a waveform of this shape which requires 60 microseconds or even 60 milliseconds to complete its buildup would invariably exhibit pulse properties. On the other hand, the waveforms corresponding to low-pitch musical tones do require consideration of the coupling-capacitor size. Since such waveforms are generally nonsinusoidal, they are decidedly pulse waveforms.

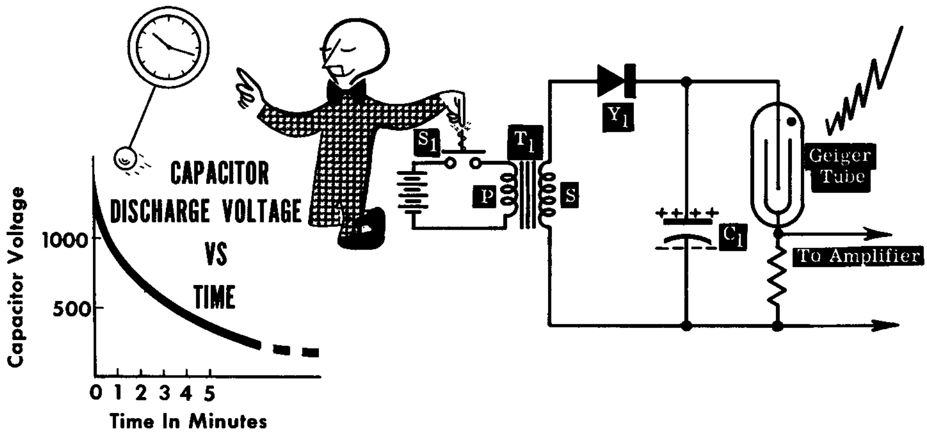


DURING THE WARM-UP TIME OF A VACUUM TUBE THE PLATE CURRENT IS A SLOW NONSINE WAVE

Another example of a slow nonsinusoid waveform which would not be considered a pulse is the variation in voltage delivered to a portable radio as battery activity diminishes with use. No frequency-selective networks within the receiver are involved in this relatively slow change. Accordingly, the graph depicting the fall of battery voltage with time does not, in a practical sense, represent a pulse waveform.

Relating Pulse Waveforms to Specific Circuitry

We see a third example of how to distinguish between a pulse and a non-sinusoidal waveform. It demonstrates the importance of associating the considered waveform with specific circuitry sections in evaluating rapidity of wave transitions. A transition which is *slow* with respect to one circuit may be reconsidered when its action in another circuit is analyzed. A good example of this concept is a Geiger counter in which the Geiger tube is energized from voltage stored in a capacitor. The design of the frequency-selective portions of the amplifier which follows the Geiger tube need not take into account the diminishing capacitor voltage, but only the staccato-like pulses delivered from the Geiger tube. However, the design of the circuitry directly associated with the charging of the capacitor and the load imposed by the Geiger tube are of direct significance with respect to this slowly diminishing voltage wave.



A Geiger Tube Energized from an Occasionally Charged Capacitor

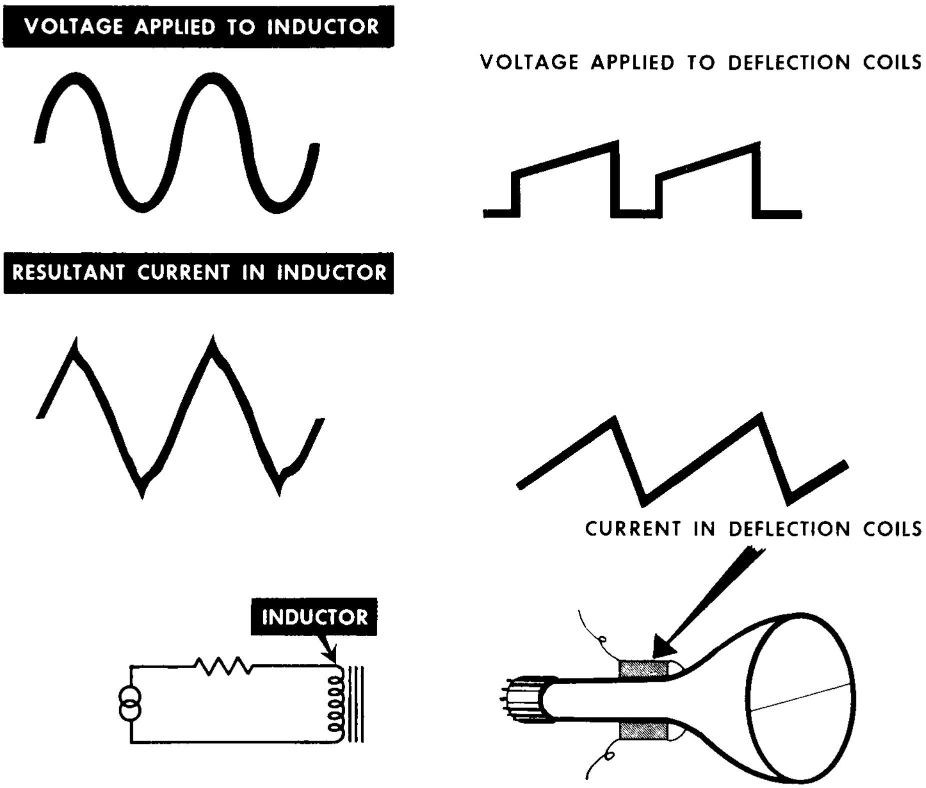
The capacitor shown is charged by manual actuation of pushbutton switch S1. This makes and breaks current flow in the primary winding of step-up transformer T1. The positive cycles of the high-voltage pulses induced in the secondary winding of T1 are passed by rectifier Y1 to capacitor C1. The accumulated charge stored in C1 then energizes the Geiger tube. Due to the load imposed by the Geiger tube and leakage paths, the capacitor voltage slowly falls until proper operation of the Geiger tube necessitates actuation of S1 again.

The relatively slow discharge of the capacitor is, in this example, an important factor in the performance of the device. The rate of capacitor discharge is measured in minutes here, which is rapid relative to the circuit function of the high-voltage supply. The waveform shown, therefore, is a pulse with respect to this high voltage supply.

PULSE USES IN ELECTRONIC EQUIPMENT

Sine Wave Distortion in an Iron-Core Conductor

It is not necessary for both voltage and current waveforms to be pulse waveforms, nor is it required that they be pulse waveforms of the same shape. If a perfect sine-wave voltage is applied to an iron-core inductor, the resultant current will be a distorted sinusoid having the general shape shown (left). In similar fashion, we see (right) the voltage and current waveforms applied to the deflection coils of a radar cathode-ray tube.

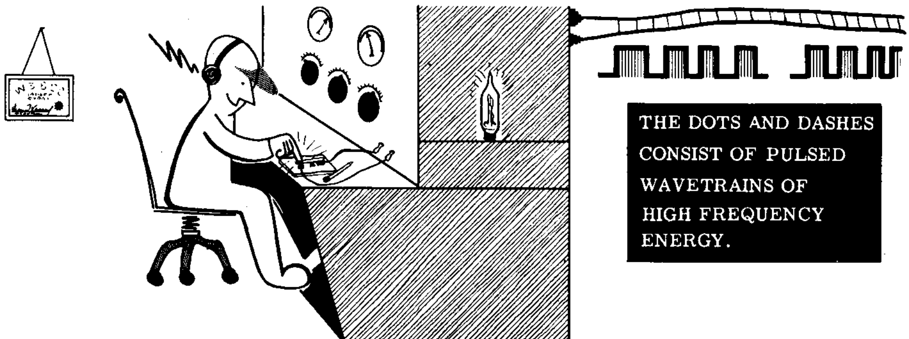


Voltage and Current Waveforms Are Distorted Because of the Use of Iron-Core Inductors.

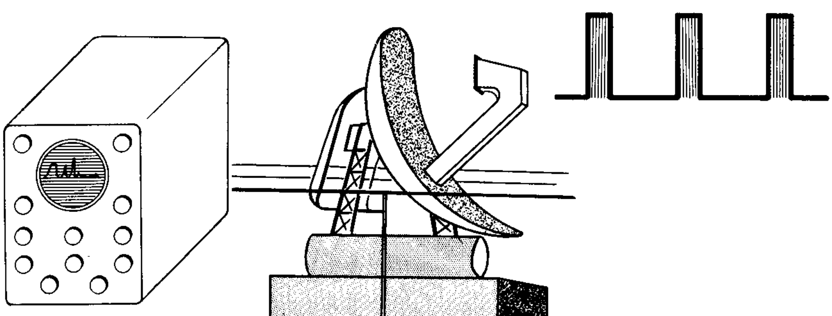
From the discussion thus far, it can be seen that *most waveforms* in electronics are *not sine waves,* and that *most of these nonsinusoids* appear in circuits as *pulses.* An understanding of pulses provides a better insight into the operational theory of electronic devices than can be obtained through the study of ordinary alternating-current principles alone.

Typical Uses of Pulses in Electronics

To understand the importance of pulses, we will study several examples of pulse techniques employed in actual electronic devices and systems. Radiotelegraphy was the first pulse application used in electronics. The dots and dashes of the Morse code represent a significant use of pulses—the communication of information.



RADIO-TELEGRAPHY --- An Early Application of Pulses

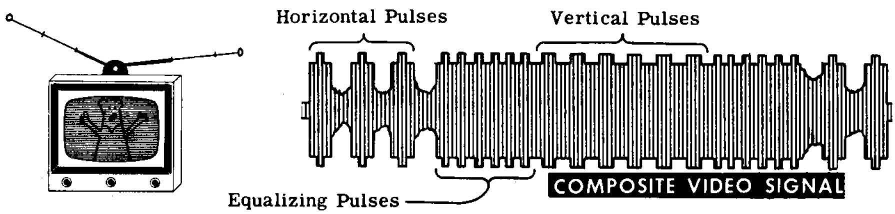


RADAR Utilizes Precisely Formed Rectangular Pulses

Radar exemplifies utilization of pulses for making refined time-interval measurements. (Although the indicated parameter is distance, the quantity is calibrated from the measured time interval.) Short-duration bursts of microwave energy are propagated into space at regular intervals. Between successive bursts, an ultra-sensitive receiver responds to the reflected microwave energy which is returned to the radar site by various objects. The length of time ensuing between the end of a transmission and the reception of an *echo* is interpreted in terms of the distance between the radar set and the object which reflects a portion of the microwave energy. Both radar and radiotelegraphy utilize discontinuous wavetrains of high-frequency energy. The requirements imposed by radar on precision and uniformity of pulse dimensions are much more severe than those required by radiotelegraphy.

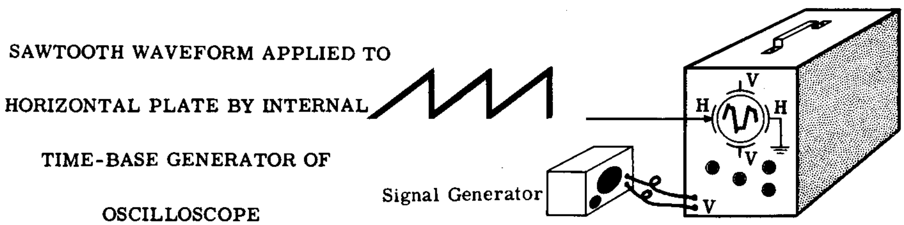
Typical Uses of Pulses in Electronics (contd.)

Television is an anthology of pulse techniques. One pulse technique it illustrates with special clarity is the process of timing, or synchronizing. This is necessary in television because the rendition of picture elements on the receiver cathode-ray tube must be synchronized with the scanning of the image pickup tube in the studio. The composite television signal contains pulses which actuate different circuits of the TV receiver.



Television is Based on the Skillful Use of Pulse Techniques

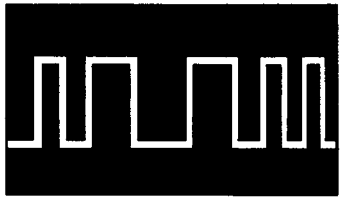
The cathode-ray oscilloscope is probably the most useful single laboratory measuring instrument. For the oscilloscope to display a true image of the waveform being monitored during service or design work, the electron beam which illuminates the phosphorescent screen must be swept across the screen at a uniform rate. This requirement is met by a deflection-voltage waveform having a sawtooth shape. The sawtooth wave is a pulse waveform important in many electronic devices. The leading edge of the sawtooth deflects the electron beam across the oscilloscope screen at a uniform rate, from left to right. The trailing edge quickly returns the beam to the left side of the screen, whereupon a successive sweep commences with the next leading edge.

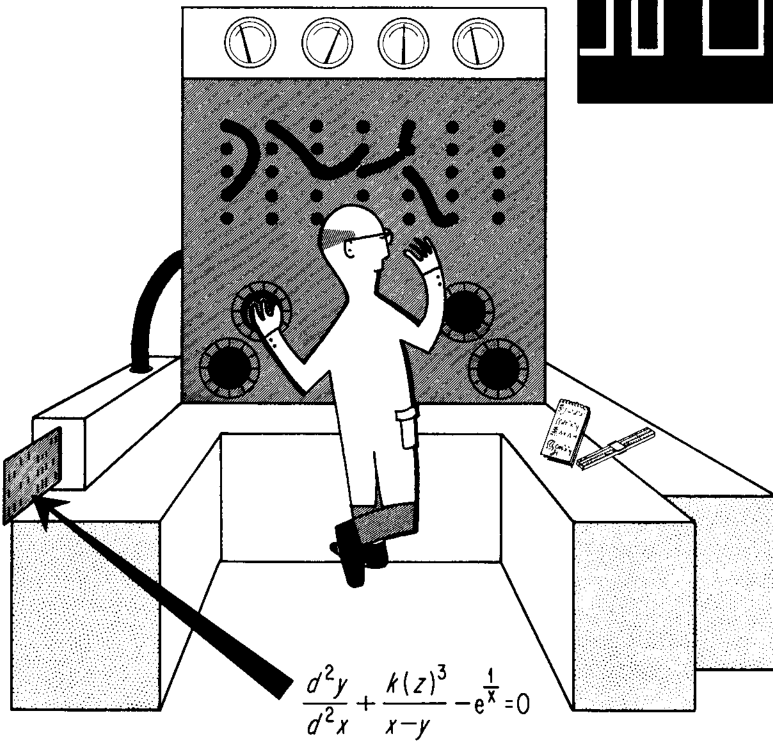


The Sawtooth Waveform Provides a Linear Time Base for Oscilloscopes

Besides its use for linear time sweeps, the sawtooth pulse is employed in signal generators and frequency multipliers because this pulse shape is very rich in harmonics. The square wave is also employed for these applications. Pulses so utilized provide numerous harmonic frequencies which have the desirable property of having the same frequency stability as the pulse-repetition rate.

Pulse Techniques in Digital Computer Logic





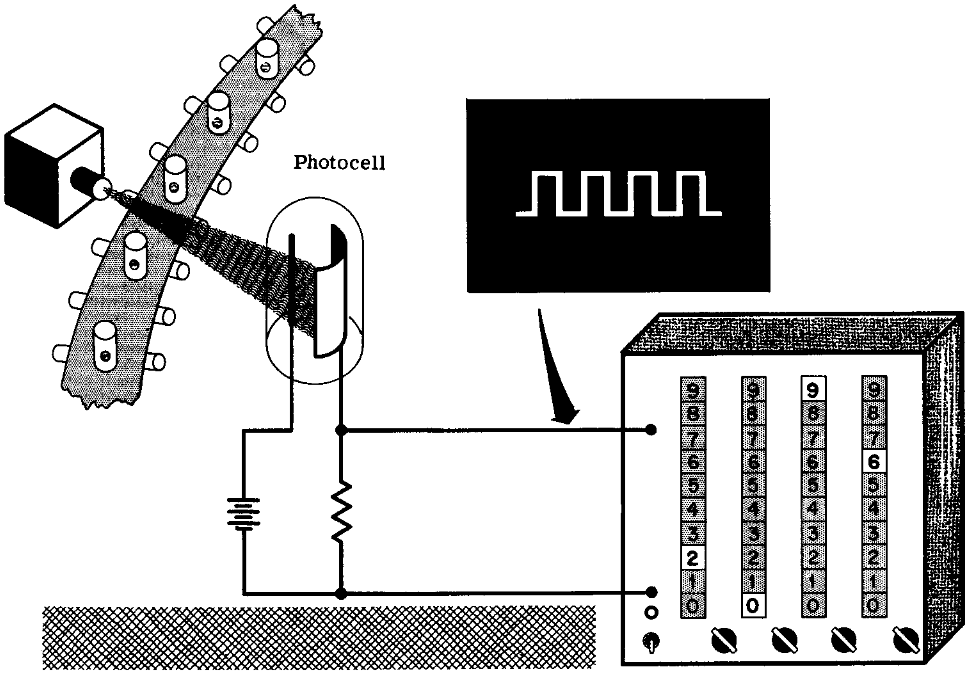
The Digital Computer Solves Problems by Storing Information Contained in Pulses

Digital computers represent a spectacular application of pulses. The digital computer can solve fantastically complex problems in minutes or even seconds. Actually the digital computer is based upon a simple concept—the storage of *bits* of information. The properties of the rectangular pulse are perfect for storage. The rectangular waveshape is produced by the *on* or *off* conditions of electronic switches.

Use of Pulses in Counting Devices

The digital counter uses pulses to trigger responsive circuitry into any one of a large number of possible stable states. Each stable state is indicated on a panel by illuminated numerals. The number of events entering the computer is thereby displayed. The display may be timed to show the total number of events counted over a precise time interval. If the time interval is 1 second, the display of lighted numbers indicates frequency in cycles per second. This instrument is extremely useful in developing stable oscillators, designing precise filters, and monitoring the output of frequency generators where extreme accuracy is needed for laboratory work. Also, the digital counter is used with various transducers which translate physical phenomena such as shaft rotation, acoustic parameters, liquid flow rate, temperature, and other quantities into electrical information. This instrument is an example of the use of pulses in counting and totaling.

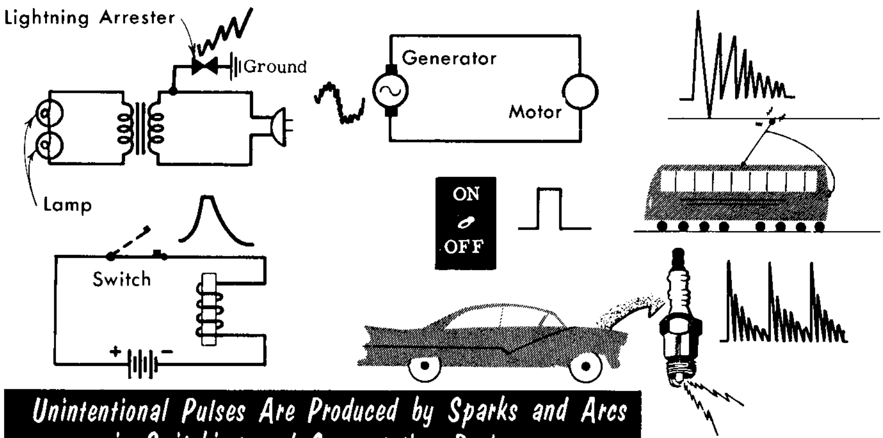
THE DIGITAL COUNTER Accurately Counts Events Which Have Been Converted to Electrical Pulses



In the illustration, cans moving along a conveyor belt interrupt a beam of light. The interruptions are converted to electrical pulses by the photoelectric cell. Each successive pulse is registered on the indicator panel of the digital counter.

Unwanted Pulses — Natural and Man-Made

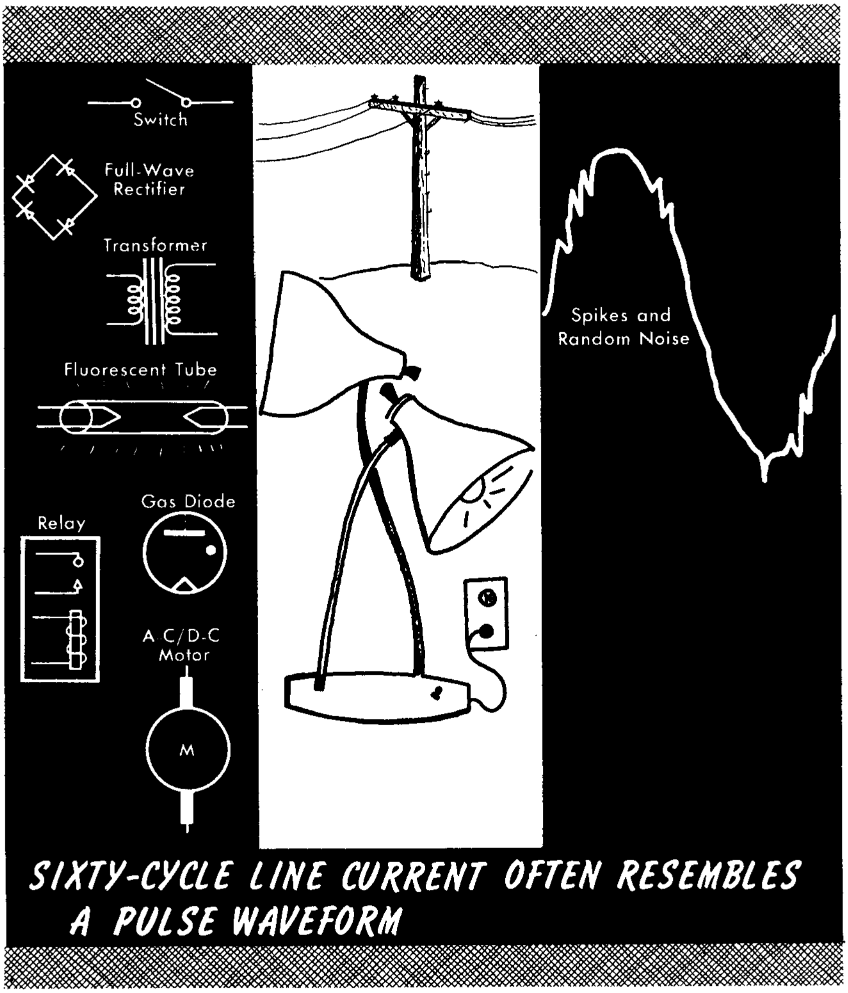
Even if pulses were not deliberately generated in electronic equipment, the abundance of unintentional pulses would require study of the nature of pulse phenomena. An example of unintentional pulses is *noise*. Noise is inherent in our universe, for wherever the temperature is above absolute zero, the orbital electrons of atoms, molecules, magnetic domains, crystals, and other structural components of matter are subjected to thermal agitation which is manifested as noise voltages. Such noise voltages are composed of randomlyoccurring pulses. A common source of these noise pulses is the generations in the input circuit of a high-gain amplifier. Indeed, unless special techniques are used, it is useless to make the sensitivity of an amplifier greater than equivalent levels of signals and noise. Another source of natural noise is produced by electrical storms and ionospheric disturbances, collectively known as *static*.



Unintentional Pulses Are Produced by Sparks and Arcs in Switching and Commutating Devices.

Man rivals and even exceeds nature as a producer of noise pulses. Almost every electrical device generates noise pulses which find their way into electronic equipment via conduction, induction, or radiation. Even in the simple switch a sharp interferring pulse is produced when it is turned on or off. We hear the disturbance as a characteristic "click" from our loudspeakers. Devices which depend for their operation on gaseous conduction, such as neon tubes, fluorescent lamps, and mercury vapor rectifiers, are often potent "hash" transmitters. Switching and commutating devices such as motors and generators produce pulse waveforms of repetitive rather than randomly occuring pulses. This may alter their capacity to interfere in a favorable or adverse way, depending upon the electronic equipment subjected to such pulses. Arcs and sparks produce vicious noise pulses. Radiation from a welding arc, or from automobile ignition plays havoc with television reception.

Noise Pulses from Power Lines

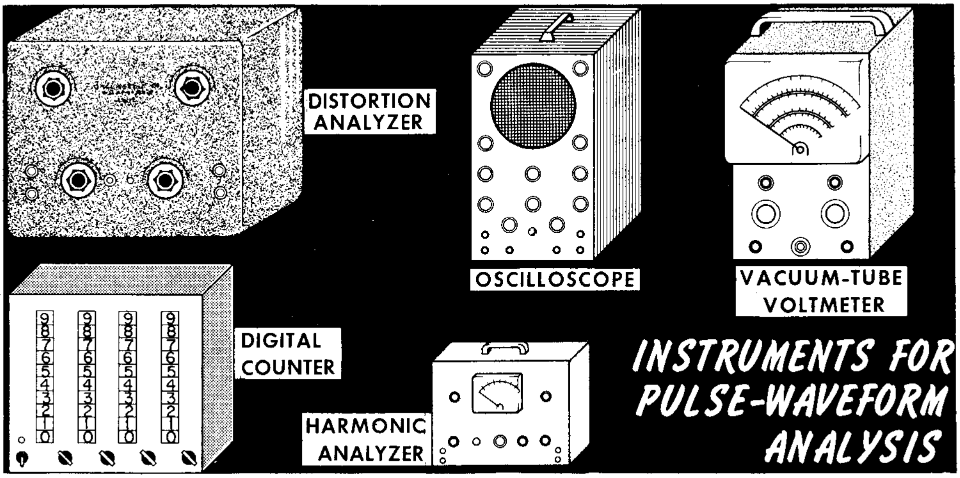


Even a 60-cycle "sinusoidal" power source is often, in practice, a generous contributor of unintentional pulses which must be taken into account to prevent malfunctioning of sensitive apparatus. The power-station generator approximates, but does not produce, a perfect sine wave. Also, there is sufficient cummulative nonlinearity in the complex of loads consuming power, to further distort the wave. Furthermore, the arcing, sparking, switching, commutating, and inductive pickup of atmospheric-earth current disturbances causes spikes and random noise pulses to be superimposed upon the "sine wave." The net result is a wave which often acts as a source of interference. The sine wave is a very rare occurence. In contrast, the pulse waveform is extremely common.

Pulse-Measuring Instruments

With waves visually displayed on an *oscilloscope,* it is possible to measure time and amplitude parameters. The nature of pulses measured by other instruments should always be checked on an oscilloscope.

With a *vacuum-tube voltmeter* the rms values of sine waves can be measured, and the vtvm can be calibrated to read peak values of voltage. When a narrow bandpass filter is used in conjunction with a vtvm, the instrument becomes a selective voltmeter providing accurate information for the fundamental and each harmonic frequency. Used with distorted waves, the vacuum-tube voltmeter requires careful judgment.



A *distortion analyzer* is essentially a tunable narrow-band rejection filter in conjunction with a vtvm. The level of the composite wave form is measured, then a measurement is made with the tunable filter adjusted to reject the fundamental frequency. From the ratio of the two measurements, the distortion percentage is obtained.

Precise measurements of pulse-repetition rate, frequency, duration, period, and interval can be made with a *digital counter.* Using the Fourier theory of pulse composition, the digital computer can provide much information regarding low-pass, high-pass, bandpass, and rejection filters.

A *harmonic analyzer* incorporates a vtvm in conjunction with tunable filters employed in such a way that a quantitative measurement of individual harmonics may be made. Thus, more detailed information is provided than with the distortion analyzer, which measures distortion products as a summation of all harmonics.

QUESTIONS

1 What characteristic distinguishes the sine wave from pulse wave forms?

2 What type of circuit is used to detect the difference between a pure sine wave and a pulse waveform which bears some resemblance to the sine wave?

3 Why is the half-sine wave output of a rectifier not considered a true sine wave? Name some other waveforms which closely resemble sine waves but which exhibit pulse properties under certain conditions.

4 Why is the charging time of the capacitor in a Geiger counter considered to be a pulse rather than a "slow" nonsinusoid?

5 List three important uses of pulses in electronics.

6 List three pieces of electronic equipment which make extensive use of the sawtooth pulse. Describe the use of this pulse waveform in the cathode-ray oscilloscope.

7 How is the television receiver synchronized with the TV camera in the studio?

8 List three uses of the digital counter.

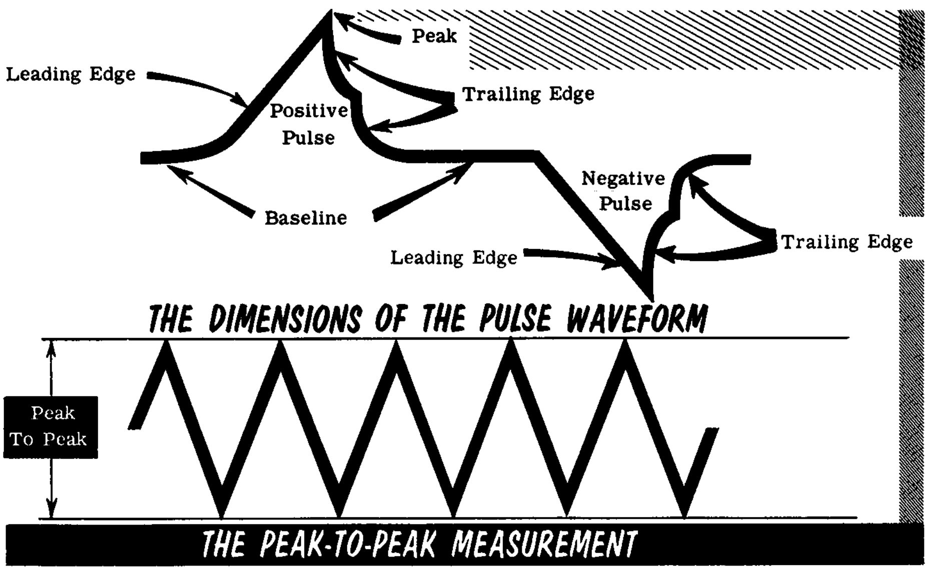
9 What is static? How is it dealt with in electronic equipment?

10 Why is the 60-cycle house current which is supposedly a pure sine wave source sometimes a cause of electrical noise?

The Measurement of Pulses

The response of a circuit exposed to pulses depends upon a number of characteristics possessed by pulse waves. Most of these characteristics deal with the geometrical measurements of the pulse waveforms. It is necessary that we agree to the meaning of the various dimensional terms which describe the visible waveform that might be observed on an oscilloscope or plotted on paper.

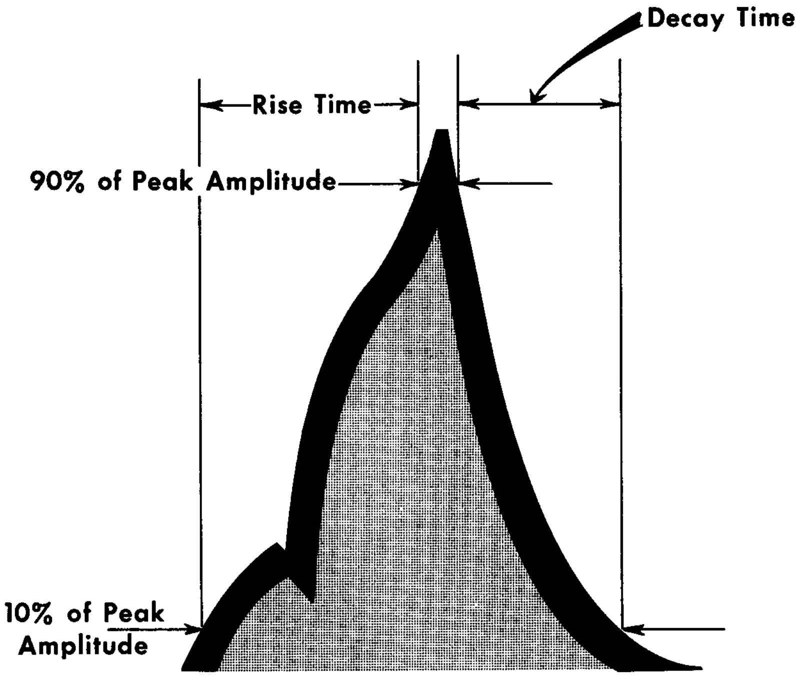
Pulses sometimes occur as individual entities, but more often in groups called *wavetrains.* In either case, there are four important elements with respect to which all pulse measurements are made. These are the *baseline,* the *leading edge,* the *peak (or top),* and the *trailing edge.* Note in the diagram that waveforms above the baseline are designated positive; those below the baseline are assigned the negative polarity.



Usually, peak amplitude is measured with respect to the baseline. In some wavetrains, such as the one shown above, it may not be easy to locate the baseline with acceptable accuracy. Here, instead of dealing with the peak amplitude measured from the baseline, we measure from negative peak to positive peak and designate the value thereby obtained as the peak-to-peak amplitude of the waveform.

Due to the universality of oscilloscopic measurement techniques, pulses are generally *voltage waveforms.* However, pulses may also represent *current* or *power* as a consequence of special measurement procedures or graphical construction. In such instances, the pulse waveforms should be appropriately identified so they will not be construed as voltage excursions.

Pulse Rise Time and Decay Time

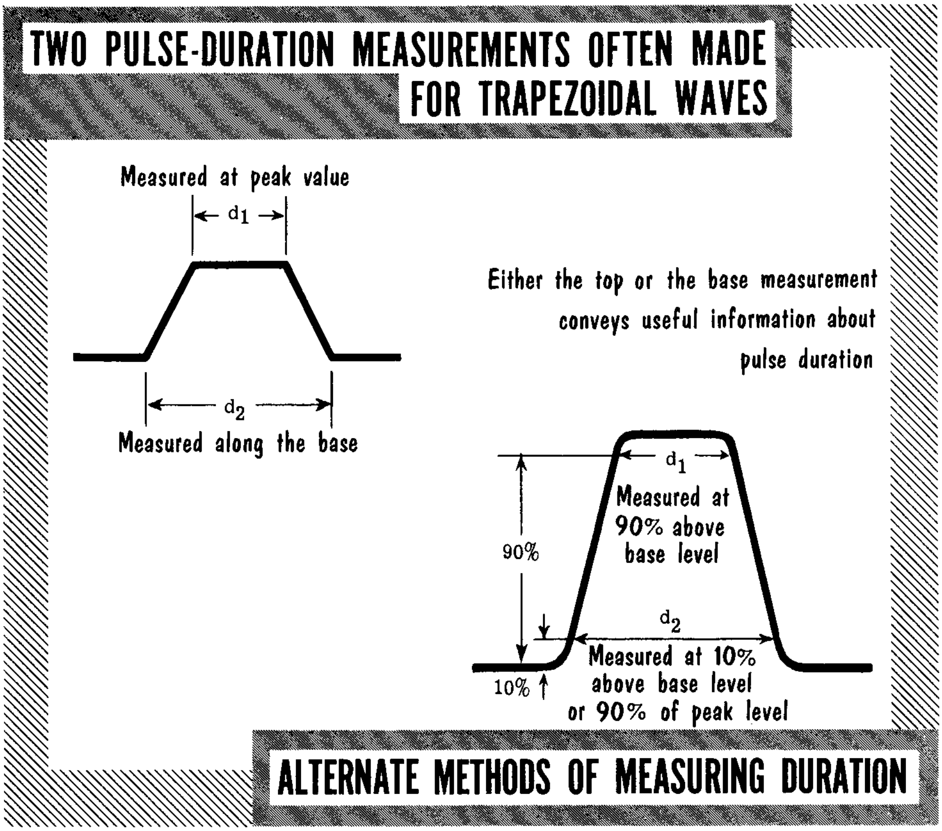


THE DEFINITION OF RISE TIME AND DECAY TIME

The steepness of their leading and trailing edges profoundly effect the behavior of pulses in circuits. It is consequently important that a measurement parameter be established for these pulse characteristics. How shall we define the steepness of an irregular leading or trailing edge and a trailing edge of nonconstant slope. The problem is resolved by means of an arbitrary rule: rise time is the time elapsing between two definite points on the leading edge. One of these points is that corresponding to 10% of peak amplitude; the other point is that corresponding to 90% of peak amplitude. There is a similar definition for the decay time of the trailing edge; decay time is the time consumed for the trailing edge to decline from 90% of peak amplitude to 10% of peak amplitude.

The Measurement of Pulse Duration

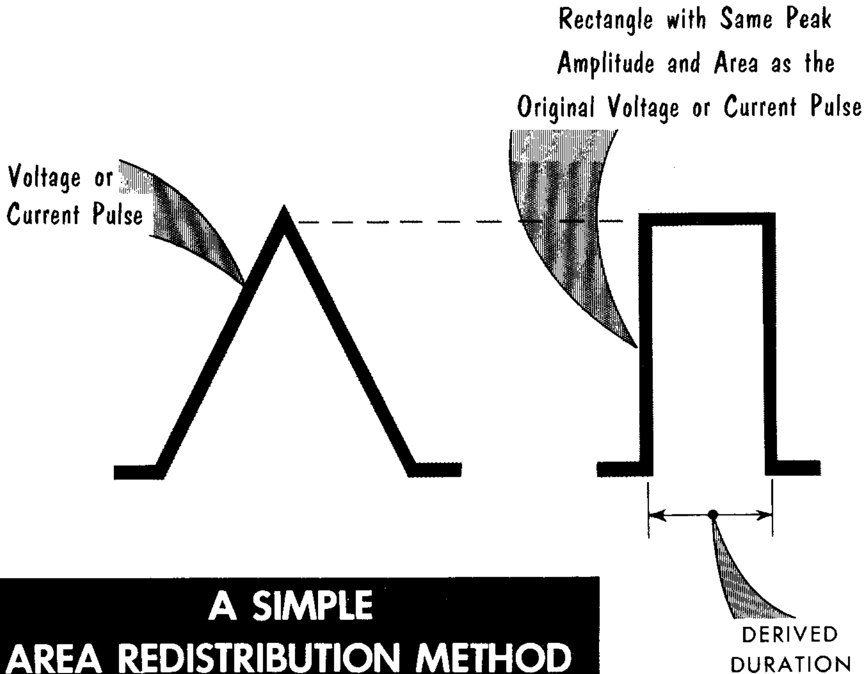
Another important pulse parameter is duration. As the term implies, the measurement involved is the length of time the pulse persists. Duration is easy enough to ascertain if the pulse shape is rectangular or square, but for other pulse shapes we must standardize a definition to avoid ambiguity. A triangular wave, for example, has a measurable duration along its base, but zero duration at its peak. Unfortunately, one does not find a consistent method of defining and measuring duration in the technical literature.



The duration of pulses having the general shape of a trapezoid is sometimes measured along the base of the pulse, but at other times the top of the pulse defines the duration. A common variation of these two methods involves the 10% and 90% points on the leading and trailing edges of the pulse. Under these conditions, the base measurement of duration will be made across points corresponding to 10% of peak pulse amplitude; similarly, the top measurement of duration will be made across points corresponding to 90% of peak pulse amplitude.

Area-Redistribution Method of Measuring Pulse Duration

Another way to establish the position on a nonrectangular pulse for measuring its duration is shown. This is the area-redistribution method. A rectangle is drawn having the same peak amplitude and the same area as the original pulse under consideration. The width of this rectangle, measured to the same time-unit scale as the original pulse, is considered the duration of the original pulse. The area of the original pulse can be evaluated by the methods of geometry. For example, the area of a triangular wave is one-half the product of base times altitude. Of course, it is necessary to establish a scale of measurement, for example so many milliseconds per inch.

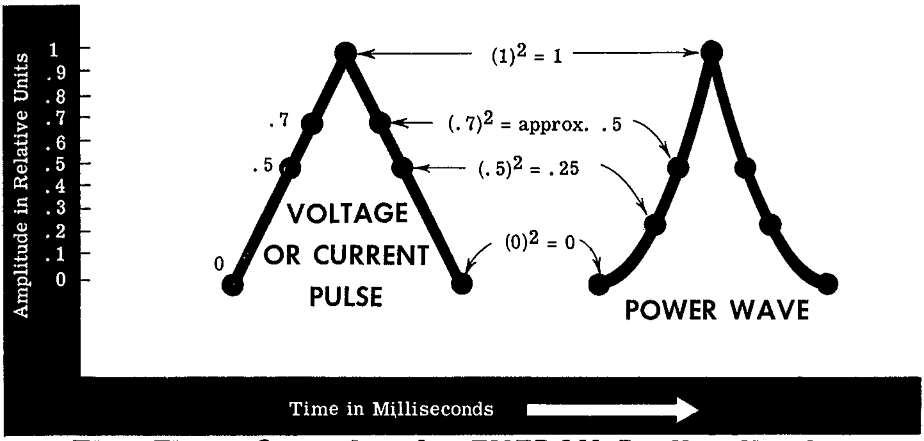


A SIMPLE AREA REDISTRIBUTION METHOD OF MEASURING PULSE DURATION

In advanced engineering and design, complex formulas are often used to evaluate one pulse function in terms of another, or several others. Such relationships are adaptable to any of the pulse-duration definitions, but must be appropriately modified for the particular definition. The fact that this is possible indicates the validity of all the methods of defining duration, providing we supply the whole story, the time in milliseconds or microseconds, as the case may be, plus the method of measurement.

The Energy Redistribution of a Pulse

There is another method of defining pulse duration. This approach, the energy-redistribution method, is mathematically more consistent than the other methods. It is a standardized or normalized rather than arbitrary means of attaining a duration-measurement method which provides the same measured quantity regardless of pulse shape. This approach is similar to the area-redistribution method, but is a little more involved.



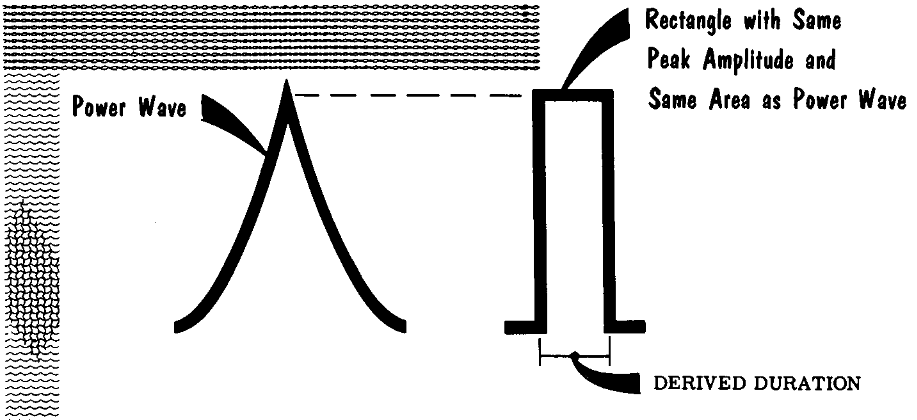
The First Step in the ENERGY Redistribution Method -- Conversion of Original Voltage or Current Pulse into a Curve Representing Power

Assume, as is generally the case, that the pulse shape represents a voltage or current. We convert this to a wave representing power by squaring a few amplitude values and plotting the resultant curve. This is because the power in an electric circuit is proportional to either current squared or voltage squared. First, the waves are drawn on graph paper. Then, regardless of actual amplitude in volts or milliamperes, the peak amplitude is designated as unity, or one. This makes it possible to perform the squaring computations mentally; thus 1 squared is 1; 1/2 squared is 1/4, 1/3 squared is 1/9, and so on.

After deriving our power curve, we evaluate the area enclosed by it. If we have plotted our waves on graph paper, this area can be closely estimated by counting the number of squares embraced within the power curve. Or an instrument such as a planimeter can be used. Sufficient accuracy for many practical situations will be provided by approximating irregular curve sections with smooth or straight lines.

Pulse Duration Derived from the Power Curve

After computing or estimating the area under the power curve, we construct a rectangle having the same peak amplitude and the same area as the area under the power curve. The width of this equivalent-area rectangle is defined as the duration of the original pulse. (The width of the rectangle is readily obtained by dividing the area under the power curve by the number of graph-paper squares between the base and peak amplitude.)

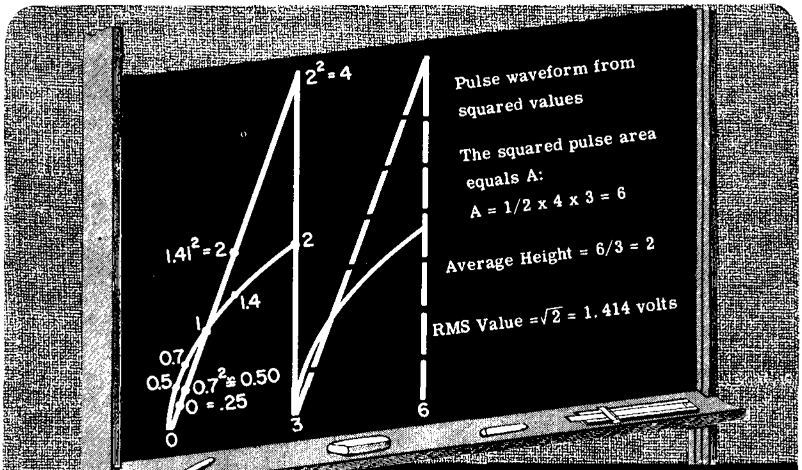


The Second Step in the Energy Redistribution Method-- Conversion of a Power Wave to an Equivalent-Area Rectangle

It is important to understand the logic involved in this computation. The power curve derived from the original voltage or current pulse is actually a graph of power plotted against time. Graphically, energy is proportional to the enclosed area under our power curve. It is the most significant property common to all pulses, for the various manifestations of pulses are fundamentally due to energy content and distribution. To standardize a definition of duration, we circumvent the different energy distributions corresponding to different pulse shapes. We do this by converting the *energy package,* that is, the power curve, to a simple *geometrical shape,* a rectangle having a peak amplitude the same as the power curve. We can then say that the energy contained in a pulse acts very much as an equivalent energy standardized rectangular pulse. An analagous situation is the center of gravity of an automobile when the automobile acts as though its distributed weight exerts its collective influence at the center of gravity.

Despite the different methods of defining duration, they are all useful if we take care to designate the measurement technique. If the simple baseline measurement is used, as is very frequently the case, it is important to specify duration as the baseline value.

Demonstration of Pulse Measurement

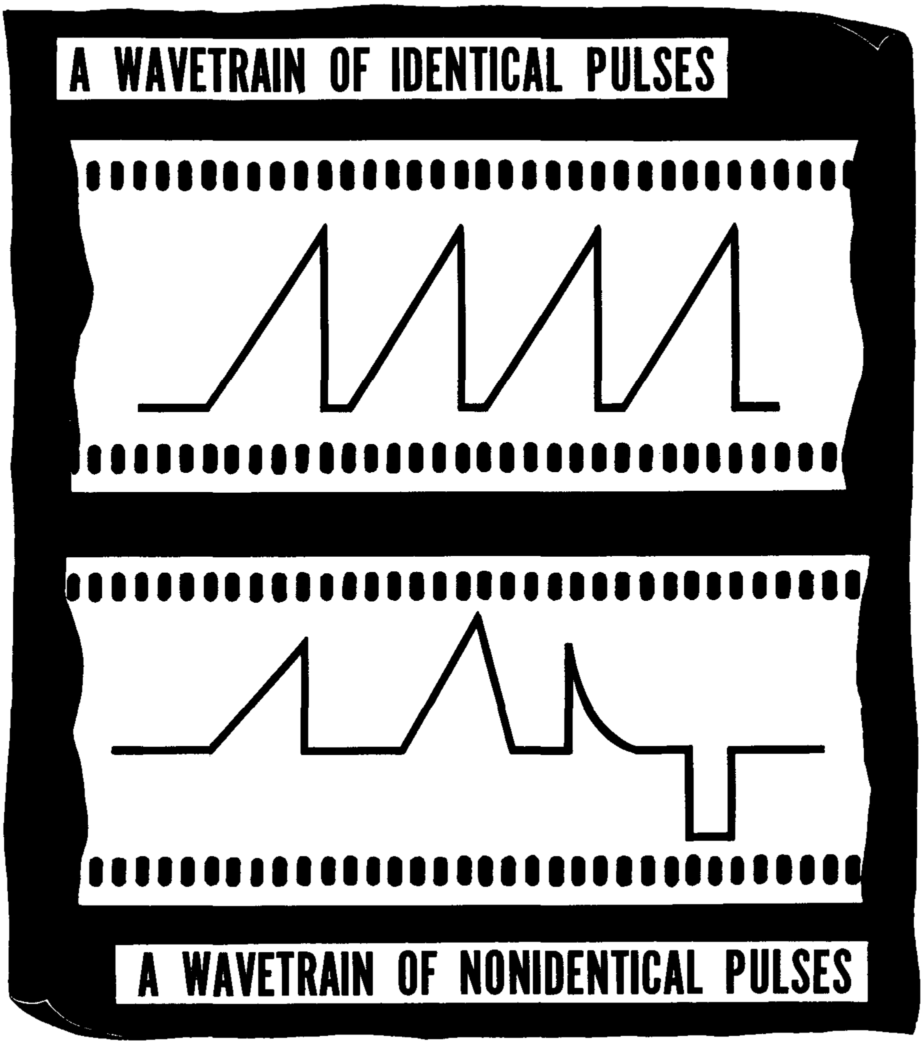


DETERMINING THE RMS VALUE OF A PULSE

Question: Do pulses as well as sine waves have effective or rms values?
Answer: Yes, and in the same sense. The effective or rms value of pulses is the value which would produce the same heating effect as a d-c voltage or current of that value.
Procedure: The procedure for finding the rms value of pulses is illustrated. A near exponential pulse with a peak amplitude of 2 volts is generated, for our purposes, by a relaxation oscillator.

1. The wave is traced or copied from the oscilloscope screen. In so doing, the scale, that is, the number of volts per inch, is noted. From this, the duration of the pulse can be dimensioned as so many volts. This serves the geometrical purpose of measuring the base line of the pulse in the same units as the amplitude.
2. Square several amplitude values of the pulse.
3. Draw a new wave using the squared values obtained in Step 2.
4. By means of graphical methods, or with a planimeter, find the area of the new wave. In our case, the new wave is a triangle with an area equal to 1/2 the base times the height. Thus the area is $1/2 \times 3 \times 4$ or 6 "square" volts.
5. Find the average amplitude of the new wave. This is obtained by dividing the area of the new wave by its base or duration. For the problem at hand, the average amplitude is equal to 6/3 or 2 volts.
6. Derive the square root of the value found in step 5 to find the rms value of the original pulse. $\sqrt{2} = 1.41$. (Most pulses have rms ratios of values other than $\sqrt{2}$. It is *coincidental* that the wave considered here has the same rms value as the sine wave with the same peak value.)

Identical and Nonidentical Pulses

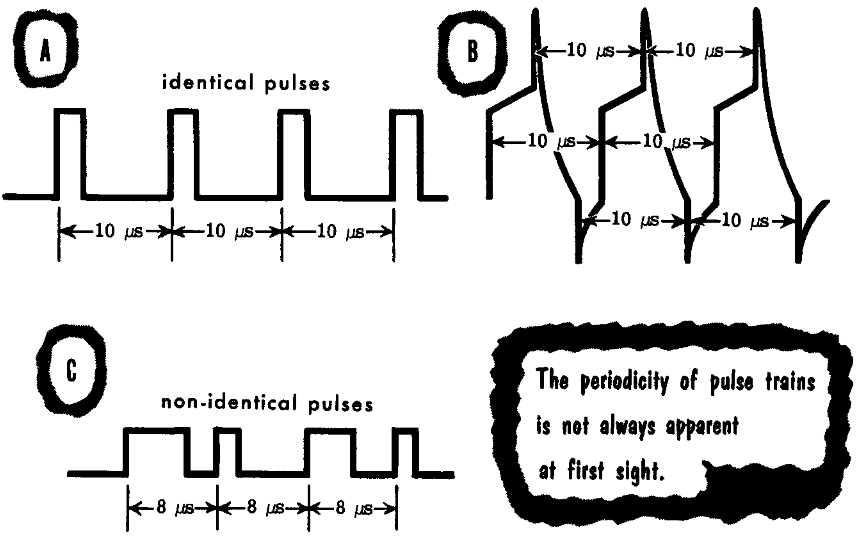


We have defined and used the important terms of pulses considered as single entities. These terms are entirely applicable to the pulses comprising wavetrains in which one pulse after another occurs. However, there are other pulse characteristics relevant to a series of pulses rather than to single isolated pulses. Accordingly, we now measure groups of pulses. A wavetrain of pulses can consist of identical pulses or pulses differing in some measurement parameter. We see one wavetrain of *identical* pulses and one wavetrain of *nonidentical* pulses.

Periodic and Aperiodic Pulses

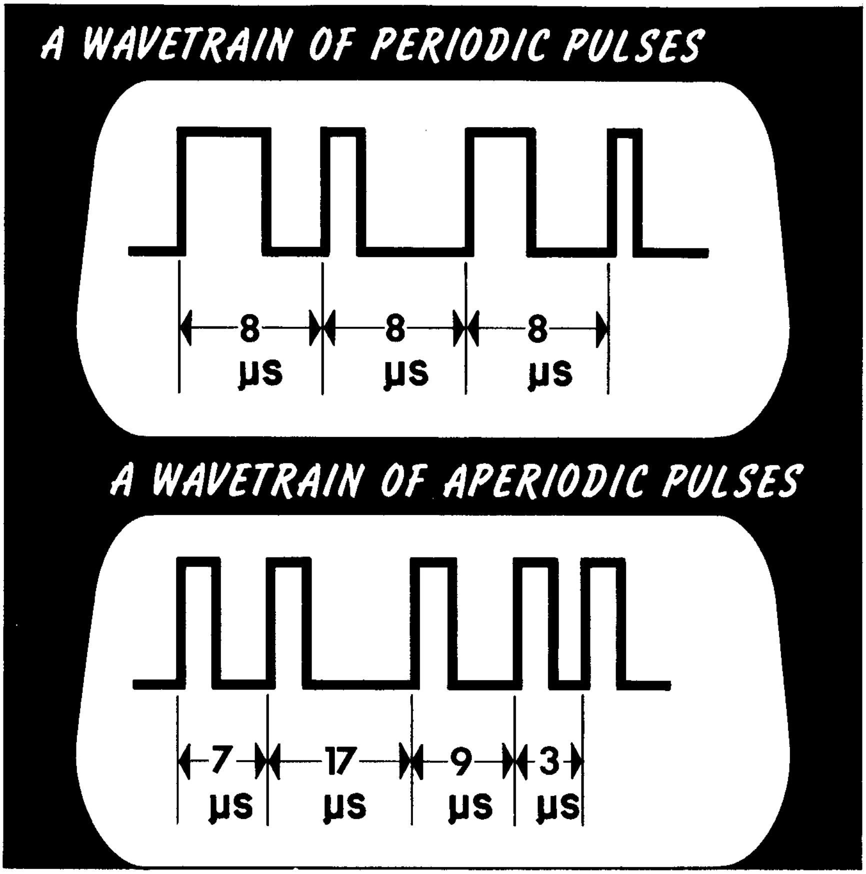
The two main classifications of pulse wavetrains are *periodic* and *aperiodic* pulses. A third classification, *transient* pulses, is not so amenable to a specific definition as the first two, but it merits discussion because of its frequent usage in technical literature. The periodic wavetrain of pulses is one in which the time interval between leading edges of successive pulses is the same. This definition holds for nonidentical as well as identical pulses. In the case of identical pulses, the definition of periodicity can be extended by stating that the time interval between *corresponding points of successive pulses is the same.* Part C of the illustration is an interesting pulse wavetrain; it is periodic, though not evidently so at first glance.

THE PROPERTIES OF PERIODIC PULSES



This definition of periodic pulses is not all-inclusive; strange and unusual wavetrains of nonidentical pulses can be devised, having a rythmic quality which classifies them with periodic wavetrains. However, we are concerned only with rules which apply to the vast majority of cases encountered in electronic devices. Generally, it will be found that periodic wavetrains involve either identical pulses (parts A and B), or nonidentical pulses of simple shape (part C). In part B, the time intervals between corresponding points of successive pulses in a periodic wavetrain of identical pulses are the same.

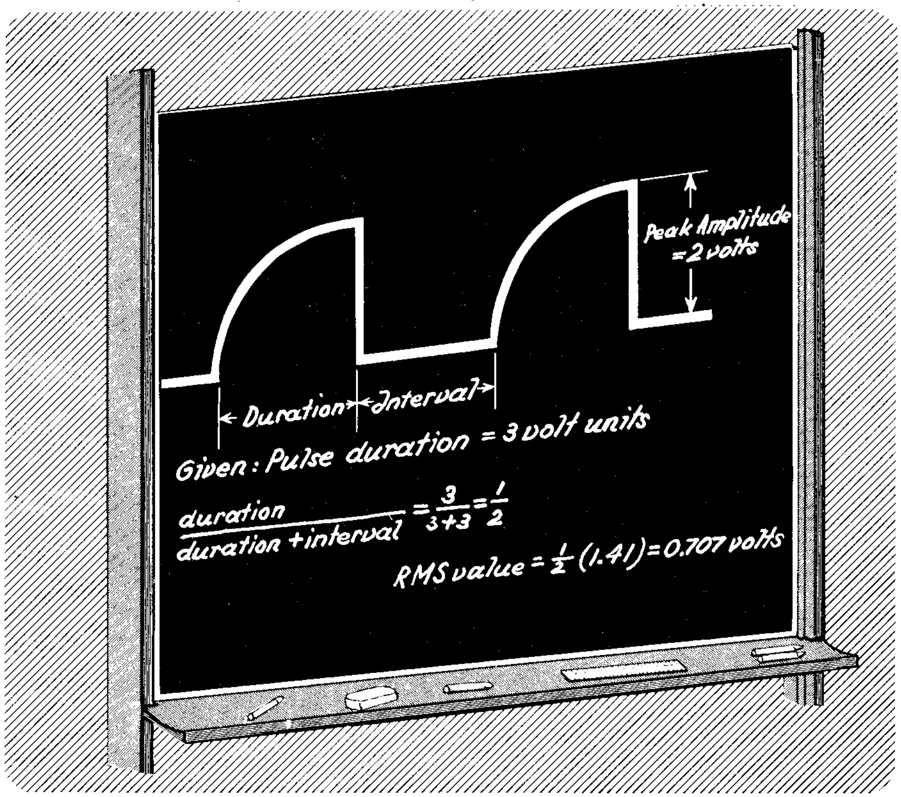
Periodic and Aperiodic Pulses (contd.)



Aperiodic pulses are those pulse wavetrains which are not periodic. If the aperiodic pulses are identical, there is no fixed time interval between corresponding points on successive pulses. If the aperiodic pulses are not identical pulses, the leading edges of successive pulses are not spaced by fixed time intervals. We see an aperiodic pulse train made up of identical pulses. It is readily seen that the intervals between successive pulses vary in length. As in the case of periodic pulses, we are concerned with a definition which will hold true in the vast majority of pulse waveforms encountered in practical electronics rather than with academic exceptions. It is easy to ascertain whether a wavetrain of identical pulses is periodic or aperiodic. When the wavetrain is made up of nonidentical pulses, one must exercise caution rather than make a quick visual appraisal. The periodic waveform shown, for example, is not obviously periodic.

Demonstrating Effect of Time Interval

Calculating The RMS Value When There Is A Pulse Interval



Question: How is the rms value of pulses effected when there is a time interval between successive pulse cycles?
Answer: The procedure is the same as shown on page 22 with an additional step involved. The result obtained in step 5, page 22, is multiplied by the factor

$$\frac{\text{duration}}{\text{duration} + \text{interval}}$$

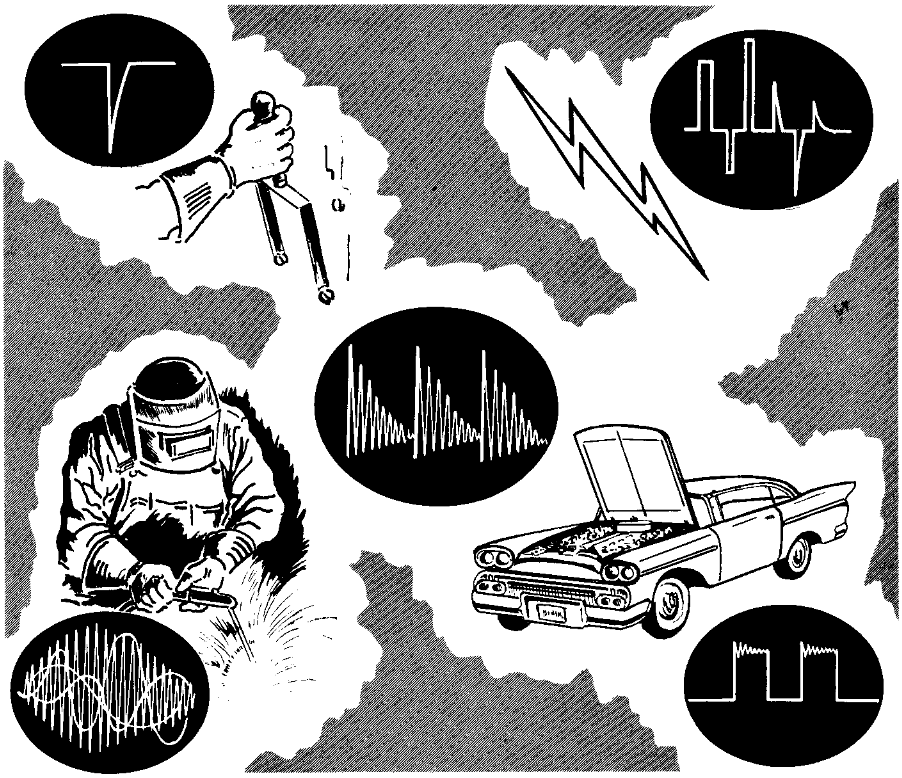
In the pulse depicted on page 22, the interval between successive pulses was zero. Therefore

$$\frac{\text{duration}}{\text{duration} + \text{interval}}$$

was equal to unity.
In the pulse train shown, the intervals are equal to the pulse duration.

TYPES OF PULSE WAVETRAINS

Transient Pulses

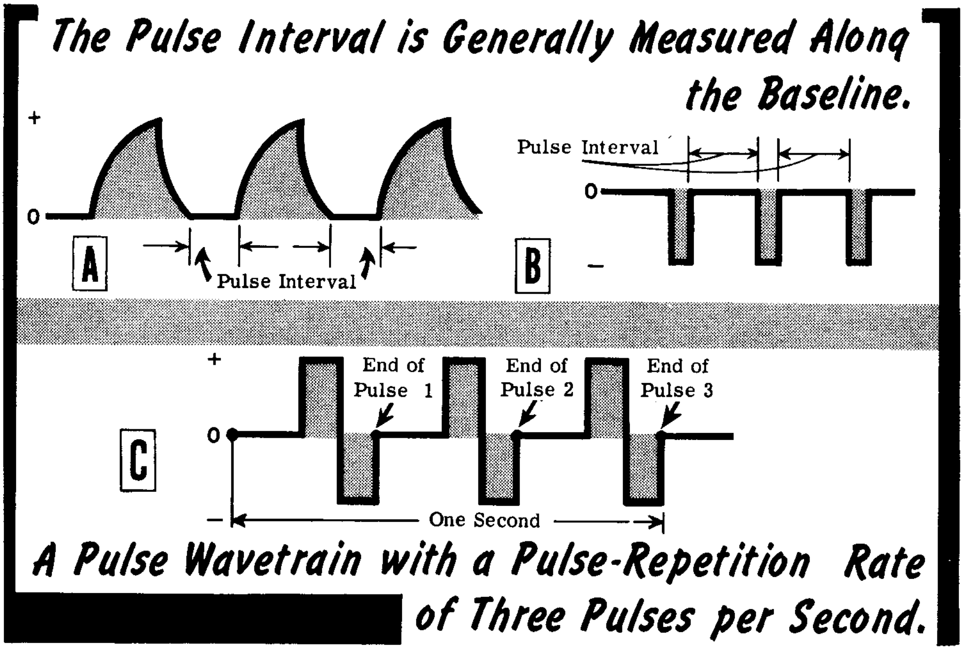


TRANSIENT DENOTES BRIEFNESS, RANDOMNESS, OR PULSES WHICH ARE NOT DELIBERATELY GENERATED.

The term "transient" is generally applied to pulses which are generated as byproducts of pulses more intimately associated with the desired performance of the electronic device. Often, transient pulses interfere with the intended operational mode of the device or system. In another use, we frequently find transients as extremely brief pulses which may or may not be intentionally produced. Sometimes the individual pulses of an aperiodic wavetrain are spoken of as transients. The irregular discharges of lightning are commonly described as transients. It is not possible to attain a rigid definition of transients in view of the several connotations of the word repeatedly found in the technical literature. However, the factor of brief duration is the underlying common denominator. Shown are transient pulses which comply with this concept.

Pulse Interval and Pulse-Repetition Rate

Pulse interval defines the length of time elapsing between pulses. This means time, measured along the baseline from the trailing edge of a pulse to the leading edge of the successive pulse. A rectangular or square wave always involves definite pulse intervals, whereas a triangular waveform has a pulse interval of zero. (In some applications, it is more convenient to measure pulse interval between pulse peaks, or between other points on the pulse envelope. This is permissible providing the points of measurement are stated.)



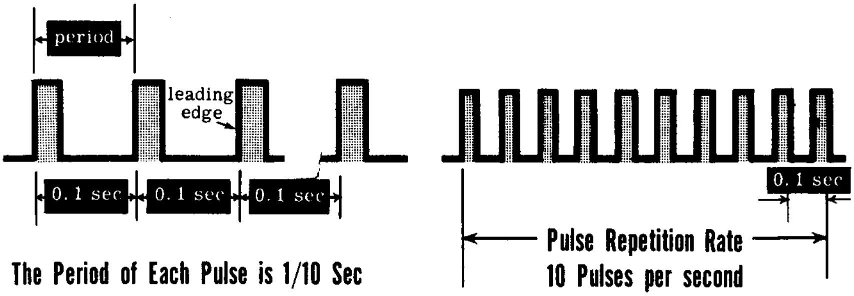
An important parameter of periodic pulses is *pulse-repetition rate*. This term defines the number of pulses occuring over a definite time span, usually one second. Pulse-repetition rate denotes the same characteristic of pulses as the frequency implies in alternating-current practice. As most alternating current waveforms are pulses, intentional or not, there is no sharp distinction to help us decide which term is appropriate. Indeed, pulse-repetition rate and frequency are used interchangeably in technical literature dealing with pulses. However, pulse-repetition rate is the preferred term when the pulse characteristic of a waveform is a relevant feature with respect to the circuit to which it is applied. A pulse entails its complete cyclical excursion when both positive and negative wave portions are involved (see part C of the figure). The pulse-repetition rate of this periodic waveform is three pulses per second not six pulses per second.

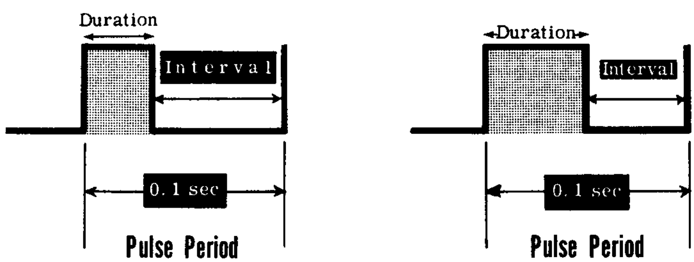
Pulse Period Defined

Pulse Period and Pulse-Repetition Rate are Reciprocals of Each Other

$$\text{Period} = \frac{1}{\text{Repetition Rate}}$$

$$\text{Repetition Rate} = \frac{1}{\text{Period}}$$

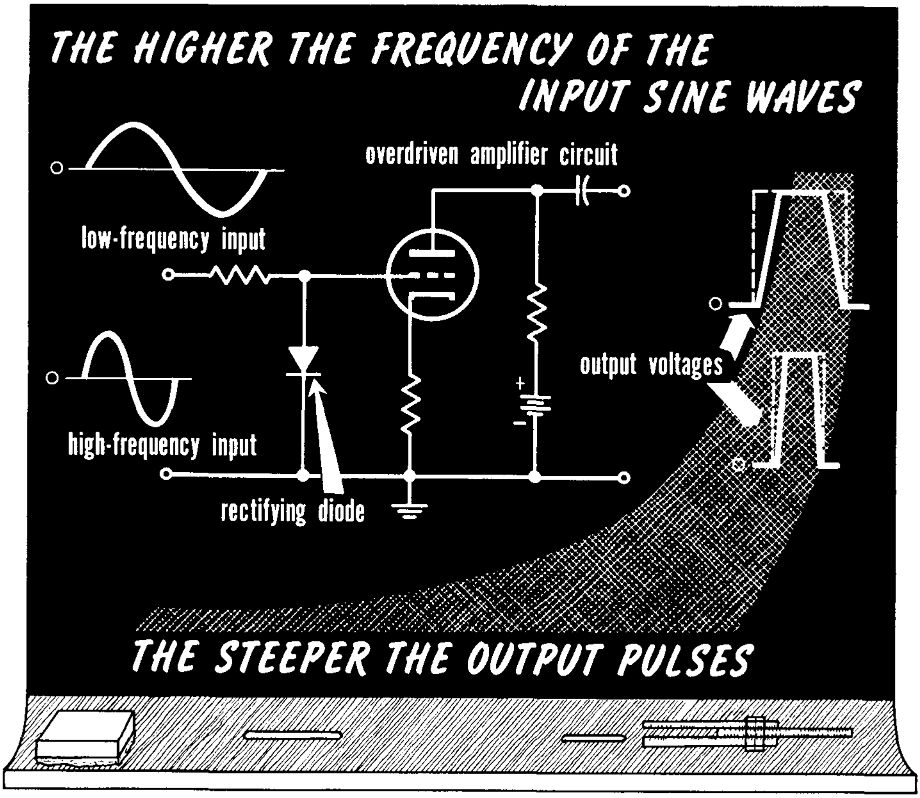




The Pulse Interval, but NOT the Period, is Affected by Varying Pulse Duration.

In a periodic wavetrain of pulses, the time elapsing between corresponding points on the leading edge of successive pulses is known as the *period*. For a given pulse-repetition rate, there is a certain definite period. In fact, period and pulse-repetition rate are reciprocally related; it is only necessary to know one in order to compute the other. Period is equal to 1/pulse-repetition rate. Conversely, pulse-repetition rate is equal to 1/period. Note that the period of wavetrain is independent of pulse duration, whereas the pulse interval is determined by pulse duration as well as pulse-repetition rate. The relationship is: *period* equals *the sum of the pulse interval* plus *the pulse duration.*

Periodic Pulse Train Parameters



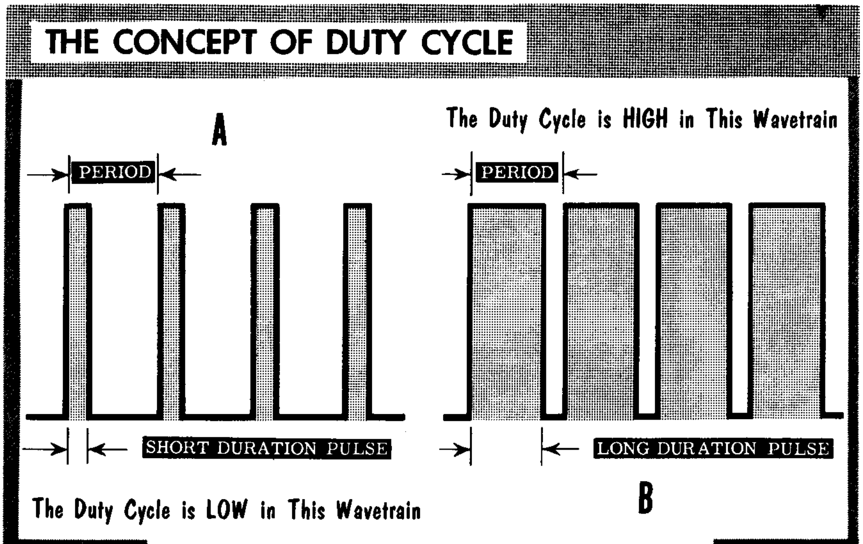
Question: What is the pulse-repetition rate of the resultant pulses produced by the amplifier shown.
Answer: Sixty pulses per second (the same as the input frequency).
Question: What is the period of the resultant pulses?
Answer: Period = 1/PRR;1/60 = 0.0167 sec.
Question: What is the duration of the pulse train?
Answer: The duration of symetrical pulses is 1/2 of the period. Thus, duration = 0.0167/2 = 0.0084 sec approximately.
Question: What is the pulse interval?
Answer: The interval and the duration of a symmetrical pulse train, such as would be derived from a circuit adjusted to clip or limit both half-cycles equally, are the same. Pulse interval = 0.0084 sec approximately. An interesting observation on the operation of the overdriven amplifier is that the higher the frequency of the original sine wave, the shorter will be the rise and decay times of the pulses made from it. It is assumed that the resultant pulse train from the overdriven amplifier is rectified before the calculations are made for the various pulse parameters.

The Definition of Duty Cycle

Duty cycle is a term mainly used in conjunction with square or rectangular pulses in periodic wavetrains. Duty cycle is expressed as a percentage; it is the ratio obtained by dividing the pulse duration by the period

$$\text{Duty cycle} = \frac{\text{Pulse duration}}{\text{Period}} \times 100$$

Duty cycle gives us a conception of the power involved in a pulse wavetrain. A wavetrain of rectangular pulses with very short pulse duration cannot represent as high an average power as the wavetrain with long duration. The voltage or current symbolized by part A is *off* most of the time, whereas the converse is true of the events depicted in part B.



The Duty Cycle Is The Active Part Of The Pulse Period

An interesting practical aspect of the concept of duty cycle is found in radar. The pulsed high-frequency energy has a very *low* duty cycle. Although the peak power of a radar transmitter may exceed several hundred killowatts, the average power may not exceed several hundred watts. Consequently, the magnetron microwave generator is a physically small tube. On the other hand, a transmitting power tube employed in a powerful radio-telegraph transmitter must be designed for a much higher duty cycle since the *on* and *off* times in a pulse wavetrain produced by Morse code dots and dashes are about equal, if we consider an average based on the letters in a typical message sentence. Due to the relatively *high* duty cycle involved in telegraphy, the physical size of the power transmitting tube must be sufficient to dissipate the high average power resulting from the electrical losses in the tube.

QUESTIONS

1 A time-interval meter indicates a period of .001 second for a periodic wave derived from an oscillator. Another measurement is made with a standard frequency source and oscilloscopic Lisajous figures; a frequency of 1000 cycles is interpreted from the oscilloscope pattern. Can the two measurement techniques be reconciled, or is an error indicated?

2 What is the period of a 1-mc wave frequency modulated by a 1000 cycles tone?

3 An oscilloscope known to be in good operating condition will not synchronize on the divided-down ignition pulse obtained from the center wire of an automobile distributor. When the test is made on another engine, a steady synchronization is readily obtainable. In terms of wave characteristics, describe a possible cause of the trouble.

4 The power delivered to a load by a half-wave rectifier is found to be the same for either way the half-wave rectifier is connected, although the d-c polarity across the load changes. The a-c is derived from the 120-volt, 60-cycle house supply. Is this an expected result? Discuss.

5 A pulse radar system rated at one-half megawatt is energized by a d-c power supply which is comparable in size and 60-cycle current drain to that of an amateur radio-telephone transmitter operating with about 900 watts input. Why isn't the discrepancy in operating powers reflected in corresponding differences in their physical size and line current consumptions?

6 Where are aperiodic pulses generally encountered?

7 In trouble-shooting an electronic device, a low duty-cycle repetitive wave should be monitored across the output winding of a transformer connected to a blocking oscillator. Instead, a high duty-cycle waveform is displayed on the oscilloscope. Before arriving at conclusions with respect to the performance of the oscillator, or proceding further, what test should be made?

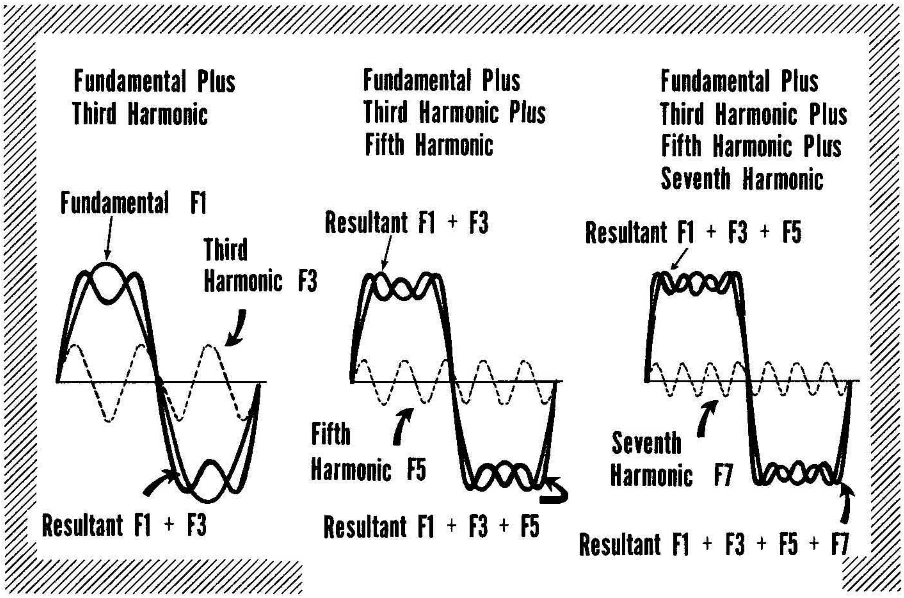
8 It is noted that the shape of a wave observed on the oscilloscope is controlled by the relative amounts of vertical and horizontal amplification resulting from adjustment of the front panel controls. How can one speak of "waveshape" when a "square wave" can be changed into a tall narrow pulse or into a low wide one?

9 Explain why it is generally good practice to use an oscilloscope in conjunction with a vacuum-tube voltmeter when measuring levels of periodic a-c waves.

10 How can the rate of rise and decay of sine waves be defined or assigned values since they vary over the excursion of the wave? Comment on the effect of frequency on rise and decay.

The Composition of Pulses

We have described a great many characteristics associated with the *shape* and *occurrence* of nonsinusoidal waves. However, the *visible* aspects of waveforms are the result of many important properties not discernible separately. A more extensive knowledge is needed to correlate the behavior of pulses with their shape and occurrence.



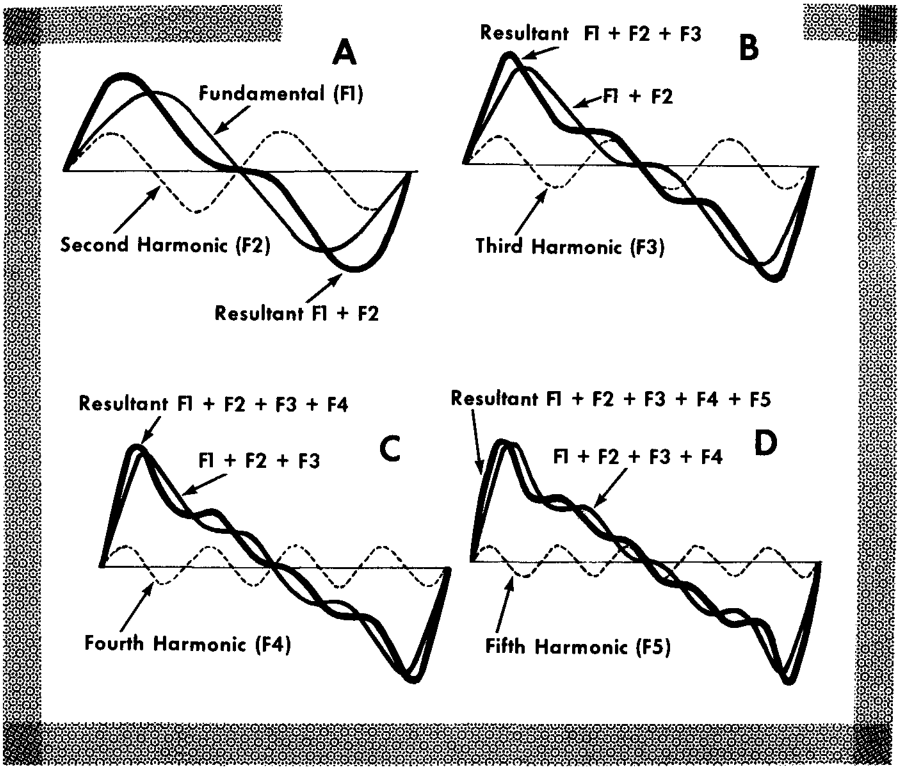
The Composition of a Pulse Waveform from Harmonically Related Sine Waves

The sine wave is unaffected in shape by frequency-selective circuits. All other waveshapes can be distorted by circuits exhibiting partiality in frequency response. The sine wave attains this unique immunity because it consists of *one, and only one,* frequency. Frequencies are not all affected to the same degree by a selective circuit. The effect of such frequency discrimination is to change the *shape* of the nonsinusoid.

What is meant when we say that a nonsinusoid is made up of more than one frequency? How can this be so when an oscilloscope display of such a waveform shows but *one* frequency, the pulse-repetition rate? The figures on this and the next page depict the manner in which a square wave and a sawtooth can be formed by the actual combining of *two or more frequencies.*

The Composition of a Sawtooth Wave

APPROXIMATION OF A SAWTOOTH TYPE PULSE

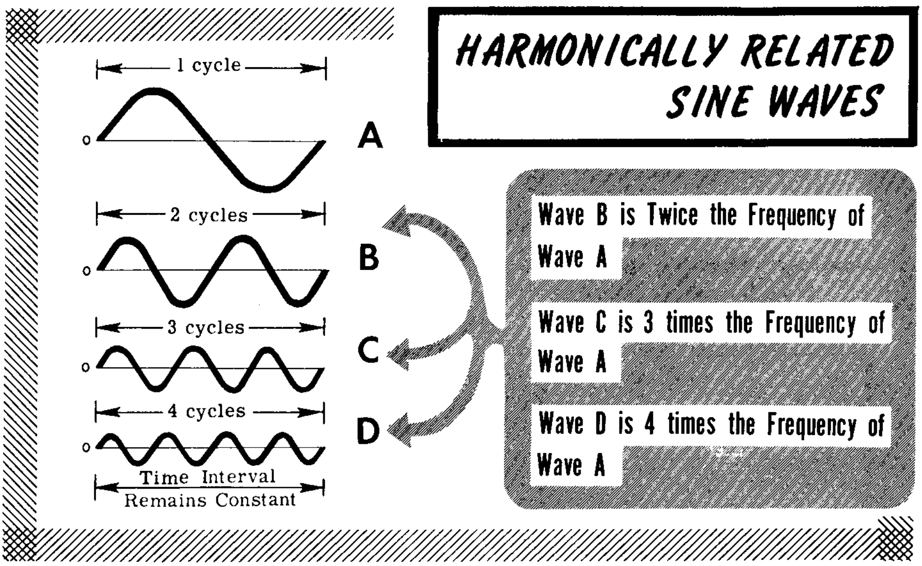


As More Harmonics Are Added to the Fundamental, the Resultant Sawtooth Becomes Smoother.

A sawtooth wave is made up of a fundamental sine wave of given frequency plus an infinite number of harmonics of the fundamental. The sawtooth wave is composed of both odd and even harmonics. As more and more harmonics are added to the fundamental, the peaks are pushed further to the side and the resultant wave comes to resemble the traditional sawtooth shape. This fact becomes apparent in the figure, where harmonics beyond the third have been added to the fundamental waveform.

Fourier Analysis of Periodic Pulses

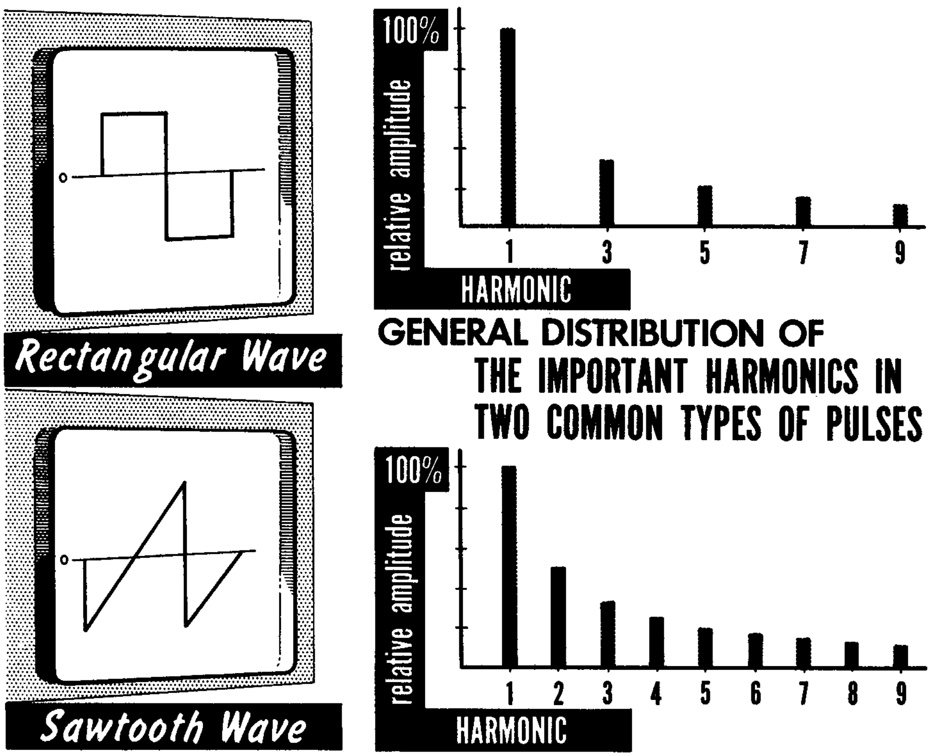
Despite the fact that graphical constructions can be made on paper, it is natural to question whether actual electrical waves having shapes corresponding to those drawn *must* contain such frequencies in addition to their pulse-repetition rates. Indeed, this is the case; *the envelope of the non-sinusoid derives its shape from the mutual effects of two or more frequencies.* The principle underlying the analysis of nonsinusoids was first formulated by the French physicist, Jean Fourier. Fourier's Theorem states that periodic pulses, or nonsinusoids, can be resolved into basic building blocks consisting of harmonically related sine waves. (We will later extend this theorem to embrace aperiodic pulses.) The constituent sine waves must be harmonically related. Our illustrations indicate that nonsinusoids can not possibly be made up of haphazardly occurring frequencies.



In order for a harmonic relationship to exist, frequencies must be related by integral multiplying factors such as 1, 2, 3, 4, 5 . . . etc or 1, 3, 5, 7 . . . etc or 1, 2, 4, 6 . . . etc. Note that the *number one* frequency appears in all three of these sequences. This, we may say, is the first harmonic. Similarly, the frequency which is two times the first harmonic is designated as the *second harmonic.* The number of the harmonic always indicates how many times higher in frequency it is than the first harmonic. The figure above depicts several harmonically related sine waves. The first harmonic has a special significance: it is *the fundamental frequency* to which all other harmonics are geared. It should be kept in mind that the very next order of harmonic after the fundamental is the second harmonic, since the first harmonic is but another name for the fundamental frequency.

Some Implications of the Fourier Theorem

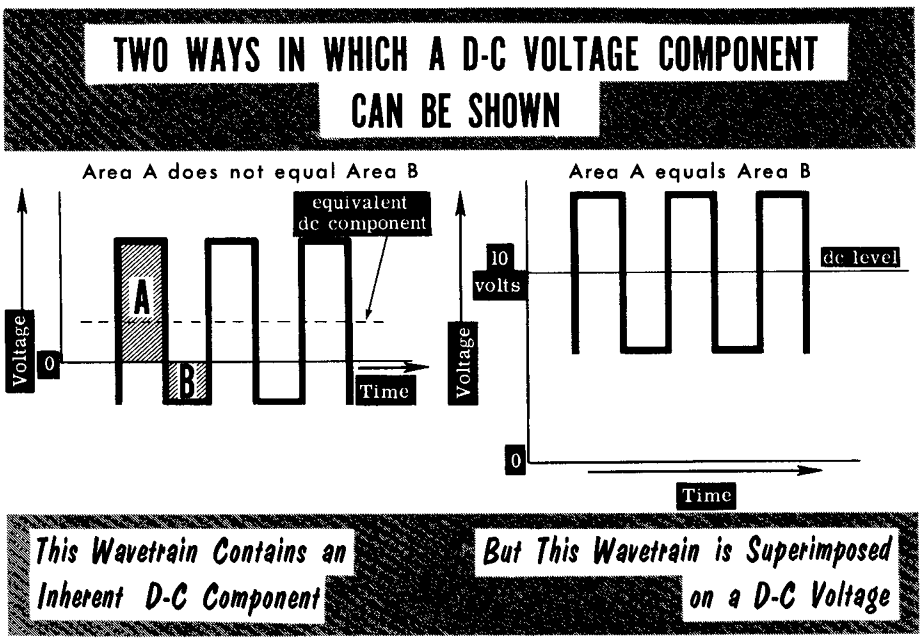
One of the implications of the Fourier theorem is that the fundamental frequency corresponds to the pulse-repetition rate of the periodic wavetrain of pulses. The pulse-repetition rate of a periodic waveform tells us something concerning the constituent frequencies of the waveform. All other frequencies contained in the waveform are simple multiples, or harmonics, of the fundamental frequency. The illustration shows the relative strength of harmonics for two pulse shapes. Note that the rectangular wave contains *no even harmonics* whereas the sawtooth is made up of *both odd and even harmonics* of the fundamental (first harmonic).



The constituent harmonic frequencies which add up to produce the nonsinusoid are, in themselves, pure sine waves. This must be so because the Fourier theorem would enable us to resolve any apparent nonsinusoidal component of a larger nonsinusoid into its own sine-wave constituents. It follows, therefore, that the harmonically related building blocks of nonsinusoids are pure sine waves. An extention of this reasoning tells us, too, that the only frequency present in a sine wave is the *fundamental* frequency; *there are no harmonics associated with a pure sine wave.*

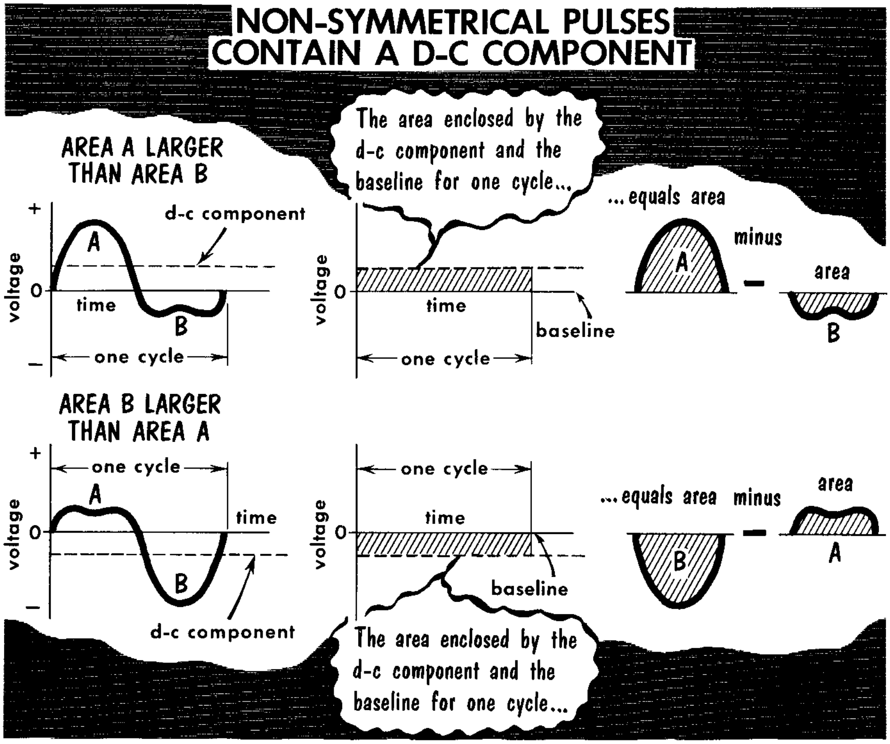
The D-C Component in Periodic Pulse Trains

Thus far we have not mentioned any basic constituent of the nonsinusoid other than the harmonically related sine-wave frequencies. We have stated that the sine wave is the entity from which diverse pulse shapes are built. Often, however, the Fourier theorem is stated in a form which includes another element, the d-c component. It is true that a d-c level may be present in a periodic wavetrain. Let us concern ourselves with *two* ways in which a d-c voltage may manifest itself. If the baseline of a wavetrain of pulses does not divide the positive and negative pulses equally, then one polarity will exceed the other and we will not have a true alternating-current wave. This elicits a net d-c level known as the d-c component, with the average value somewhere between the highest peak value and the baseline. Note that the d-c component is a direct consequence of the waveshape.



Another way in which d-c can be present is by superimposition. In this instance, the baseline of the wavetrain is simply at a d-c potential other than zero. This condition is easily comprehended by imagining a battery inserted in series with a pulse generator. When d-c is superimposed upon a wavetrain, the waveshape is not affected. Even a sine wave can be associated with a d-c voltage in this manner. A superimposed d-c level is not the d-c component sometimes indicated as a constituent of nonsinusoids. The above shows the two different ways in which d-c can be associated with periodic pulses.

The D-C Component in Harmonic Combinations



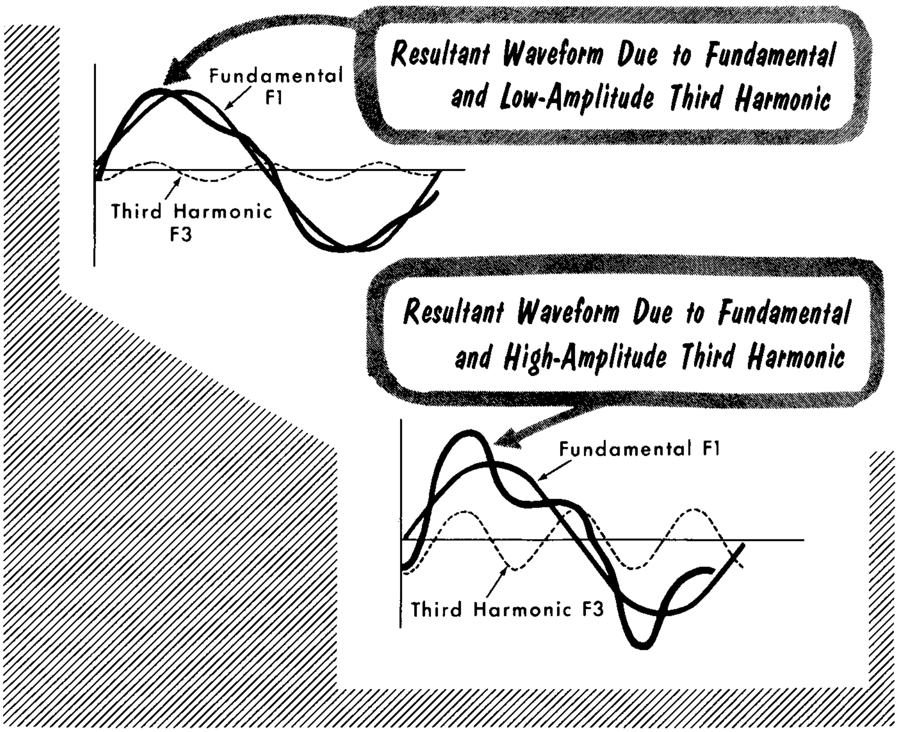
The illustration shows waveforms containing a fundamental and a second harmonic component. In both waveforms there is a net d-c polarization or "d-c component" due to the presence of the second harmonic, which causes the waveform to be nonsymmetrical. The value of the d-c component is such that the area enclosed between it and the baseline, for the duration of 1 cycle of the waveform, equals the difference of area A minus area B or area B minus area A of the composite waveform, depending which area is larger. Therefore the d-c component may be either of positive or negative polarity. Symmetrical waveforms containing the fundamental and the third harmonic frequency component have no d-c component.

We have not cited enough instances to justfy any conclusions from these waveforms. Nevertheless it is true that the properties illustrated demonstrate a rule which can be mathematically deduced from the Fourier theorem. This general rule states that only even harmonics can produce a d-c component, and that odd harmonics do not give rise to a d-c component. Even harmonics are those of the series 1, 2, 4, 6, 8, etc. Odd harmonics, those of the series 1, 3, 5, 7, 9, etc cannot combine to disturb the symmetry of a waveform about its baseline.

Effect of Harmonic Amplitude on Waveshape

We have suggested ways in which a waveshape can be influenced by its constituent harmonically related sine waves. As implied in our discussion of the d-c component, *even and odd harmonics make unique contributions to waveshape.* The relative strength of the harmonics, even or odd, exert a pronounced effect upon the shape of the resultant nonsinusoid.

THE CHANGE OF THE HARMONIC-COMPONENT AMPLITUDE AFFECTS THE SHAPE OF THE RESULTANT WAVEFORM

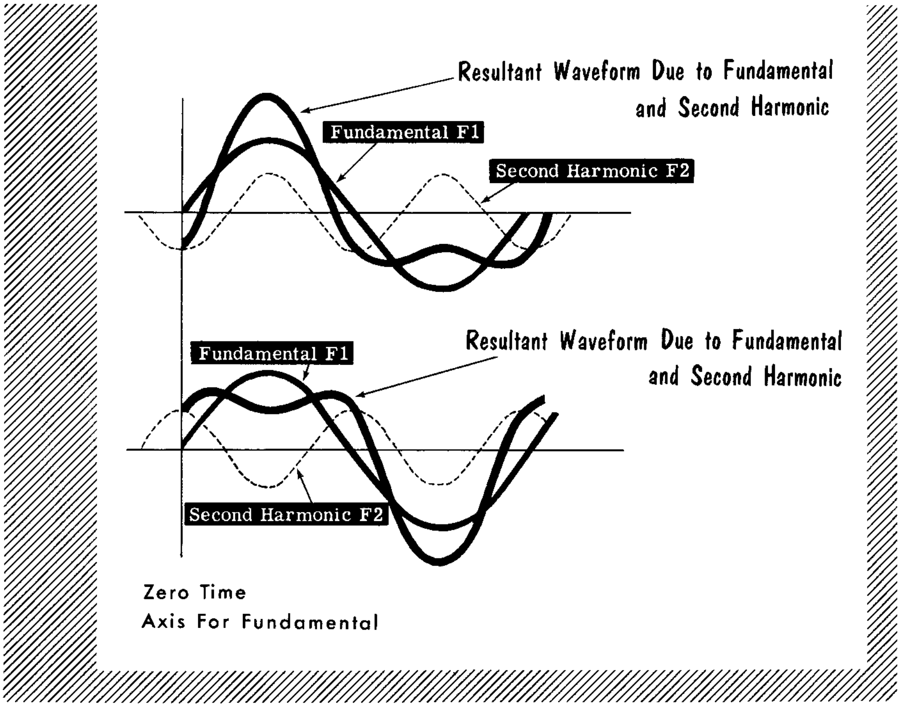


The amplitude of the fundamental frequency in both waveshapes is the same, as is the phasing of the third harmonic. The only difference in the constituent sine waves is the amplitude of the third harmonic. Where the amplitude of the third harmonic is low, there is relatively little distortion of the fundamental sine wave. A high-amplitude third harmonic produces a peaked waveform.

Effect of Harmonic Phase on Waveshape

Another important waveshape-determining factor is the relative phase of the various harmonics, that is, the time relationship between corresponding cyclic variations of the harmonics. For example, if all harmonics start at the same time as the fundamental, they have the same phase as the fundamental. This and the following illustration shows the effect of phase on waveshape. The *frequency* of the harmonics is always synchronized to the *fundamental,* but the *phase* of each harmonic can be independently influenced by *circuitry* conditions. Generally, both the amplitude and the phase of the harmonics are affected by the circuit in which pulses are generated or to which they are applied.

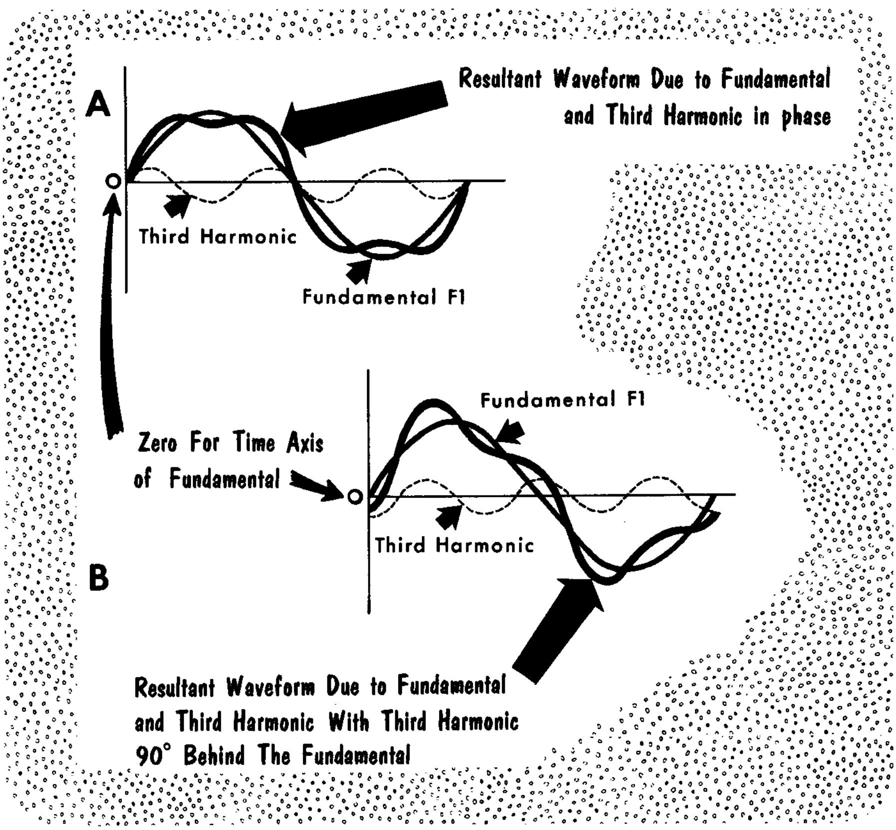
THE RELATIVE PHASES OF THE CONSTITUENT SINE WAVES OF A PULSE WAVEFORM AFFECT ITS SHAPE



We show the constituents of a simple nonsinusoid made up of a fundamental and a second harmonic. The resultant waveshapes owe their differences to the different phase conditions.

Effect of Harmonic Phase on Waveshape (contd.)

Another Example of the Effect of Harmonic Phasing on the Shape of a Pulse Waveform

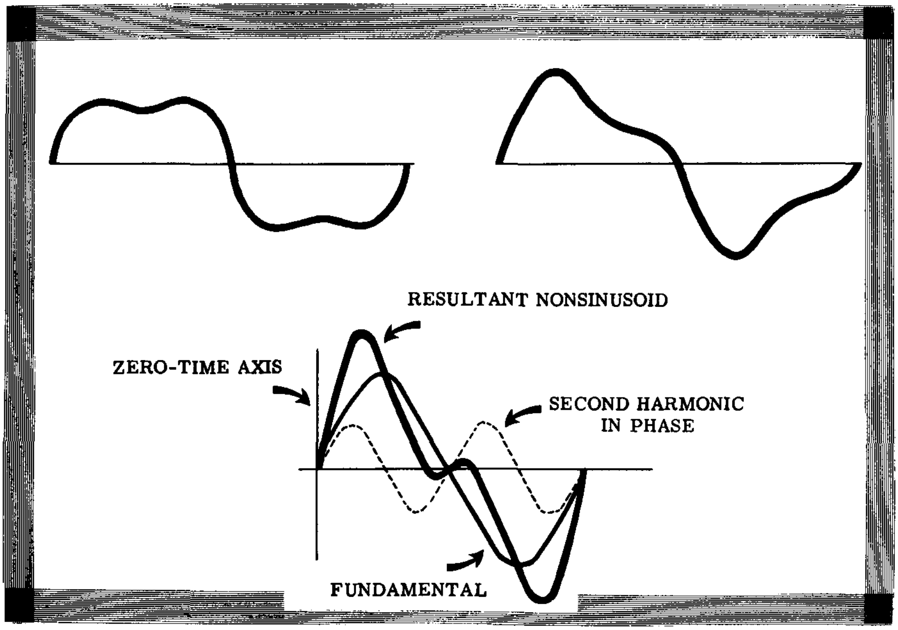


We see the effect of harmonic-wave phase shift on the resultant waveform, in a fashion similar to that shown previously. The fundamental and the third harmonic, rather than the second harmonic, is combined to produce the resultant waveform. The waveform in part A is the first step in the construction of the square wave. Shifting the phase of the third harmonic in relation to the fundamental results in the waveshape shown in part B. This waveform can be recognized as the beginning of the sawtooth.

Waveform Analysis from Types of Wave Symmetry

Much regarding the constituents of a nonsinusoid can be seen by inspecting the waveform for certain conditions of symmetry. We have already dealt with one type of symmetry; zero-axis symmetry. In zero-axis symmetry, the baseline divides the positive and negative portions of the waveform equally.

Waveshapes which are symmetrical about a baseline... usually do not contain even harmonics.

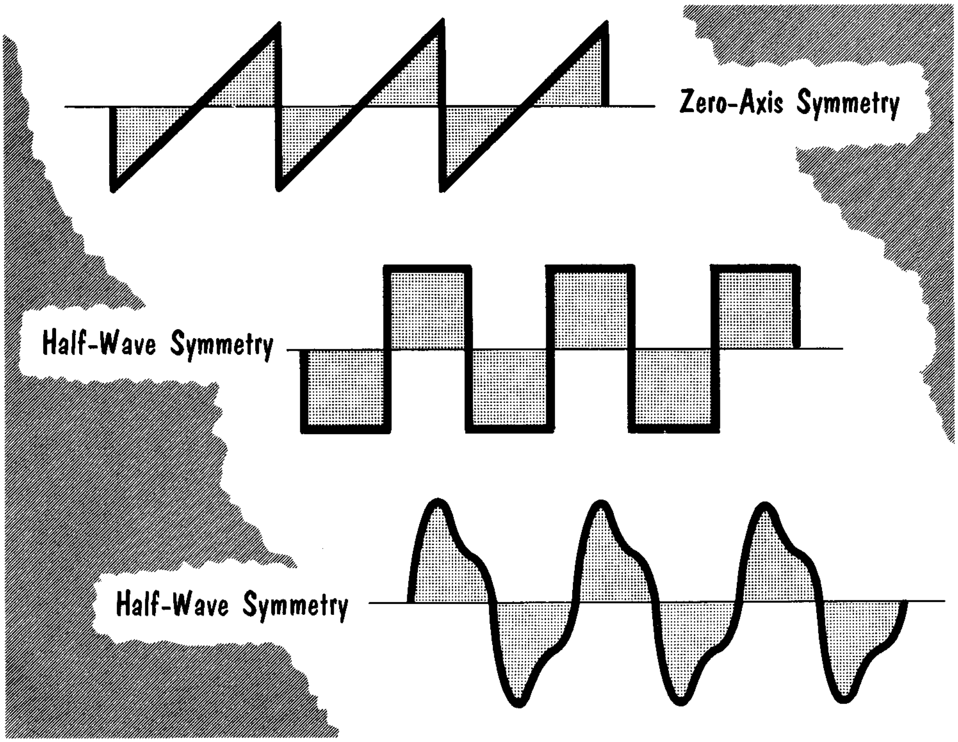


A Phase Condition in Which an Even Harmonic does NOT Disturb Zero-Axis Symmetry or Produce a D-C Component

Zero-axis symmetry always indicates the absence of the d-c component. Generally, this implies the absence of even harmonics. However, there is a phase condition which makes possible the presence of even harmonics without disturbance of zero-axis symmetry, and the resultant appearance of the d-c component. A fundamental and a second harmonic, each with zero phase at the origin, or zero-time axis, are shown. Odd harmonics, no matter what their relative phases, *always* combine to produce *zero-axis symmetry.*

Half-Wave Symmetry

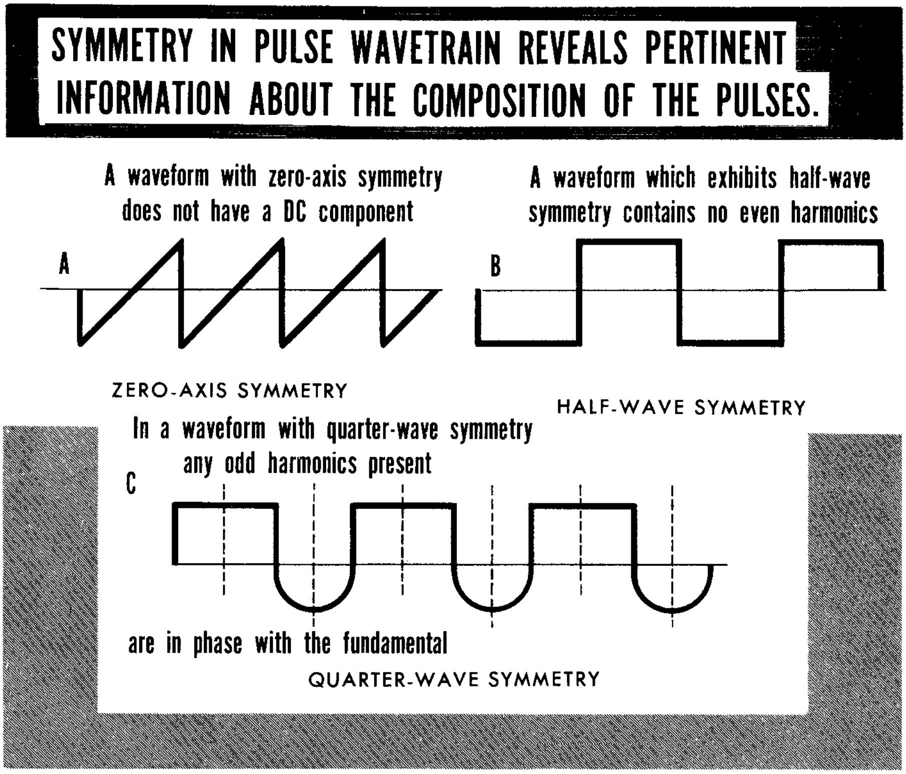
When Half-Wave Symmetry is Present, the Waveform Has no Even Harmonics



Another condition of symmetry which provides useful information concerning the harmonic constituents of a periodic nonsinusoid is the half wave, or *mirror symmetry*. This is established by a vertical line dividing the pulse cycle into two equal portions, identical but transposed from left-right, as is a mirror reflection. The third sawtooth shown has half-wave symmetry. The first sawtooth does not have half-wave symmetry because the leading and trailing edges are not transposed in mirror fashion. Both of these waveforms have zero-axis symmetry. When half-wave symmetry is present, no even harmonics are present. There is no exception to this rule regardless of the phasing of the harmonics.

Quarter-Wave Symmetry

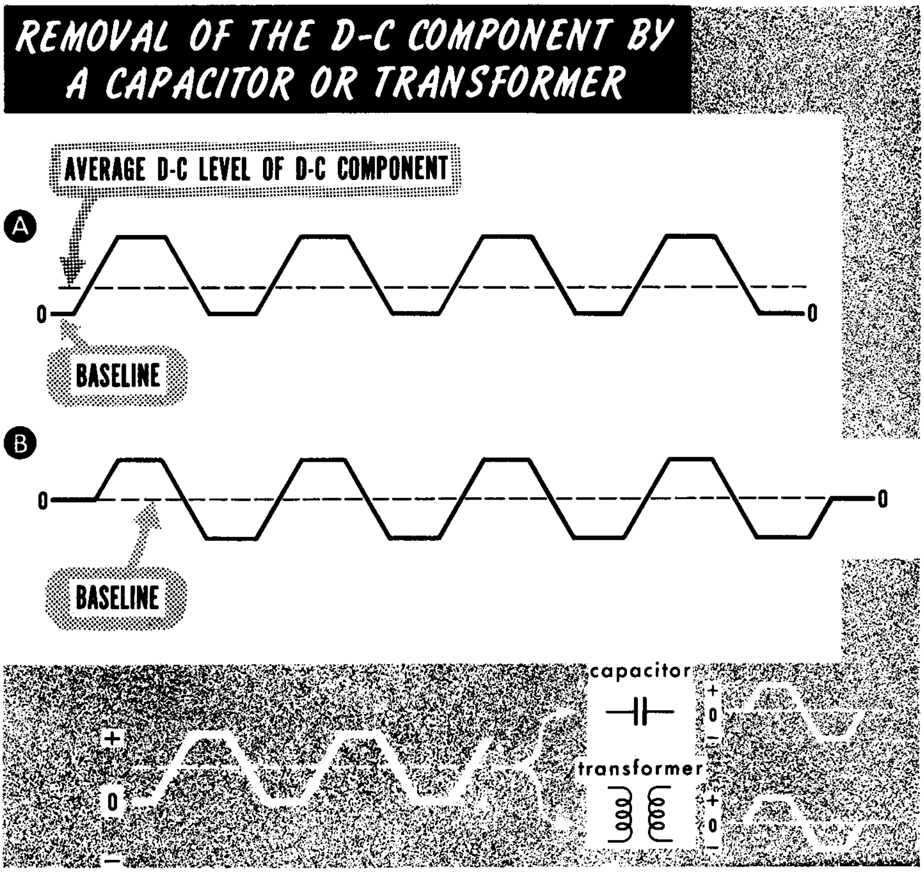
An example of the employment of symmetry as an indication of pulse components is shown. The wave has all three symmetries. The presence of *zero-axis symmetry* excludes the existence of a d-c component. The presence of *half-wave symmetry* informs us that no even harmonics are contained in the wave. The presence of *quarter-wave* symmetry indicates that the odd harmonics are all in phase with the fundamental, that is, they start their cyclic excursions at the zero-time axis along with the fundamental.



A third type of symmetry is that which can be established by an imaginary vertical axis which divides a half-cycle into two identical portions. An example of this kind of symmetry (quarter-wave symmetry) is shown in part C. Even harmonics always produce this symmetry. Odd harmonics produce quarter-wave symmetry only when they are at zero phase along with the fundamental. Part C of the illustration shows this phasing condition. The quarter-wave symmetry does not exist for the odd harmonic wave in part B. Despite the presence of even harmonics, if odd harmonics are present, quarter-wave symmetry will generally not exist.

Removal of the D-C Component by Circuitry

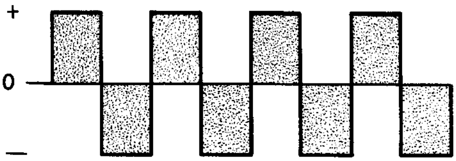
When a wavetrain of pulses has been passed through a capacitor or through a transformer, a definite output waveform evaluation is possible regardless of the composition of the impressed wave. The wave emerging from either of these components *will never contain a d-c component* because neither the capacitor nor the transformer will pass steady-state d-c. They respond to amplitude changes, not to sustained levels. We see the removal of the d-c component from a waveform due to passing capacitors and transformers.



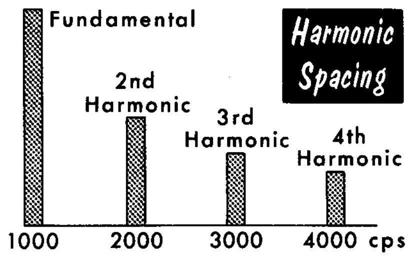
Part A of the figure shows the waveform at the input of a capacitor or across the primary of a transformer. Part B shows the waveform at the opposite plate of the capacitor or across the secondary winding of the transformer. It is assumed that the size of the capacitor and the characteristics of the transformer are such that no waveshape modification other than removal of the d-c component results.

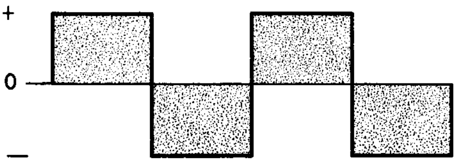
Decreasing the Pulse-Repetition Rate to Zero

THE CONSTITUENT HARMONICS OF THE PULSE TRAIN ARE SPACED CLOSER AS THE REPETITION RATE DECREASES

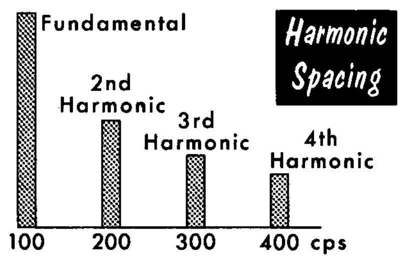


1000 Pulses per Second





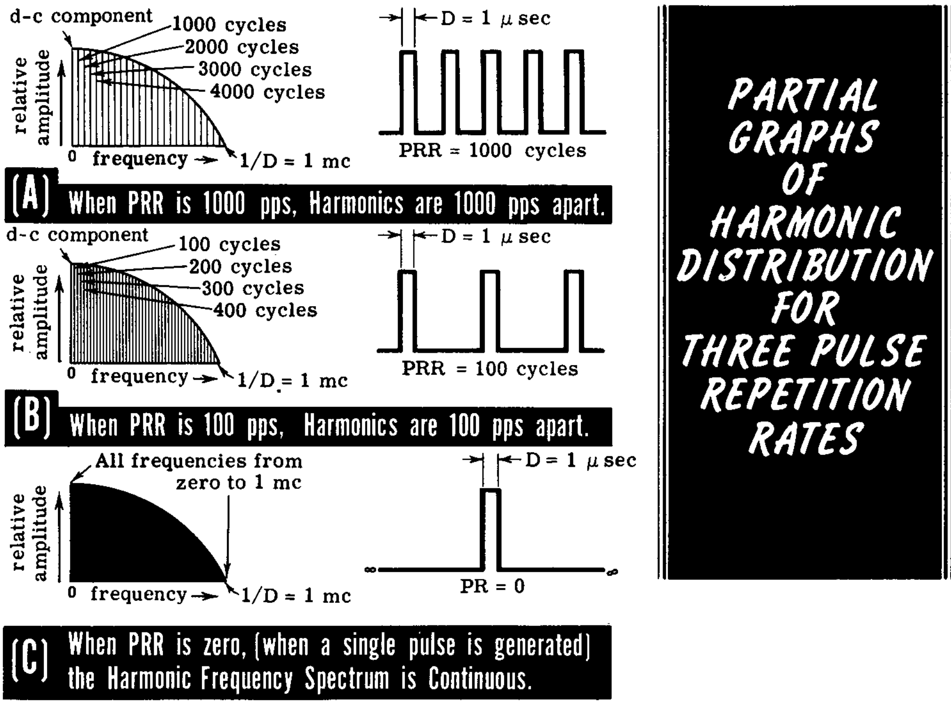
100 Pulses per Second



A periodic wavetrain of pulses can be made up of a fundamental frequency and a number of harmonics. When the pulse-repetition rate is high, the spacing between the adjacent harmonics is greater than when the pulse-repetition rate is low. For example, a periodic pulse train having a pulse repetition rate of 1000 pulses per second: the harmonic frequencies are integral multiples of the fundamental, consequently the frequencies comprising the waves are 1000 cycles, 2000 cycles, 3000 cycles, 4000 cycles, and so on. Note that the constituent frequencies of this pulse train are each spaced 1000 cycles from one another. Suppose now that we lower the pulse-repetition rate to 100 pulses per second, but still maintain the same pulse-shape and dimensions. The wavetrain of pulses now comprises the decreased fundamental frequency of 100 cycles and its series of harmonics, 200 cycles, 300 cycles, 400 cycles, etc. For the lower repetition rate, the constituent frequencies are spaced by 100 cycles rather than 1000 cycles as in the case of the higher pulse-repetition rate.

Decreasing the Pulse-Repetition Rate to Zero (contd.)

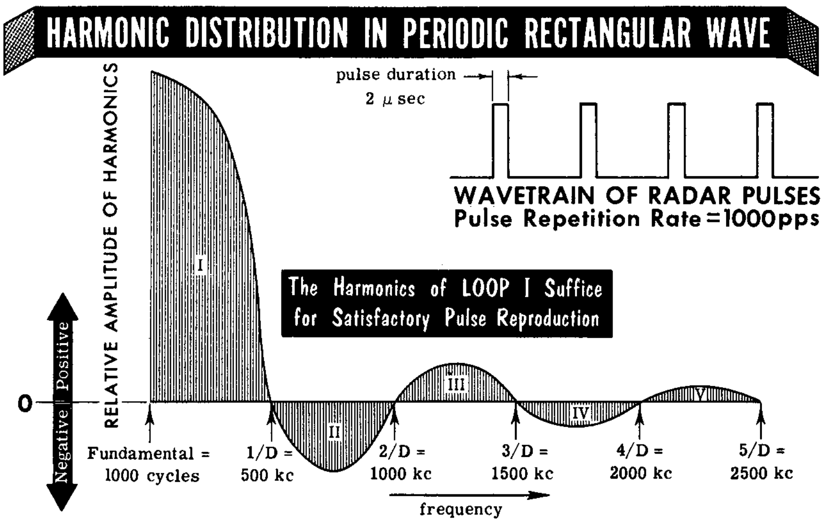
The physical significance of zero pulse-repetition rate is that it is in actuality a single isolated pulse. The harmonic constituents of a periodic wave-train of pulses are spaced closer together as the pulse-repetition rate is lowered. The harmonic spacing in the ultimate case of *zero* pulse-repetition rate may not be so obvious. However, for the single isolated pulse, the frequencies composing it are present in a continuous spectrum, and we no longer can speak of its fundamental or its harmonics. Thus, the repetitive pulsing of a waveform is, in essence, a *modulation technique* which imparts spaces in what would otherwise be a continuous spectrum of frequencies.



The concept of the single isolated pulse can be useful even if we are dealing with periodic waveforms. An example of this is found in radar practice when steep-sided rectangular pulses are generated. A true rectangular pulse with vertical leading and trailing edges cannot be formed, because *no* circuitry will provide uniform response to the infinite number of harmonics required by this waveshape. It is important, however, that the good approximation of a perfect rectangular pulse which is actually formed be reproduced with acceptable fidelity. The degree of excellence involved in acceptable fidelity must necessarily vary with the application for which the radar is designed.

Harmonic-Distribution Graph of a Periodic Wave

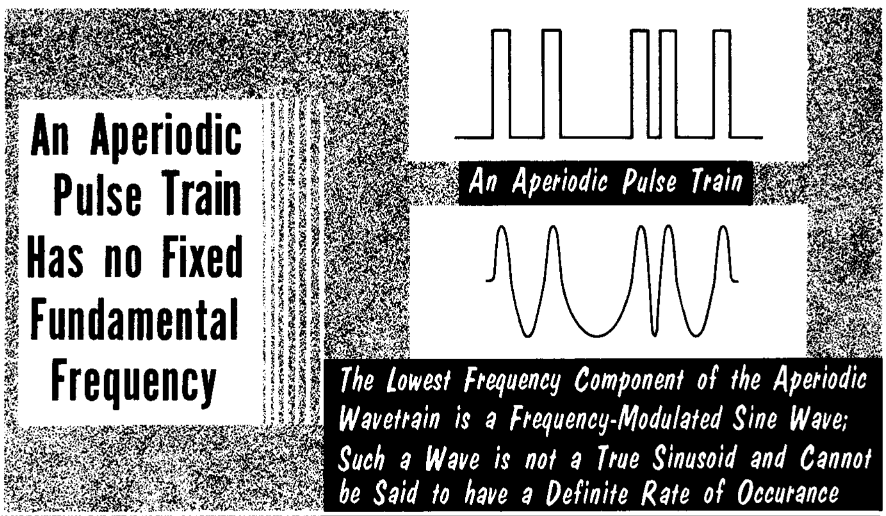
The graph represents the harmonic distribution of a periodic rectangular pulsetrain with a pulse-repetition rate of 1000 pulses per second, and a pulse duration of 2 μ sec. This graph enables us to determine the response required of pulse circuitry to reproduce the pulses without severe distortion. Note that the preponderance of the area of this graph is contained under the first large loop. This loop embraces the fundamental and harmonics up to frequencies equal to the reciprocal of the pulse duration. When the duration is a small fraction of the pulse interval, as in radar, there are many harmonics in each loop of the distribution curve. Note that the curve crosses the zero axis of the graph at 1/D, 2/D, 3/D, etc., where D represents the pulse duration. The area embraced by the first loop is much greater than the areas under the other loops. This implies fairly good pulse response, if we disregard all harmonics higher than the simple reciprocal of the pulse duration, that is 1/D.



The reciprocal of the pulse duration in our example is ½ μ sec, or 500,000 cycles. From this we conclude that a circuit providing a bandpass throughout the range of 1000 cycles to 500,000 cycles should yield a fairly good reproduction of the rectangular pulses. The *high-frequency* end of this bandpass is *independent of the pulse-repetition rate.* It is determined only by the *pulse duration.* This is true in wavetrains in which pulse duration is a very small fraction of pulse interval, and usually occurs in pulse-radar systems. If pulse duration and pulse interval are similar, the pulse-repetition rate governs the high-frequency response required for preservation of pulse shape.

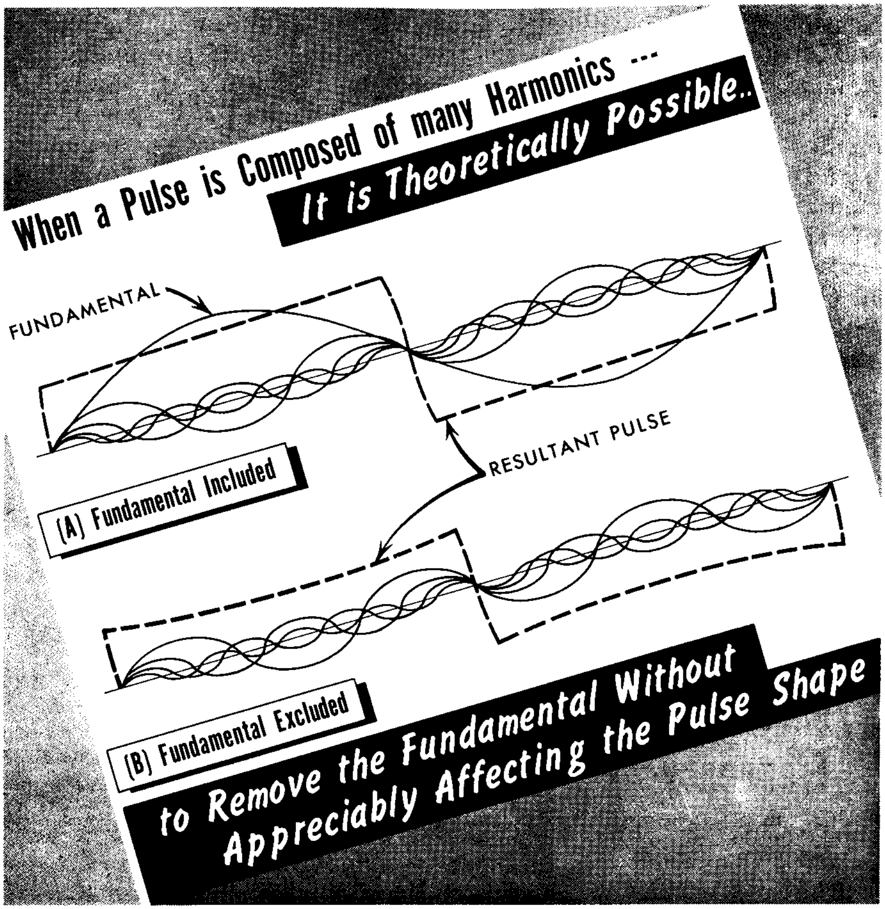
An Aperiodic Pulse-Repetition Rate

Since the aperiodic wavetrain is characterized by *on* and *off* states, a similar modulation effect to that existing in periodic waves prevails. That is, we find spaces in the spectrum of the constituent sine-wave frequencies. On the other hand, there being no fixed fundamental frequency, it cannot be possible to assign actual frequencies to the harmonics. The spaces between harmonics and the harmonics themselves constantly change. Although the Fourier theorem remains valid, its practical value is virtually nil if the aperiodic pulse train is extremely random. However, regardless of the erratic shifting of harmonic frequencies due to the aperiodic occurence of the pulses, the relative distribution of harmonics remains the same as long as the pulse envelope does not change. For example, the third harmonic will be perhaps twice the strength of the fifth harmonic no matter whether the temporary rate of pulse occurrence is fast or slow.



Let us now consider the occurrence of a single pulse. After this pulse has ceased to exist, there is a shock excitation of briefly enduring transient oscillations. However, after circuit conditions have quieted down, let there be an occurrence of a *second* pulse. It does not matter whether the two pulses are spaced by a *minute,* a *month,* or a *year,* as far as the quality of reproduction of the second pulse is concerned. The "pulse-repetition rate" effects the low-frequency bandwith requirement of narrow pulses such as are employed in radar, but not the high-frequency response necessary to yield good pulse reproduction. No matter what the pulse rate is, the large area of the spectral distribution graph contains those harmonics from the first (the fundamental) to the harmonic corresponding to the reciprocal of the pulse duration.

The Fundamental Waveform in Fact and Theory



The importance of high-frequency harmonics is based upon their contribution to the area under the graph of harmonic distribution. Applying this concept to the harmonics in the low-frequency region of the required bandpass, we can eliminate the fundamental frequency and scarcely effect the area under the curve. Our rectangular wavetrain of periodic pulses is not adversely affected by rejecting the fundamental. Many lower-frequency harmonics may be eliminated by the same reasoning. There must be a "fictitious" fundamental, if not an actual one: if we have a nonsinusoid comprised of the third, fifth, seventh, and ninth harmonic, all of these harmonics are multiples of a fundamental, whether present or not. In most cases, the fundamental frequency will be present, and for this reason the Fourier theorem commonly includes the fundamental as a building block of pulses.

QUESTIONS

A simplified form of the Fourier harmonic-composition equation is
$C = C_0 + C_1 + C_2 + C_3 + C_4 + C_5 \ldots\ldots$ etc
where C is the rms value of the periodic a-c wave
where C_0 is the value of the d-c component
where C_1 is the rms value of the first harmonic (the fundamental)
and similarly, where C_n would be the rms value of the n^{th} harmonic.

1 A balanced push-pull amplifier cancels even distortion generated by tube nonlinearity. However, odd distortion does not cancel. Modify the simplified Fourier equation to apply to the wave monitored across the secondary winding of the output transformer associated with a push-pull amlifier. A single frequency sine wave is impressed at the amplifier input.

2 An ideal single-phase full-wave rectifier produces only even distortion, assuming the impressed a-c wave is sinusoidal. Modify the simplified Fourier equation to describe the waveform resulting from such a circuit.

3 The waveform from the full-wave rectifier above is passed through a filter providing very high attenuation for the fundamental and harmonic frequencies. Express the result in terms of the simplified Fourier equation.

4 The terms in the simplified Fourier equation cannot be added arithmetically, but must be combined under the square root sign. Thus, if we are interested in the *net* quantitative effect of the harmonics, the Fourier equation is used in the following form:

$$C = \sqrt{(C_0)^2 + (C_1)^2 + (C_2)^2 + (C_3)^2 + (C_4)^2 + (C_5)^2 \ldots} \text{ etc}$$

where the terms have the same significance as in Question 1
What is the rms value of a wave in which the frequency components are d-c component = 0; fundamental frequency = 10 v; second harmonic = 5 v; third harmonic = 3 v; fourth harmonic = 2 v; fifth harmonic = 1 v;

5 It is possible to express the values of the various Fourier terms in peak as well as rms values, the only requisite being consistency. If rms values are used, they should be used for all terms involved; similarly peak values should be used for all terms involved. Prove that the solution to problem of Question 4 is valid for harmonics expressed in peak values.

6 Show that harmonics which are less than about one-quarter of the strongest harmonic present in a wave will not greatly affect the amplitude of the resultant wave.

7 A wave which contains a d-c component from even harmonic distortion and is also rich in odd harmonics is passed through a video amplifier with an open diode in the d-c restorer circuit. Represent the emergent wave in terms of the Fourier equation (Question 1)?

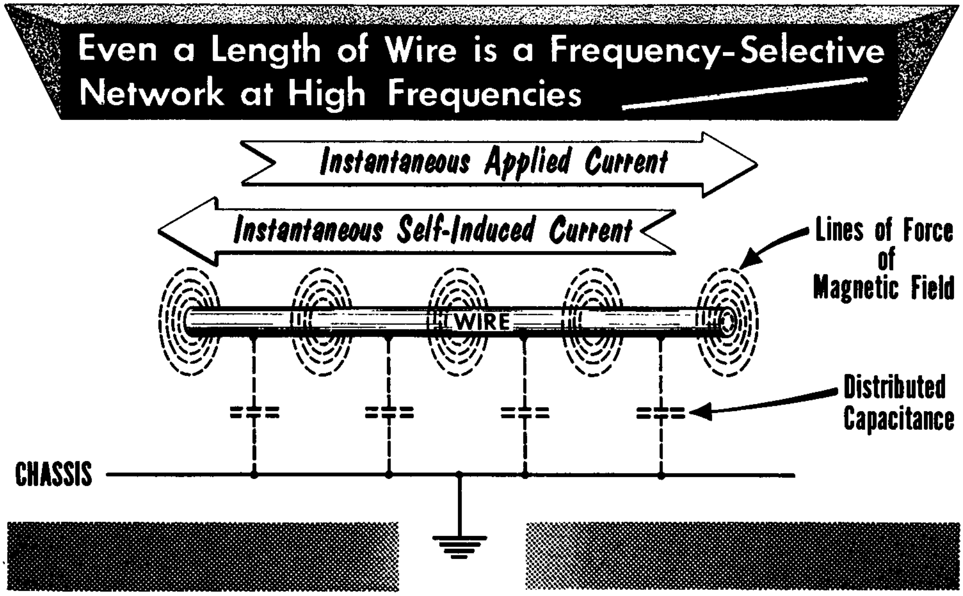
8 What are some of the frequencies on which interference could be caused by a transmitter tuned to 2.0 mc.?

9 The input level to a class A amplifier is gradually increased. A point is reached where the plate current suddenly changes from its quiescent value. What is the predominant order of distortion indicated?

10 A periodic sinusoidal wave is applied to the input of a binary-type multivibrator circuit. The wave derived from the binary has half the frequency of the applied signal. How can this be reconciled with the Fourier equation? Is a harmonic term of $\frac{1}{2}$ C_1 indicated? Explain.

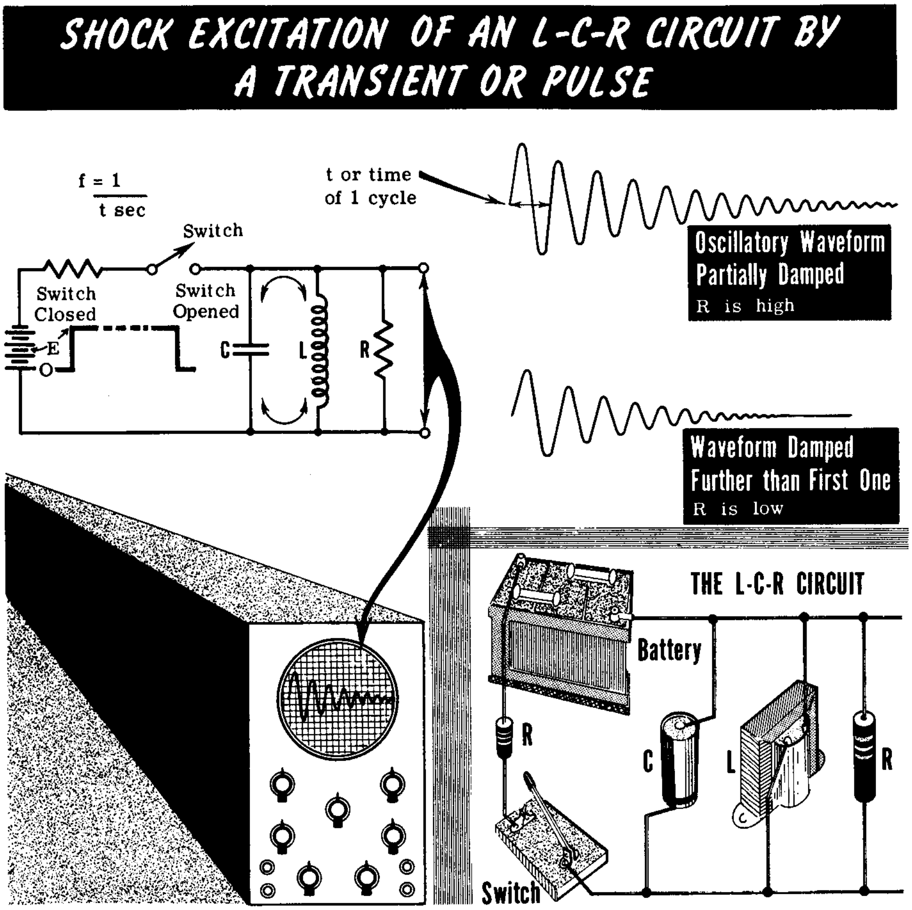
Pulses in Frequency-Selective Circuits

We have discussed the important fact that pulses are made up of more than one frequency. In a circuit in which uniform response is accorded the important harmonics of a pulse, the pulse shape will be substantially preserved. Conversely, a circuit displaying partiality in response to the constituent frequencies involved in pulses will distort or modify the shape of the pulses. Now we consider the nature of the changes imparted to waveshapes by frequency selectivity. Although some pulses and some circuits are so related that negligible distortion of pulse shape occurs, it is generally necessary to give attention to circuitry arrangements to bring this condition about. It is also necessary to adapt circuitry to waveform for deliberate changes in pulse shape.



All practical electric circuits, even simple ones of point-to-point connections, are in reality complex networks. Even a length of wire possesses the three circuit parameters: resistance, inductance, and capacitance. We may have conditioned ourselves to think of these stray or distributed parameters as negligible. However, pulses commonly involve high frequencies. Short durations and near-vertical edges are formed by the Fourier addition of a great many high order harmonics. At these high frequencies, the small self-inductance of a length of wire or the small capacitance between the wire and the chassis are as significant as their physical counterparts employed at lower frequencies. As a matter of fact, the pulse circuit cften must be designed and adjusted to impart the desired response to both very low and very high frequencies.

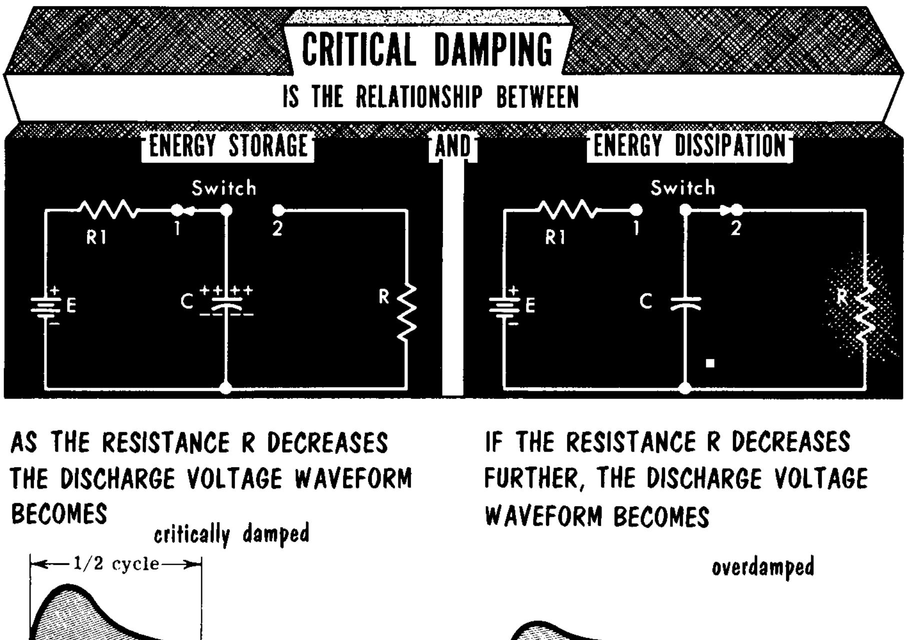
Shock-Excited Oscillation in an L-C-R Circuit



Although the stray parameters, as well as the parameters of actual physical components, combine in complex ways, we can study the effect of pulses in circuitry by seeing what happens in an L-C-R circuit composed of these elements in parallel. We see a bench set-up in which a sharp wavefront is impressed upon the parallel combination of L, C, and R. In the first waveform, R is extremely high, or even absent. When the switch is suddenly opened, the applied voltage abruptly changes from a finite value to zero. Surprisingly, however, the voltage across the L-C-R circuit does not simply *fall* to zero. Rather, it *oscillates* for many cycles, the amplitude of each cycle being less than the one which preceded it. The frequency of oscillation is the *resonant* frequency of L in conjunction with C. This is *not* a violation of the law of conservation of energy.

Shock-Excited Oscillation in an L-C-R Circuit (contd.)

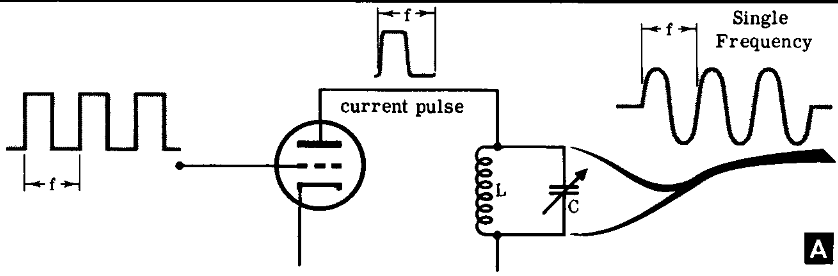
The oscillatory wave derives its energy from that stored in the capacitor and inductor while the switch was in its *on* position. When the switch is *off*, the stored energy undergoes a cyclic exchange between the capacitor and inductor. As the current flows from capacitor to inductor, and back again, energy is lost in the resistance of the circuit. This resistance consists of physical resistor R, plus the inherent resistance in any conductor or component. The energy loss is responsible for the continuously diminishing amplitude of successive cycles. Ultimately, all of the originally stored energy is dissipated as heat in circuit resistance, and the oscillations cease. The lower the value of resistance R, the more quickly the energy is spent.



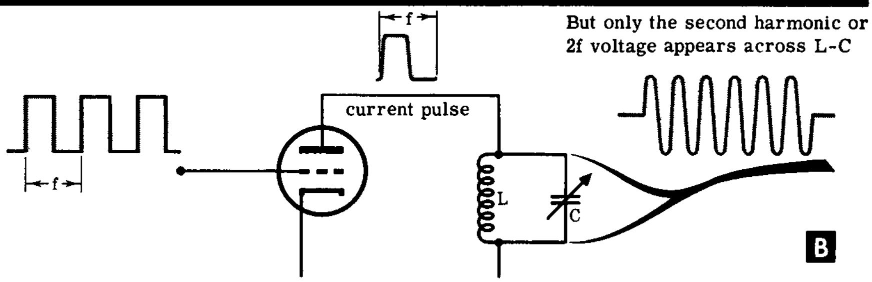
At a discrete value of R (or of R in conjunction with the inherent resistances of both the capacitor and inductor), the oscillation is restricted to a single half-cycle. This unique relationship between energy storage and energy dissipation is called *critical damping*. The wavetrain of many cycles resulting from values of R higher than that corresponding to critical damping is due to *under-damping*. Conversely, the distorted half-cycle excursion resulting from values of R lower than that corresponding to critical damping is said to be an *overdamped* condition.

Sustained Oscillations — Fundamental and Harmonic

An L-C Circuit Resonated at the Pulse-Repetition Rate Removes Harmonics above the Fundamental Frequency



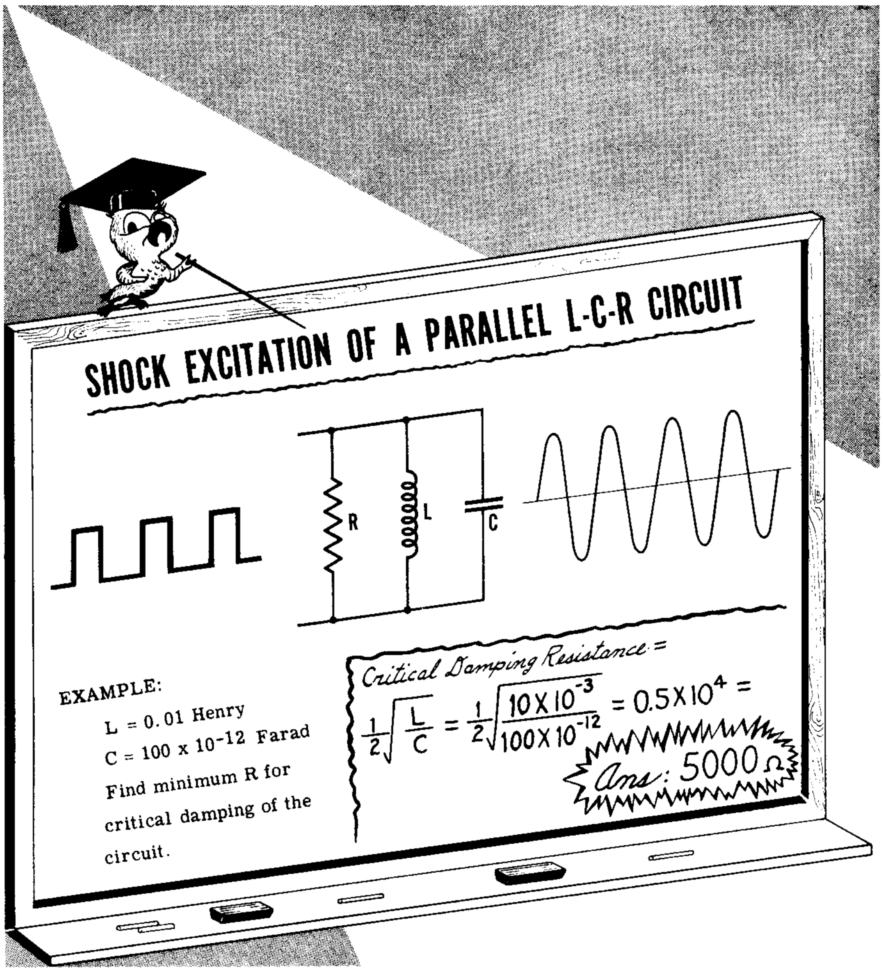
A Frequency Multiplier is Obtained by Resonating the L-C Circuit at the Frequency of One of the Harmonics of the Pulsetrain Applied to the Tube



The phenomena of shock excitation is called *ringing*. In many instances ringing is useful. If the natural ringing frequency is the same as, or is a harmonic of, the exciting pulses, the ringing may not die down, but may be sustained. The partial schematic diagram shows a class-C radio-frequency amplifier in a transmitter. The L-C tank circuit is continuously excited by strong pulses. These pulses, repetitive at the ringing frequency, synchronize with the shock-excited oscillations and produce a sustained oscillatory current in the L-C circuit. This oscillatory current is at the *fundamental frequency (f)* of the exciting pulses. It is a sine wave because the harmonics of the fundamental are relatively ineffective in causing current flow in an L-C circuit not resonated at their frequencies. The same principle holds true in the partial schematic of the frequency-multiplier shown in diagram B, above. In this case, the L-C circuit is resonated at a *harmonic* of the exciting pulses. As with the "straight through" class-C amplifier, sustained ringing is produced at the resonant frequency of the L-C circuit. Similarly, the oscillation is sinusoidal. Neither the fundamental nor the harmonics higher in frequency than the one corresponding to resonance of the L-C circuit can provoke appreciable response of their respective frequencies in the resonant L-C circuit.

PULSES IN L-C-R CIRCUITS

Conditions for L-C-R Circuit Oscillation



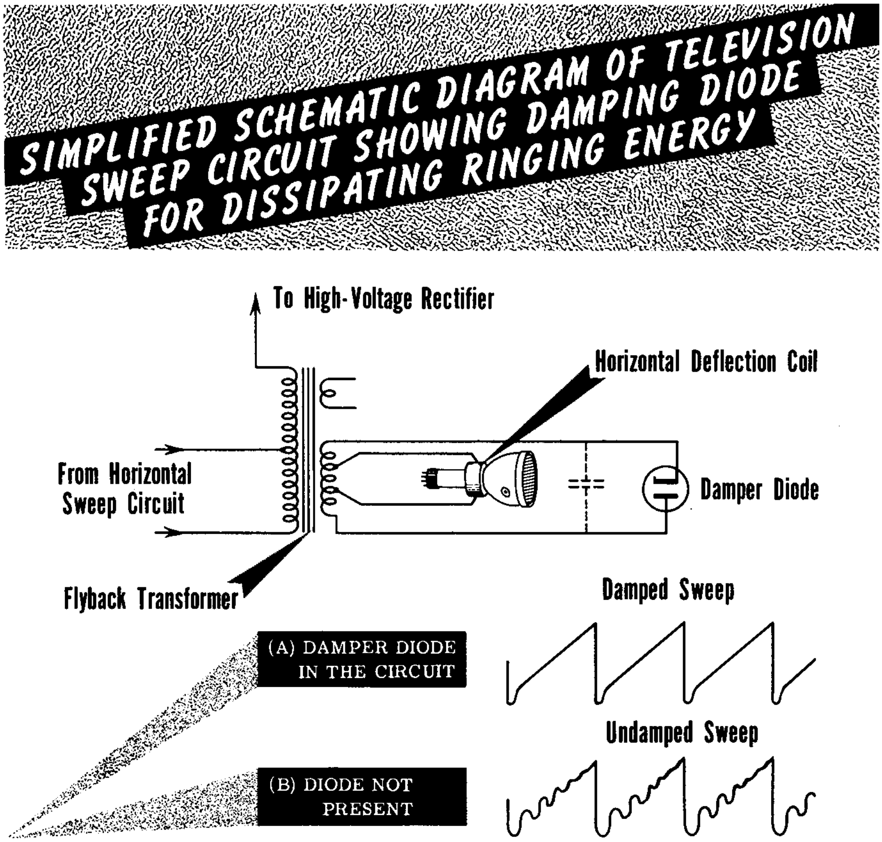
Question: A parallel L-C-R circuit is subjected to steep pulses. How can we know whether or not oscillations will be shock excited.

Answer: *Condition 1.* When R is greater than $1/2\sqrt{L\ C}$, oscillations will be produced by the pulses.

Condition 2. When R is equal to $1/2\sqrt{L\ C}$, oscillations will not be produced by the pulses. This is the condition of critical damping. Also, the Q of the circuit is equal to 1/2 at this time.

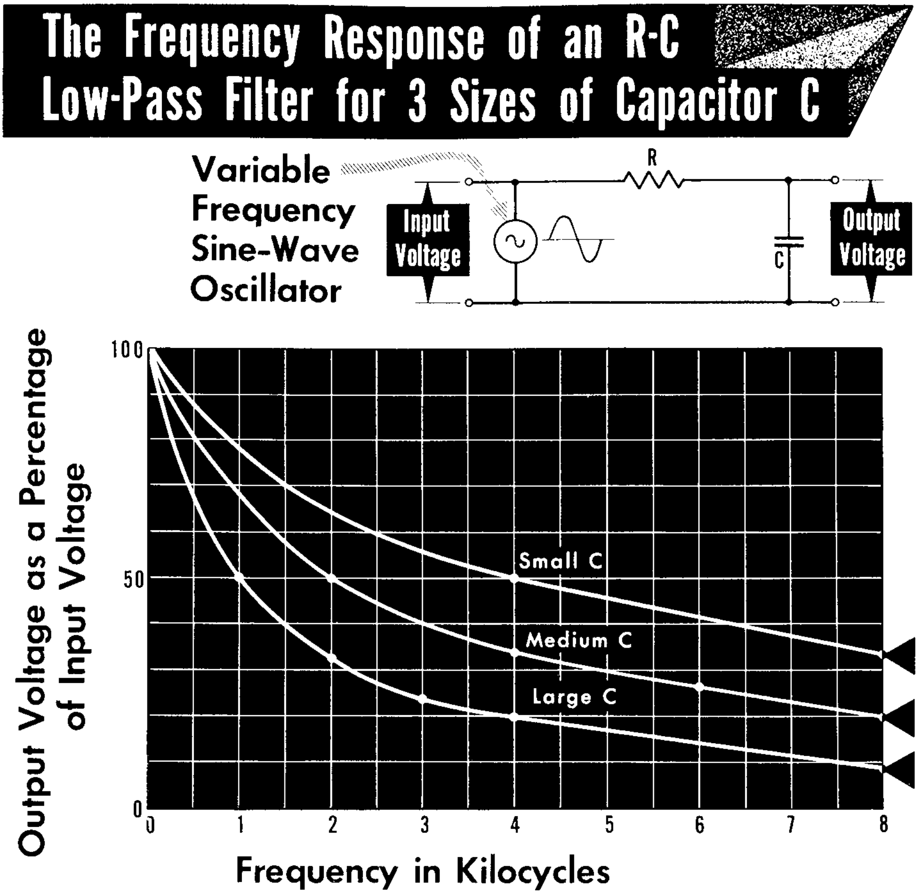
Condition 3. When R is less than $1/2\sqrt{L\ C}$, oscillations will not be produced by the pulses and the amplitude of the excited oscillation will be less than in condition 2. This is the overdamped condition.

Diode Damping of Unwanted Oscillations



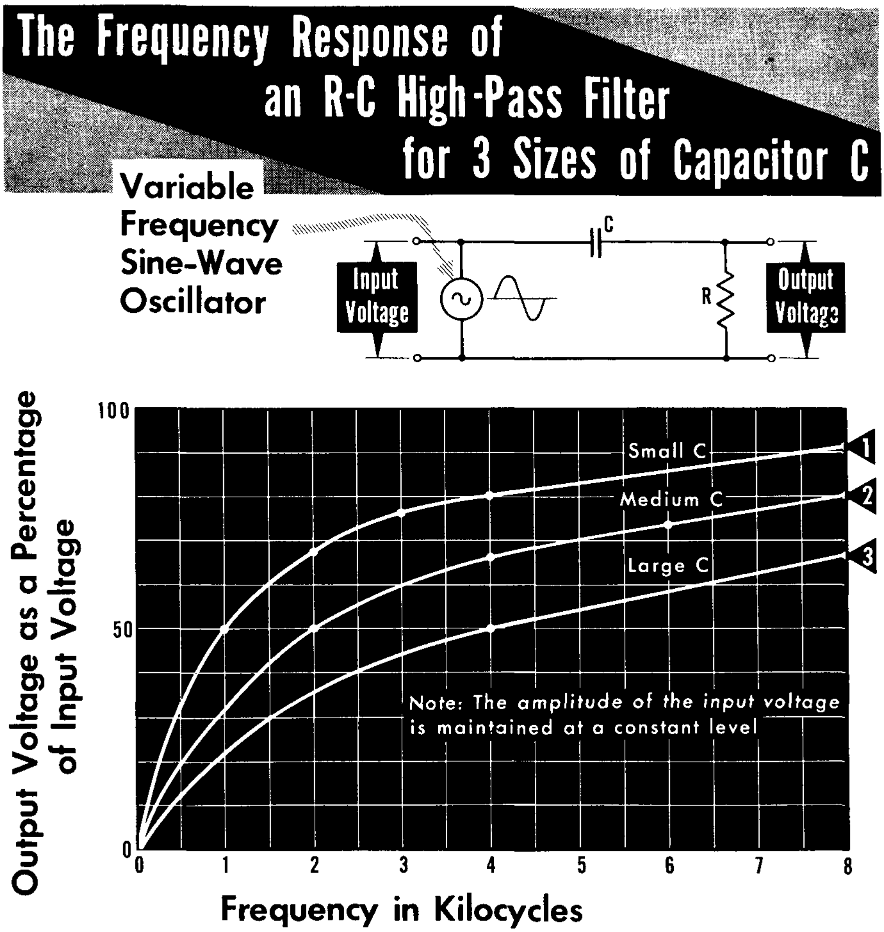
Ringing is often an undesired circuit response, and remedial measures are required to prevent it from causing equipment malfunctioning. When other considerations permit, it sometimes is helpful to insert resistance in order to increase the damping of the stray parameter oscillatory circuit. In some instances, the addition of capacitance or inductance shifts the resonance to a range which is attenuated by other circuit characteristics. When possible, considerable reduction of ringing amplitude is generally brought about by slowing the rise and decay times of the pulses which provoke the ringing. When the function of the circuit would be impaired by these remedies, a very effective damping technique is provided by a diode. The diode is polarized to pass current in the direction opposite to that of the desired pulse. The energy which otherwise would manifest itself as a wavetrain of shock-excited oscillations is dissipated in the diode. The figure shows this application as it is commonly found in television receivers.

Frequency Response of a Low-Pass R-C Filter



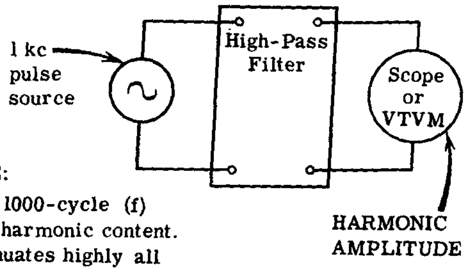
The ringing produced by shock excitation of stray capacitance and stray inductance is generally of a frequency high with respect to the pulse-repetition rate. Another aspect of pulse generation and reproduction concerns the response at frequencies nearer to the pulse-repetition rate than are the ringing frequencies. Such response is usually governed by the cummulative effects of resistance and capacitance. We now consider the frequency response of the simplest resistance-capacitance combinations consisting of one resistance and one capacitance. The arrangement depicted allows unimpeded passage of d-c, little attenuation to low frequencies, but increasingly greater attenuation as the frequency is increased. It behaves essentially as a low-pass filter. Frequency-response curve 1 of the graph represents the response with the smallest capacitor. Curve 3 depicts the response with the largest capacitor.

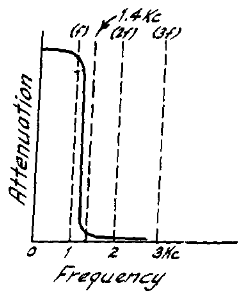
Frequency Response of a High-Pass R-C Filter



By transposing the R and C elements of the simple network discussed on page 58, we obtain a network with opposite frequency-response characteristics. The network permits relatively easy passage to high frequencies, but increasing attenuation to lower frequencies; i.e. we have a high-pass filter. As the input frequency to the R-C high-pass filter increases, the reactance of the capacitor becomes less and the output voltage increases in amplitude. As shown in the accompanying figure, an increase in the size of the capacitor, C, extends the frequency response of the R-C high-pass network for a given input frequency. Curve 1 represents the frequency response of the R-C filter for a certain size of capacitor. Curves 2 and 3 represent the frequency response for increasing sizes of C. In all cases, the voltage amplitude of the input frequency remains the same.

MEASURING HARMONICS WITH A HIGH-PASS FILTER





EXAMPLE:

Evaluate a 1000-cycle (f) source for harmonic content. Filter attenuates highly all frequencies below 1.4 kc.

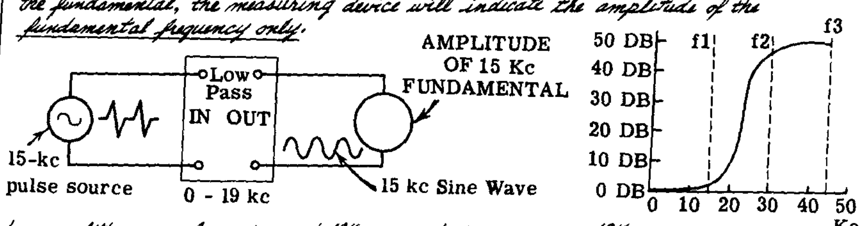
ANSWER: Indicated voltage V is the rms value of combined harmonics (2f, 3f, 4f, 5f, etc.) $V = \sqrt{(V_2)^2 + (V_3)^2 + (V_4)^2 + (V_5)^2 \text{ etc.}}$

The Pure Fundamental Frequency of a COMPLEX WAVE can be Separated with a LOW-PASS FILTER

Measuring the Fundamental

It remains to measure the "pure" fundamental frequency.

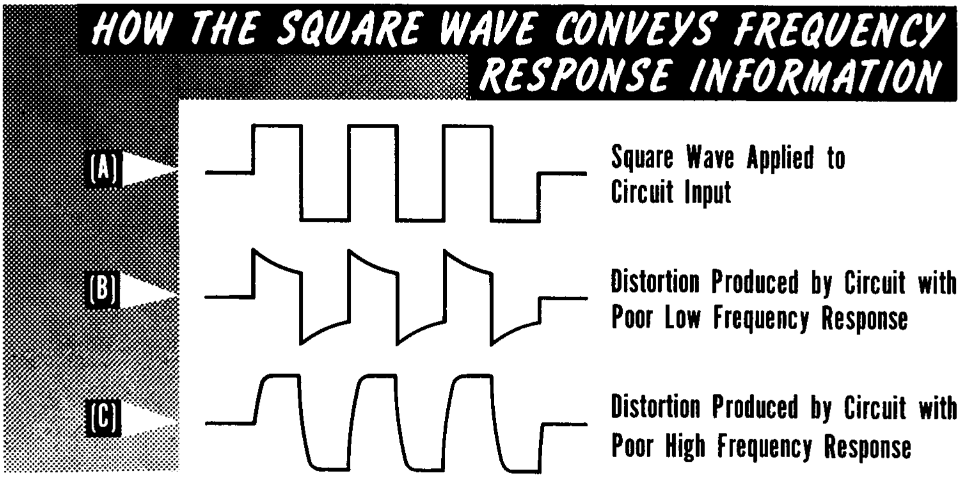
Technique: Insert a ***low pass*** *filter between the source and the 'scope or VTVM. If the filter provides high attenuation for frequencies immediately above that of the fundamental, the measuring device will indicate the amplitude of the* ***fundamental frequency only.***



Low pass filter passes frequencies, say to 19Kc..... rejects frequencies above 19Kc.

Evaluating Frequency Response with Square Waves

Amplifiers and many other circuits display frequency-selective properties similar to those indicated for the elemental low-pass and high-pass R-C networks. With this in mind, and remembering the harmonic composition of pulses, we can employ an interesting measurement technique in order to evaluate the general frequency-response of a circuit. The leading and trailing edges of a good square wave contain the high-frequency constituents of the wave. This we know because only higher frequencies have rise and decay times sufficiently rapid to form leading and trailing edges with near-vertical slopes. The edges of the square wave are, in essence, transients with near-vertical slopes. If a square wave emerges from an amplifier with slowed rise and decay times, the amplifier is not providing as good response for the high frequencies contained in the leading and trailing edges of the square wave as for somewhat lower frequencies. The distortion produced by an amplifier or circuit with poor high-frequency response is shown.

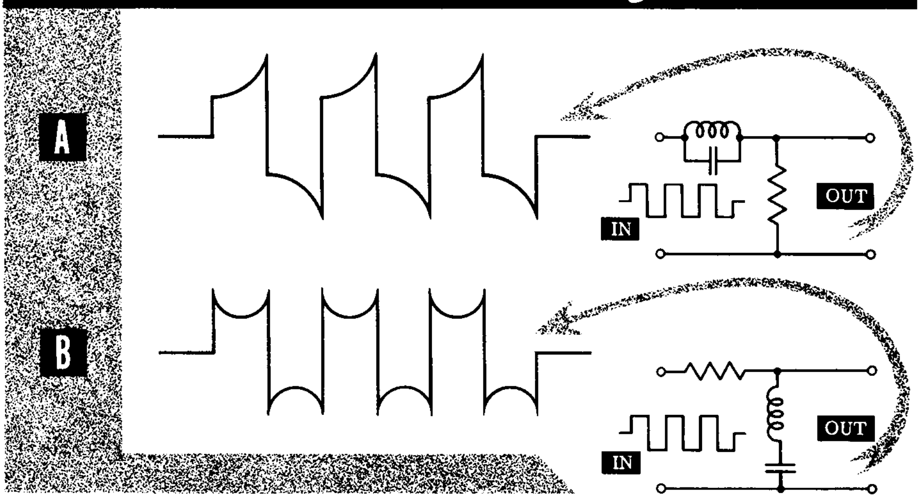


The horizontal parts of the square wave also contain vital information. The rate of amplitude change is zero for an appreciable portion of each cycle. It is as if a d-c level was cutoff or modulated by the frequency corresponding to the pulse-repetition rate, fundamental. Indeed, the fundamental is the lowest frequency component of the square wave which must be accorded good response; no adverse effects in fidelity of reproduction result from poor response to frequencies lower than the fundamental. However, the top and bottom parts of the square wave will not be flat or horizontal if the response is not uniform for an appreciable number of harmonics *above* the fundamental. In general, poor reproduction of the top and bottom peaks of the applied square wave is caused by poor low-frequency response.

Evaluating Frequency Responses with Square Waves (contd.)

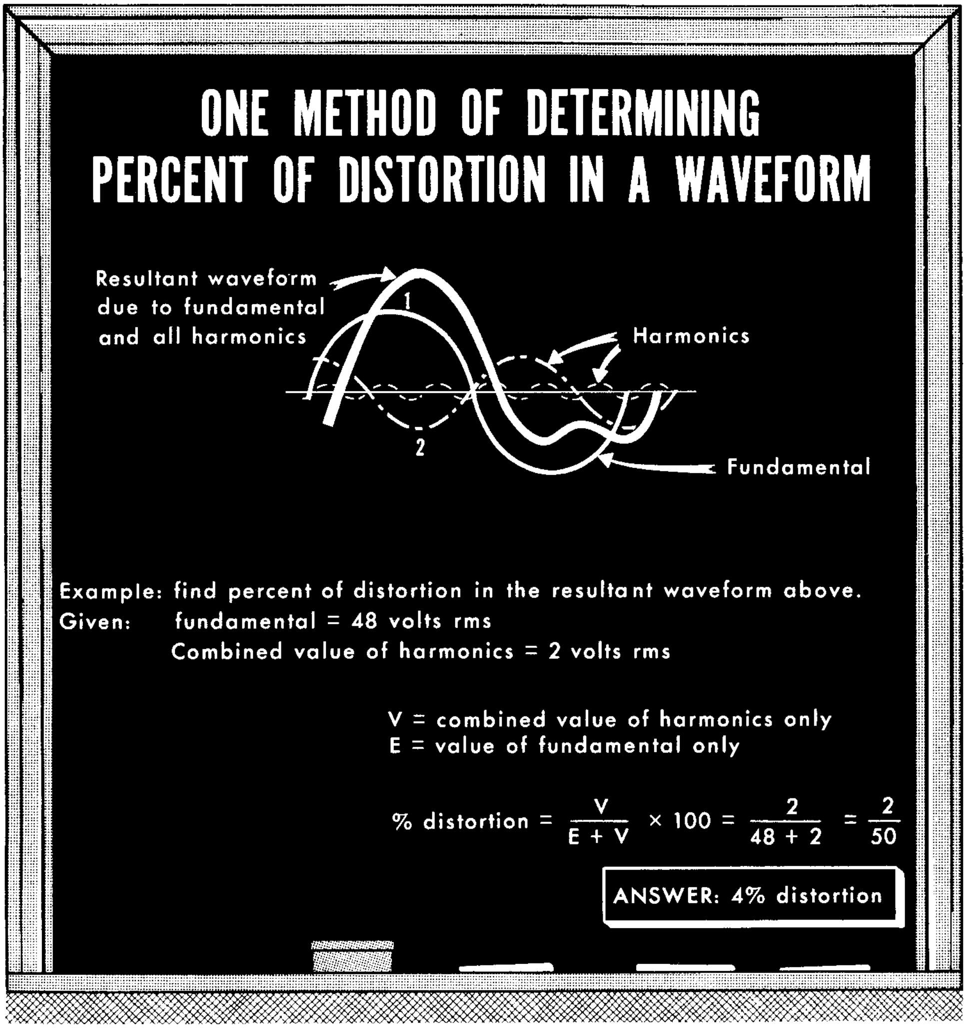
The poor low-frequency response illustrated on page 61 could be due to coupling capacitors in R-C coupled amplifiers which do not have sufficient capacitance. In more complicated amplifiers—ones of several stages, containing transformers, and using feedback—various distortions are inflicted upon an applied square wave due not only to frequency response but also to phase conditions. Such an amplifier can degrade low-frequency response as in a simple R-C high-pass filter, but opposite phase shifts are imparted to the respective harmonics of the square-wave test signal. The emergent wave shown in A of the figure is essentially a mirror image of a poor low-frequency response waveform. In waveform A, the harmonic voltages lag their counterparts in an applied square wave. This contradicts the case typified by the voltage harmonics leading their square wave counterparts. Networks which possibly could produce the indicated distortion are shown.

Poor Low-Frequency Response Accompanied by Phase Shift Conditions Different from Those in the Simple Resistance-Capacitance High-Pass Filter.



Waveform B is another instance of poor low-frequency response, but again accompanied by different phase conditions than other waves with unfaithfully reproduced tops and bottoms. These various phase conditions may be produced also by various L-C-R networks. Phase distortion of audio signals is of little consequence as far as aural perception is concerned. However, phase shifts are often the underlying cause of bad frequency-response and of feedback troubles. In video amplifiers, phase shift merits more serious attention in terms of faithful reproduction of the input information.

Percent of Distortion in a Waveform

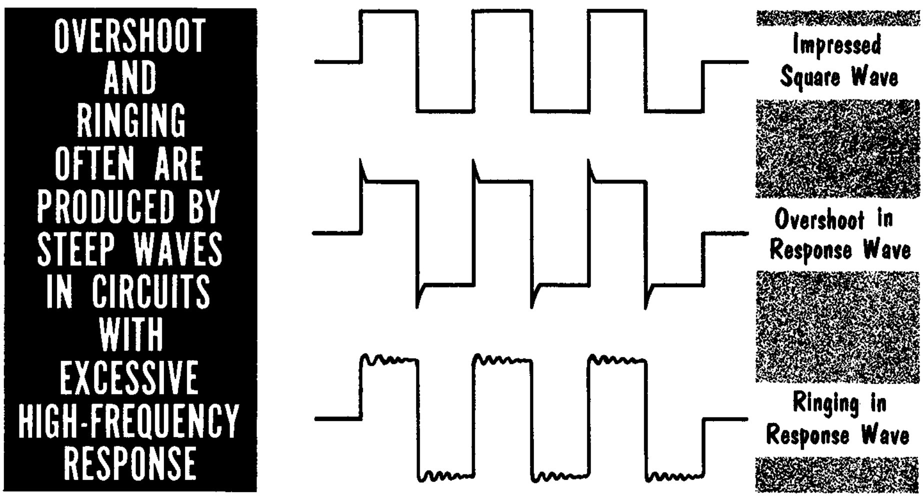


When the value of the fundamental and of the combined harmonic components other than the fundamental are known, the distortion percentages may be readily calculated. It is not necessary to know the value of all the individual harmonics. The required information may be obtained by a filter which stops or rejects the fundamental, but permits passage of the harmonics. Distortion percentage is given by the relationship: % distortion =

$$\frac{\text{rms value of combined harmonics higher than fundamental}}{\text{rms value of fundamental + combined harmonics}} \times 100$$

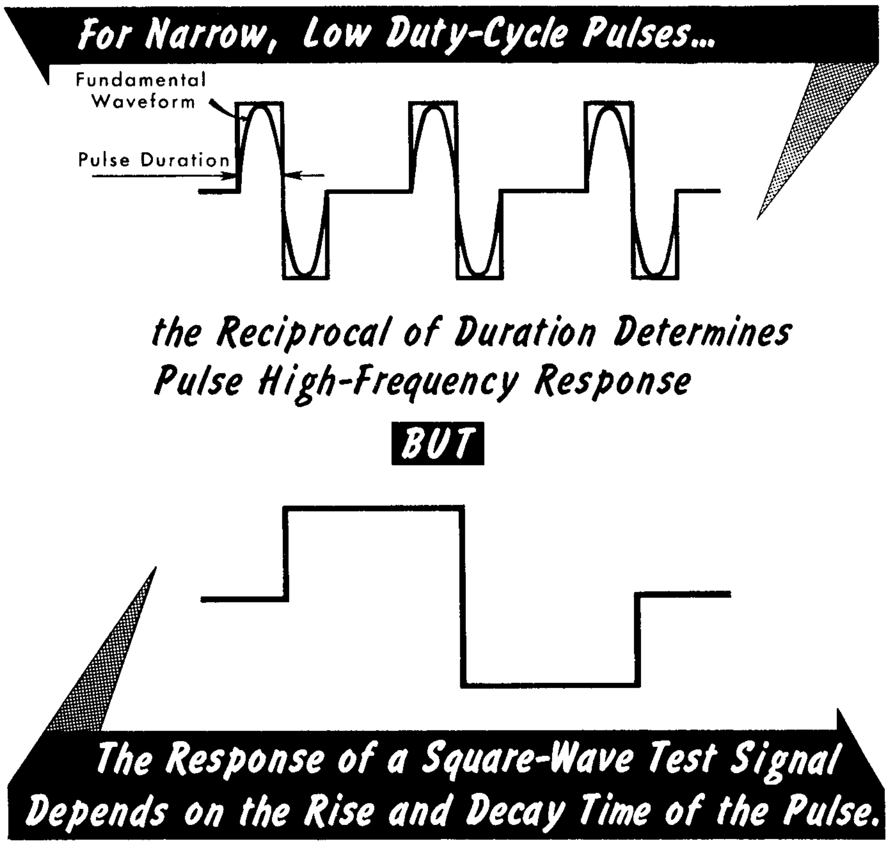
Response Testing in Radar and R-C Networks

Unfortunately, preserving high-frequency response may cause overshoot, which is essentially a ringing phenomena produced by shock excitation of stray parameters. Often the ringing assumes a very obvious form. This effect often requires compromises to be made in the actual allowable high-frequency response. An amplifier or circuit which is relatively free from overshoot and ringing is said to have good transient response. Thus, testing with square or rectangular pulses provides a quick and convenient way of evaluating frequency response.



There is apparently a conflicting situation concerning the duration of rectangular pulses. The highest response-frequency required to give good reproduction of radar pulses was determined by the pulse duration. However, we are now making use of the pulse element which governs duration, the horizontal top, to provide information concerning the low-frequency response of a circuit. The difference in the two cases is due to the very great difference in duty cycle between the radar pulsetrain and the rectangular or square pulses used for response testing. The radar pulse may have a duration of one-thousandth of the period of the pulse train. Conversely, a response-testing square wave often has 50% duty cycle, which means that the pulse duration is one-half the period. Suppose we apply the same analysis to the test wave that we employed for the radar pulses. Let the test wave have a pulse repetition rate of one thousand pulses per second, and a duty cycle of 50%. Such a wave will have a duration of one-half the period, or one-half of 1/1000, or .0005 second. Now, as we did with the radar pulses, let us take the reciprocal of the duration. This is equal to 1/.0005 which is 2000 cycles per second. This is only the *second* harmonic and cannot be representative of the required high-frequency response.

High and Low Duty-Cycle Wavetrains

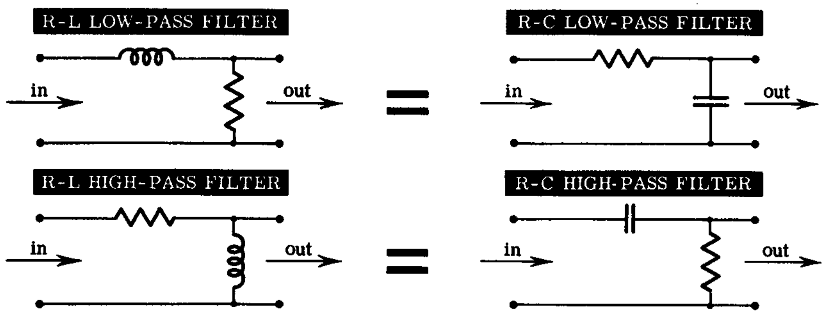


The reciprocal of the pulse duration has little significance when the duration is an appreciable fraction of the period, that is, for high duty cycles. However, as the pulse becomes narrower, the reciprocal of duration corresponds to higher frequencies. Ultimately, for very narrow pulses (low duty cycles) the reciprocal of duration corresponds to the highest frequency needed for good pulse response. Thus, the use of pulse duration for ascertaining required high-frequency response is valid for radar pulses, but not for the square-wave test signal. For the square-wave test signal, the highest response frequency will be determined by the *rise* and *decay* times, and may be between 10 and 100 times the pulse-repetition rate in practical test procedures. It is interesting to consider that the way in which the wavetop reproduction conveys low-frequency response information for the radar pulses as well as for the square wave test pulses. A drooping top indicates poor low frequency response in both instances.

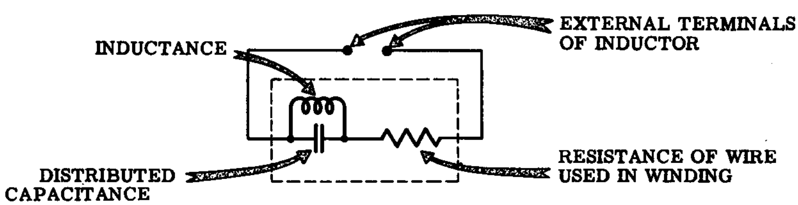
Resistance-Inductance Networks

Resistance can be combined with inductance to produce essentially the same type of frequency-response as provided by the resistance-capacitance networks just considered. We see the two R-L combinations and their R-C counterparts. Theoretically, the responses of the equivalent networks can be made identical by appropriate choice of parameters. Practically, however, the R-L networks are not easy to work with, especially where sharp pulses are involved. A practical inductor cannot be made so pure as a capacitor.

The L-R Equivalents of R-C Networks



Approximate Equivalent Circuit of an Inductor

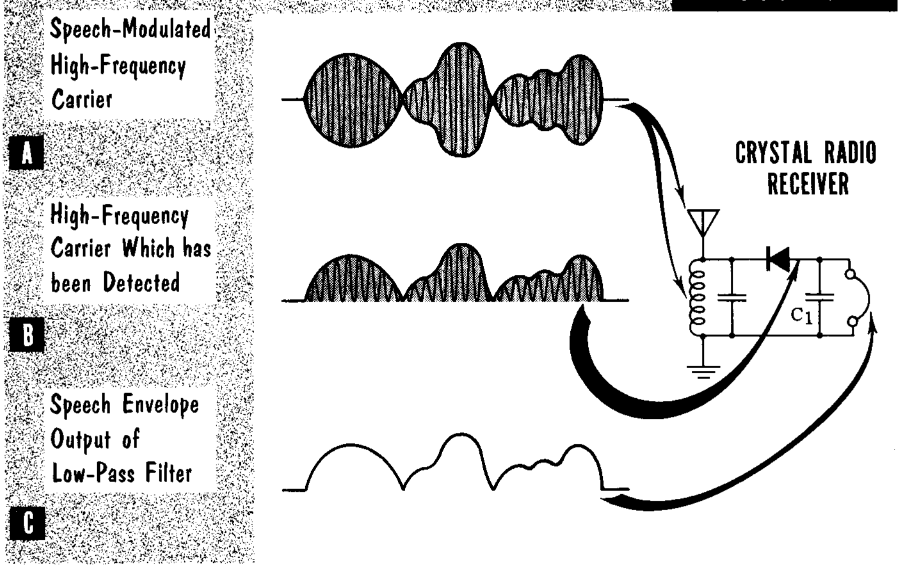


The capacitor can be made to exhibit primarily the intended parameter of capacitance over a large frequency range, but not so with the inductor. In addition to the intended parameter of inductance, the inductor generally contains sufficient resistance and distributed capacitance to drastically alter its pulse response with respect to that which would be expected from a true inductive element. Furthermore, if the inductor has an iron core, varying degrees of nonlinearity can be anticipated, depending upon the strength of the pulses. Nonlinearity makes the inductance have different values at different amplitude levels, a condition which prevents faithful reproduction of pulses, or which, in the event of deliberate pulse-shape modification, must be taken into account. Inasmuch as the inductive element of an R-L network is in itself an L-C-R circuit, such networks generally agitate ringing difficulties.

The R-C Network in High-Frequency Detection

An interesting selective-circuit effect on pulses is encountered in the detection of amplitude-modulated high-frequency carrier waves. The process of detection is essentially one of partial or complete rectification. The objective is to recover the modulation, or what we have previously called the d-c component of the high frequency carrier. This is necessary because amplitude variations in high-frequency waves cannot be heard by the ear. Thus, the portion of speech modulation illustrated would not be audible as such.

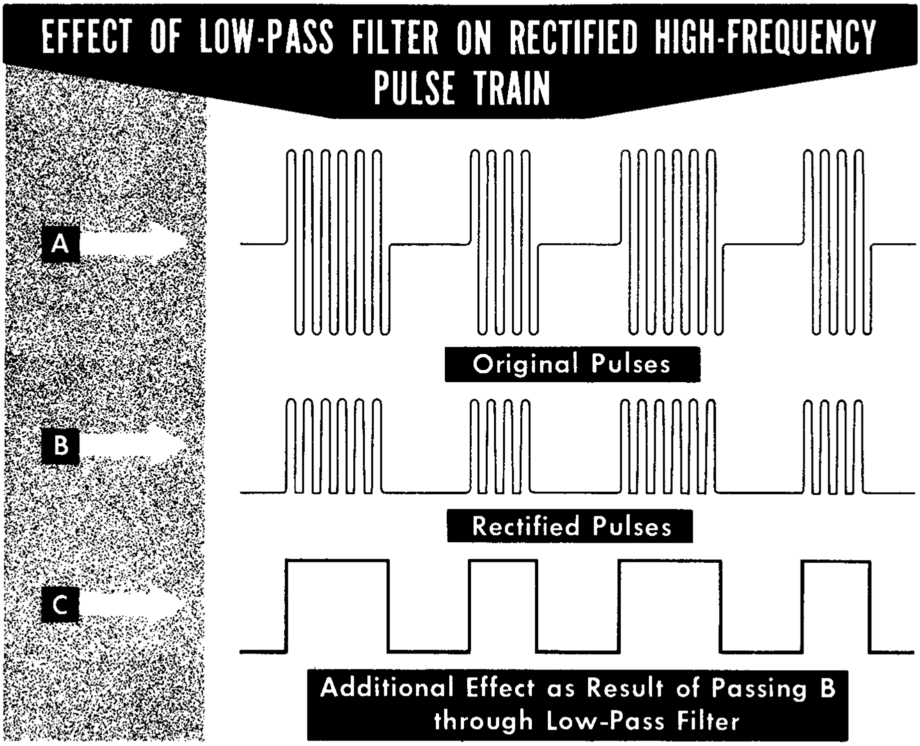
Detection of Speech Waveforms in a Radio Receiver



The ear responds to frequencies approximately in the range of 30 to 16,000 cycles; the carrier frequency of the speech-modulated carrier may be several megacycles. Since such a frequency is outside aural response, the amplitude fluctuations impressed upon this frequency are also not heard by the ear. The action of a rectifier such as a crystal diode removes one polarity of the high-frequency carrier. This is illustrated in waveform B. Detection commonly consists of rectification plus filtering. In the crystal-detector type radio receiver shown, the crystal diode rectifies the original modulated carrier, which is symmetrical about its zero axis. Wave B is the result of rectification but without the low-pass filtering action provided by capacitor C. Wave C is the residual wave applied to the headphones with capacitor C_1 in the circuit.

Eliminating the Carrier in the Radio Receiver

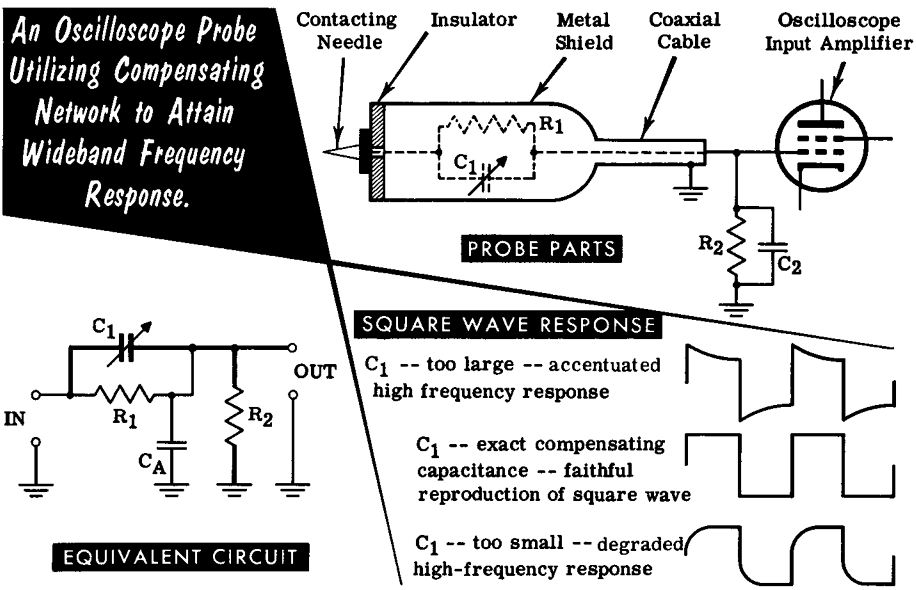
Rectification has produced the *d-c component* which is the original modulation imparted to the high-frequency carrier. We now investigate other uses of the carrier frequency.



The carrier frequency is well named; it carries the modulation. A carrier frequency is not necessary, following recovery of the modulating d-c component by detection. In fact, there are several reasons why it is desirable *not* to use the carrier. Its presence could cause feedback and biasing in audio amplifier tubes. Its elimination by a low-pass filter improves detection efficiency. This is so because the low-pass filter generally consists of a capacitor which more or less charges up to, and follows, the peak amplitude of the carrier cycles. In so doing, the carrier-frequency cycles are effectively filtered out and the information-bearing d-c component is left. This wave, shown in C on page 67, varies at voice frequencies and is reproduced as such by the headphones or speaker. The same phenomena is depicted here for code pulses instead of speech modulation. In this case, the high-frequency carrier wave has been eliminated by a low-pass filter, leaving only the pulse envelope.

R-C Networks in the Oscilloscope Probe

By properly combining the simple R-C low-pass and high-pass filter, a condition may be attained wherein the response of the two filters are exactly compensated. Then frequency selectivity does not exist until frequencies are encountered that are so high that compensation is spoiled by stray capacitances and inductances. Consequently, such a network is suitable for handling steep waves and high frequencies. The probe for an oscilloscope is constructed so that the stray shunt capacitances between the metal shield and the contacting needle, as well as the internally contained components, are negligible up to very high frequencies. C2 plus the coaxial cable capacitance form a low-pass filter in conjunction with R1. Also, C1 in conjunction with R2 forms a high-pass filter. A small hole is provided in the metal probe housing for the adjustment of internally contained variable capacitor C1.



We see the need for adjusting for exact compensation. This type of probe generally provides considerable attenuation of the signal being monitored. This in itself is not desirable. However, the impedance of the probe as seen by the circuit being investigated is thereby made relatively high by virtue of a high resistance for R1. This, at the same time, isolates the scope input amplifier from the circuit undergoing measurement. Thus the high-frequency components of pulses suffer negligible degradation when monitored by a scope using a properly adjusted probe. The attenuation of the probe is made up by the gain of a well-designed input amplifier inside the oscilloscope cabinet.

QUESTIONS

1 Upon what principle does the operation of the R-C low-pass filter depend?

2 List three ways in which the cutoff frequency of an R-C high-pass filter can be made higher.

3 Suggest a way in which the rate of attenuation with respect to frequency or the selectivity of the R-C low-pass filter can be improved.

4 What might be expected as an accompanying result of the cascading R-C low-pass filters?

5 Can the basic R-C high-pass filter be cascaded to increase the rejection of frequencies eblow the cutoff value?

6 Is the cascading technique applicable to L-R filters?

7 Although R-C filters have their counterparts in appropriate L-R networks, it is generally not good practice to attempt cascading of the two types. Comment on this.

8 An R-C high-pass filter will not pass d-c, whereas an L-R high-pass filter will generally pass an appreciable zero frequency, or d-c component. Explain why this should be so, considering that the two types of filters are theoretically equivalent.

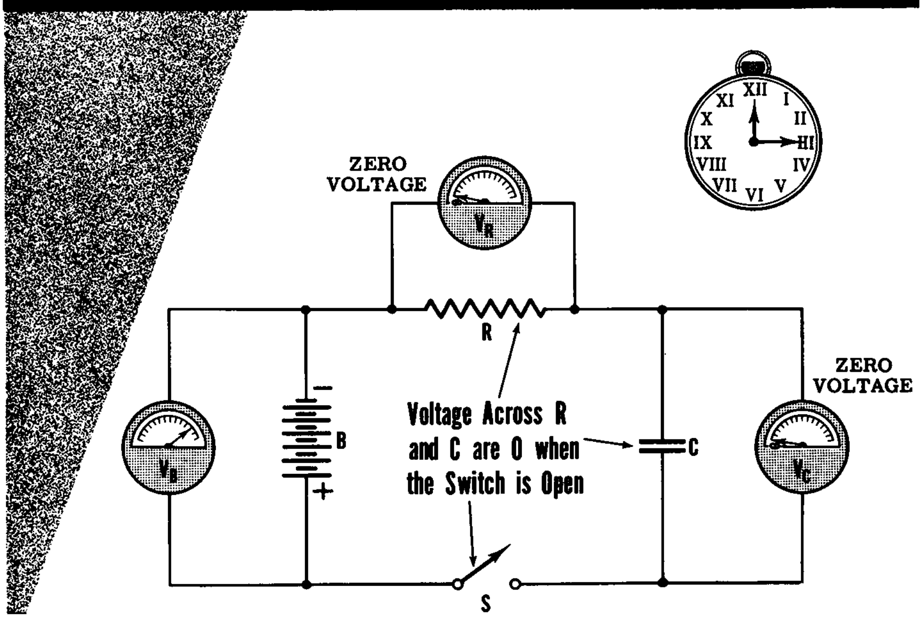
9 Cite a disadvantage of cascading basic R-C and L-R filter networks.

10 A low-pass R-C filter is made up of a 1-megohm resistor and a $50\mu\mu f$ capacitor. It is found that such a combination is effected by stray capacitances from proximity with the metal chassis. How can this problem be overcome so that no special consideration will have to be given to mounting of the resistor and capacitor.

The Energy-Storage Viewpoint of Pulses

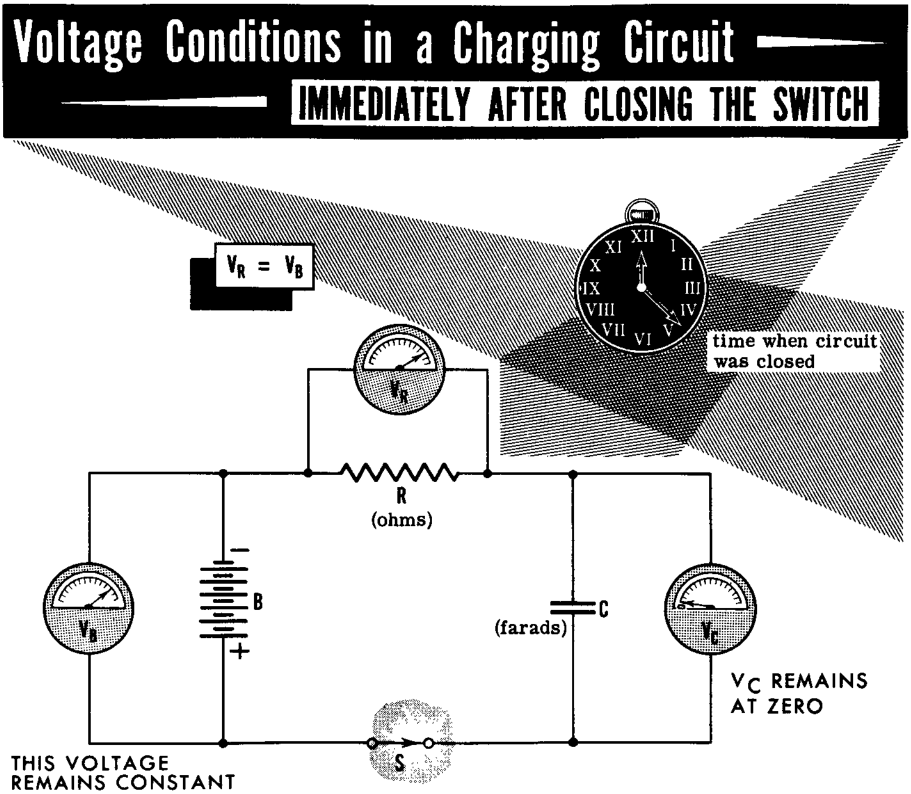
We have considered pulse response and shape in terms of the way circuit parameters affect the constituent harmonic frequencies of the pulse. Another very useful method of analyzing pulses is based upon energy storage rather than frequency composition. The important aspects of this method concern the charge and discharge characteristics of the simple resistance-capacitance network when subjected to rectangular or square waves. Many inferences can be drawn from these characteristics which are applicable to other wave-shapes and also to resistance-inductance circuits. Learning another system of pulse analysis provides a choice of ways to obtain pulse information.

CIRCUIT FOR INVESTIGATING CHARGING CHARACTERISTICS OF A SIMPLE R-C NETWORK



The second pulse-analysis procedure is known as transient analysis. We see a simple arrangement of series-connected elements: battery, switch, resistor, and capacitor. Suitable voltmeters are also connected across the battery, resistor, and capacitor. Assume that the voltmeters consume negligible current and therefore do not materially disturb the circuit. (In practice, this is accomplished by using vacuum-tube voltmeters which have extremely high-input impedances.) The stop watch shown is necessary because the circuit phenomena requires a definite time to undergo its cycle.

Practical Considerations of a Basic Experiment

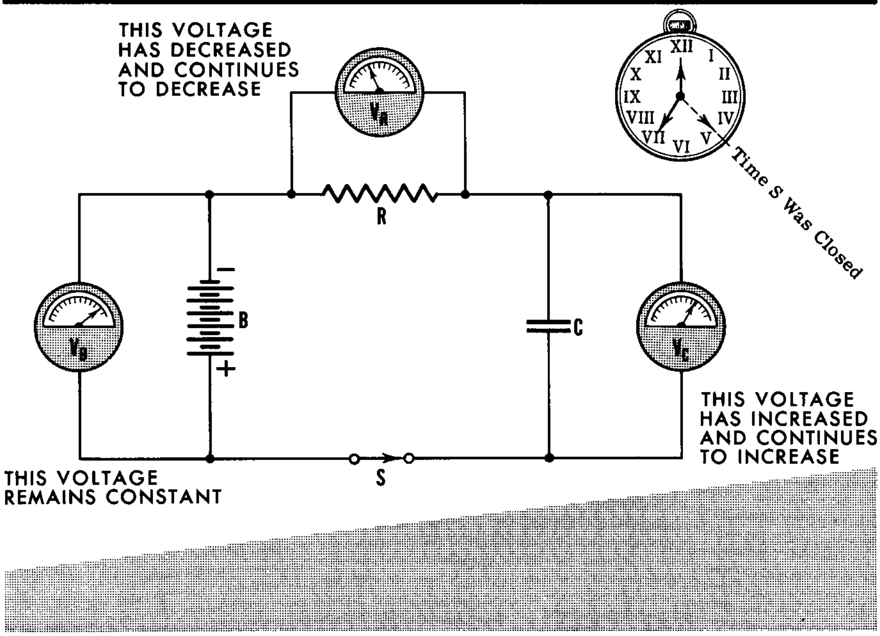


Consider the circumstances of the circuit when S is open. V_B indicates the battery voltage. V_R and V_C indicate zero voltage. Upon closing S, we perceive three facts: the battery voltage remains constant; the voltage across the resistance monitored by V_R jumps to the same value as battery voltage V_B; the capacitor voltage V_C remains zero. In the actual experiment, there are at least three factors which might interfere with our objectives. There is the visual difficulty of making an almost instantaneous observation. There is the mechanical response of the meter needle to contend with; the sudden deflective force applied to V_R when the switch is closed generally causes at least some overshoot or undershoot of the meter needle. Finally, dielectric leakage in the capacitor can disturb the ultimate voltage division between R and C. Fortunately, these disturbing factors can be reduced to negligible consequence and the idealized circuitry response can be very closely approximated. We will assume that a high-quality capacitor is used and that the values of resistance and capacitance cause the phenomena under observation to endure for a relatively long time.

Voltage Distribution in a Capacitor-Charging Circuit

The readings of V_R and V_C are not steady. Both voltages shown in intermediate readings undergo a continuous change until the action culminates with interchanged readings with respect to the two voltages; that is, V_R becomes zero and V_C becomes equal in value to E_B. This is characteristic of the charging of a capacitor. If the value of the resistance is decreased, the cycle completes itself in a shorter time.

Voltage Conditions in a Charging Circuit — before the Capacitor is Fully Charged



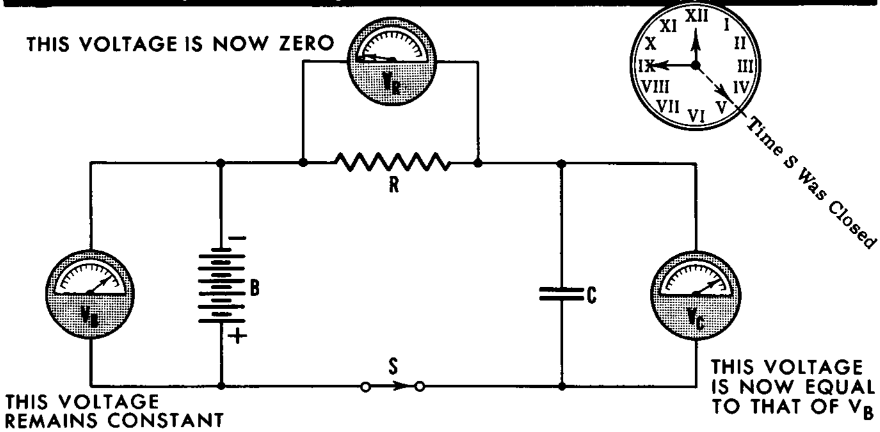
When a capacitor is in any state of charge, its action in the circuit is equivalent to that of a voltage source of a polarity that opposes the flow of current from the charging source. In our simple circuit, the charging source is the battery. Whatever it is that charges the capacitor must flow through the resistance. We might be tempted to say that current flows through the resistance and into the capacitor, thereby charging it. But this is not exact. What we speak of as *current* flow is actually the passage of a certain number of electrons over a certain time interval from one part of a circuit to another. This is, admittedly, a subtle distinction. However, introducing the time factor helps clarify the phenomena.

Voltage Distribution in a Capacitor-Charging Circuit (contd.)

When electrons flow into a capacitor, they accumulate on one plate, imparting to it a negative charge. Due to the continuity of electric circuits, the same number of electrons which pile up on the negative plate are removed from the opposite plate, thereby making that plate positive. During the time in which the electron equilibrium of the capacitor plates is being shifted there is a movement of electrons (current flow) in the circuit. The more electrons extracted from the positive plate and deposited on the negative plate, the higher the potential difference between the two plates; indeed, the voltage across the capacitor is a direct indication of its state of charge.

VOLTAGE CONDITIONS IN A CHARGING CIRCUIT

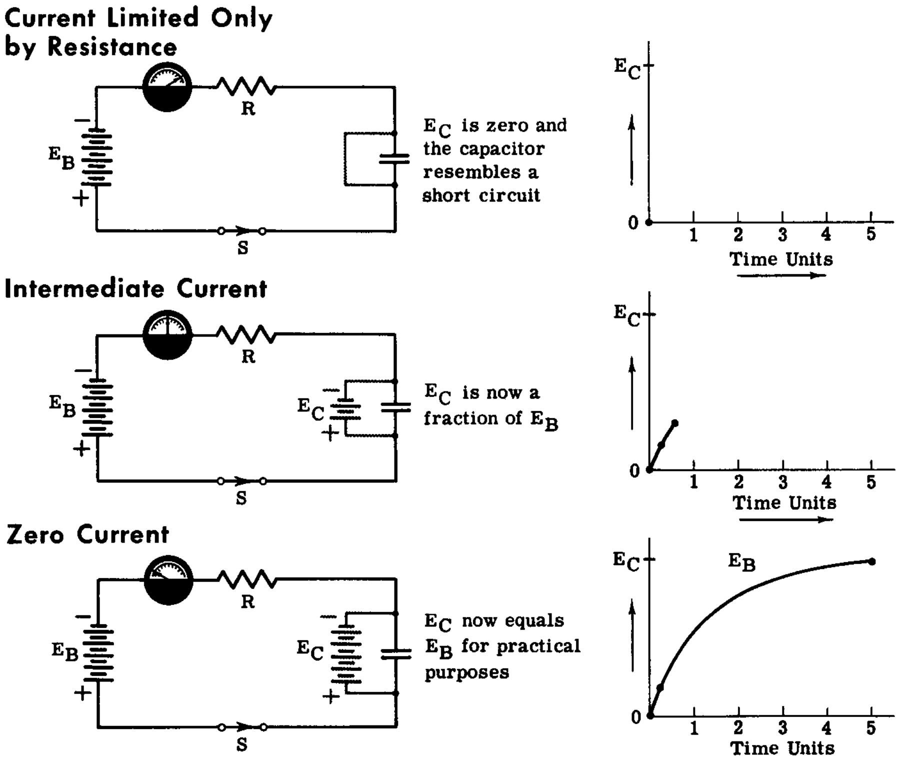
The Time Elapsed Corresponds to 5 or More Time Constants.



The number of electrons flowing past a point in a given time manifests itself as current flow. The number of electrons stored on the negatively polarized capacitor plate is the capacitor voltage. Note that time is not a limiting factor with ultimate capacitor voltage, as it is with circuit-current flow. A given capacitor voltage can be the result of a great number of electrons making their exodus from the positive plate, through the circuit, then accumulating on the negative plate in a very short time. Conversely, the same capacitor voltage can be attained by a restricted electron flow over a relatively long period of time. Thus, resistance in a capacitor-charging circuit does not effect the *ultimate* capacitor charge or voltage, but only the time for ultimate charge to be attained. Ultimate charge, in turn, is governed by the voltage of the charging source; when ultimate charge is reached, the capacitor voltage is equal to the voltage of the charging source, and like two parallel-connected battery cells, there is no current flow (due to the mutual bucking effect of the two voltages).

Equivalent Circuit of Capacitor-Charging Network

EQUIVALENT CIRCUITS OF A CHARGING CIRCUIT FOR DIFFERENT CAPACITOR-CHARGE STATES

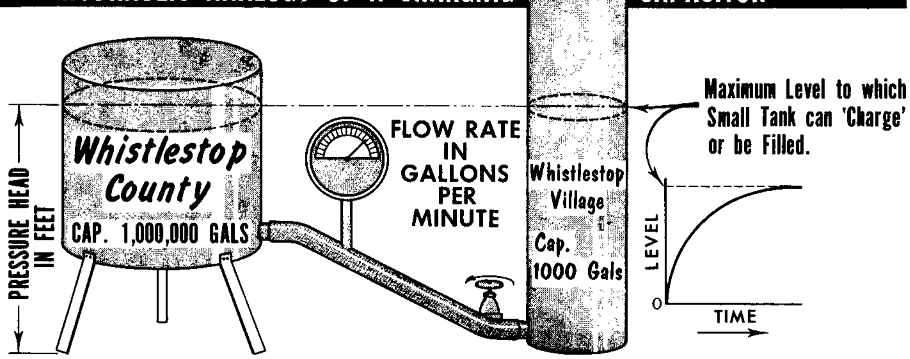


We see the equivalent circuits of a capacitor-charging network for different amounts of capacitor charge. Immediately after closing the switch, the capacitor behaves as a short or as a direct connection. At an intermediate charge state, the capacitor behaves as a battery which is polarized the same way as the source battery E_B, but of lower voltage. E_C is now a fraction of E_B. After the passage of more time, the capacitor behaves finally as a battery of the same voltage as E_B. The polarities of the two "batteries" tend to force current flow toward one another, the two tendencies are neutralized, and no net current flow takes place. Consequently, circuit action is stopped. The capacitor is considered fully charged after 5 time-units, or time-constants.

Hydraulic Analogy to a Charging Capacitor

Current flow in a circuit governs the rate at which a capacitor can charge. It follows that low resistance in series with the capacitor provides quicker charging time than can be attained from circuits with high charging resistance, other conditions being equal. Resistance is one of two factors which determine the time required for the capacitor to attain the condition of charge corresponding to a voltage equal to that supplied by the charging source. The other factor is the capacitance of the capacitor itself. A large capacitor requires a greater displacement of electrons from the positive to the negative plate than does a small capacitor, in order to charge to the same voltage. A corollary of this statement is that with a given resistance, the large capacitor will require a longer time than the small capacitor to attain maximum charge.

HYDRAULIC ANALOGY OF A CHARGING CAPACITOR

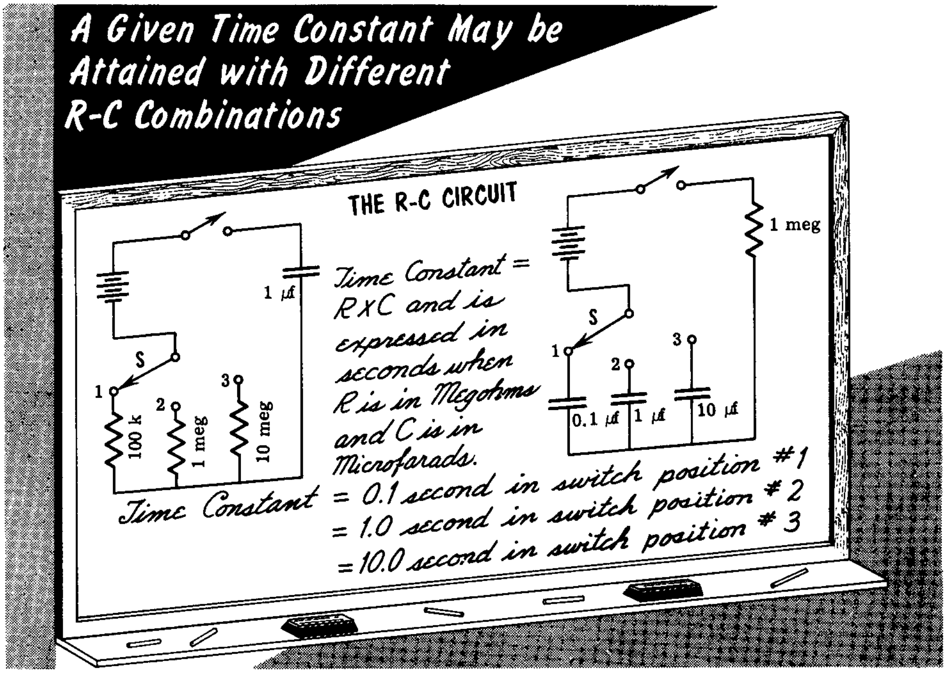


The term capacitance is very descriptive, applied to a capacitor. It is the measure of the number of positive and negative charges required to bring the capacitor to a given voltage level. In an analogous situation, we would say that the capacity of a water tank is the measure of the number of gallons of water required to bring the stored water to a given tank level.

In this hydraulic analogy, the water flow in the pipe supplying the tank could be measured in gallons per minute. This measurement would correspond to current flow in the electric circuit.

The large-capacity tank represents the battery of the electric circuit. It has a large water supply such that its level (pressure head) is practically unaffected by the filling of the smaller tank. The flow rate of the water is analogous to current flow. The pressure head, determined by the water level in the large tank, is analogous to voltage. The hydraulic friction within the connecting pipe is analogous to electrical resistance. As the small tank fills, it exerts more and more back pressure, slowing the rate of water flowing into it.

Effect of Source Voltage on Charging Time

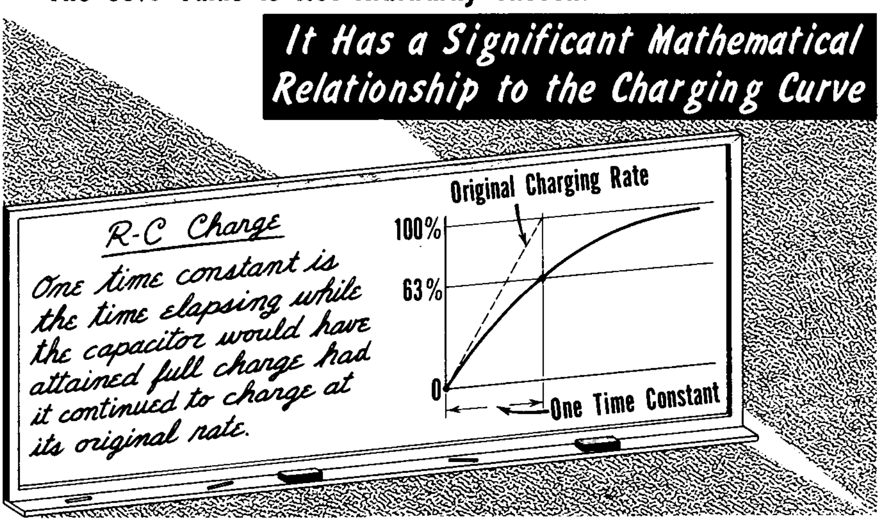


The charging time of the capacitor is governed by the resistance in series with the capacitor and the size of the capacitor. We can simultaneously account for these two charge-time factors by stating that the charging time is proportional to the product of resistance and capacitance. A given charging time can be attained with a large resistance and small capacitance, or in the converse arrangement, a small resistance and a large capacitance; it is only necessary that resistance times capacitance yields the same number in the two instances. We must now consider whether a high-voltage source can cause the fully charged condition of the capacitor to be reached sooner than with a low-voltage charging source. It is true that a given value of capacitance voltage will exist across the capacitor sooner with the high voltage charging source, but this does not imply that the complete charging cycle will occur in a shorter time interval. Indeed, the shape of the curve representing percent of maximum charge voltage versus time is precisely the same regardless of the amount of voltage supplied by the charging source; the time required to reach maximum capacitor voltage is also the same. The voltage supplied by the charging source does not influence charging time. Only the product of resistance and capacitance affects charging time; a given fraction of ultimate charge voltage is attained in the same time regardless of source voltage.

The Meaning of Time Constant

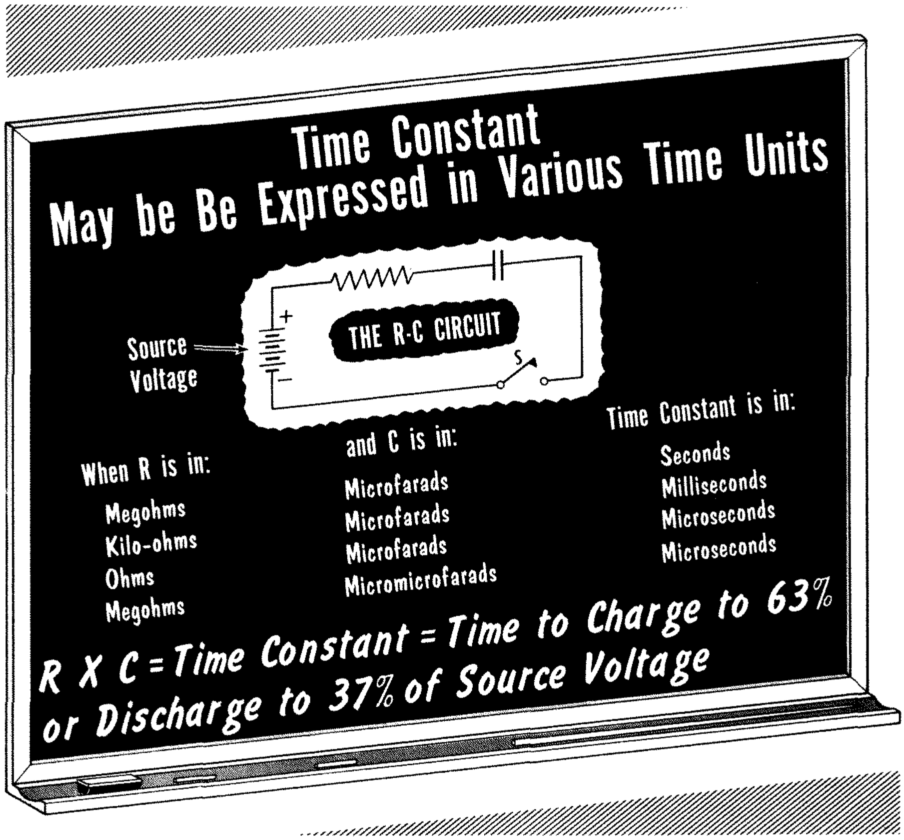
The product of resistance and capacitance is the time constant of the circuit. Time constant provides us with a measure of the time required for charging the capacitor, but we can not completely account for the time required to attain the fully charged condition. Theoretically, it requires infinite time for a capacitor to charge fully, no matter what the time constant is. It is the condition we would find if we tried to walk across the room with each successive step half the length of the preceding step. It would take an eternity to attain our goal. As the voltage across the capacitor approaches the charging-source voltage, the rate of charge displacement—and therefore the current flow in the external circuit—diminishes. From a purely mathematical standpoint we should accept the fact that after many hours, days, or months, the capacitor would still be charging, though at an infintesmally slow rate. For practical purposes, however, we can assume the state of full charge was attained after passage of time corresponding to 5 time constants.

The 63% Value is Not Arbitrarily Chosen.



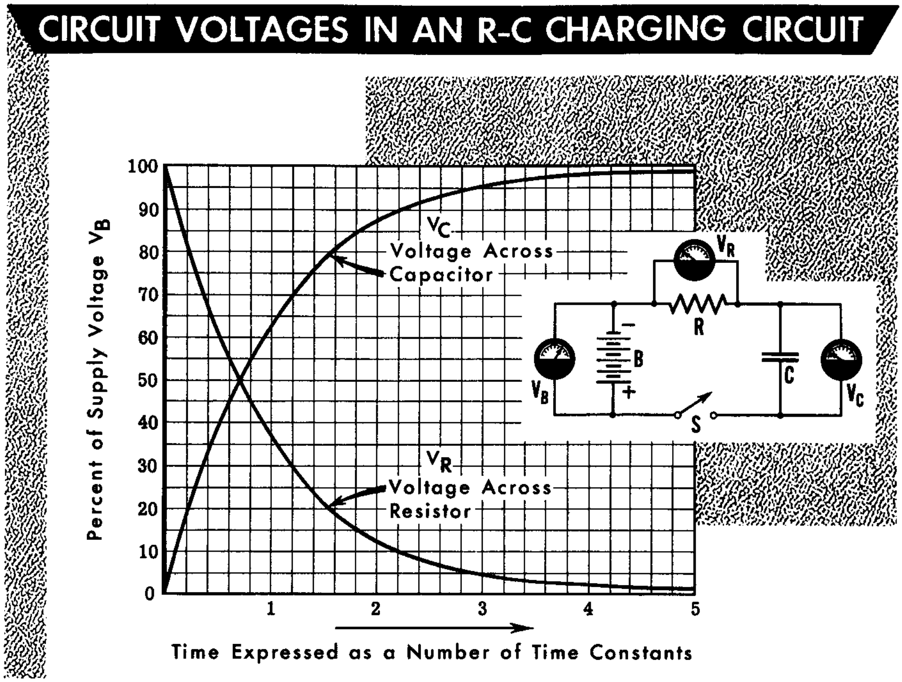
This has been a prelude to the definition of the time constant. We have already stated that the time constant indicates the rapidity of the charging cycle, but we have also described the difficulty in ascertaining *when* the capacitor is fully charged. It has been agreed that one time constant is the length of time required for the voltage across the capacitor to build up to 63% of the charging source voltage. This avoids the ambiguity which would result if we attempted to deal with the ultimate charged condition. Furthermore, the 63% charge state is easier to handle graphically than the near-charged state corresponding to 5 time constants.

The Meaning of Time Constant (contd.)



In electronic circuits, it is usually convenient to derive the time constant of an R-C circuit by multiplying resistance (expressed in *megohms*) by capacitance (expressed in *microfarads*). This causes the resultant time constant to equal the number of seconds required to charge the capacitor to 63% of its maximum attainable voltage. Thus, if we have one megohm and one microfarad, the value of one time constant is one second. Similarly, one-tenth of a megohm in conjunction with three microfarads yields a time constant of three-tenths of a second. To employ this procedure, we must first convert to megohms and microfarads if the resistor and capacitor are not already so designated in our circuit diagram. For example, the time constant for a 100,000-ohm resistance and a capacitance of 500 $\mu\mu$fs is obtained by first converting 100,000 to meg, then multiplying by the number of μfs equivalent to 500 $\mu\mu$fs. Thus, we have the product of $0.1 \times .0005$, which obtains for us a time constant of .00005 sec.

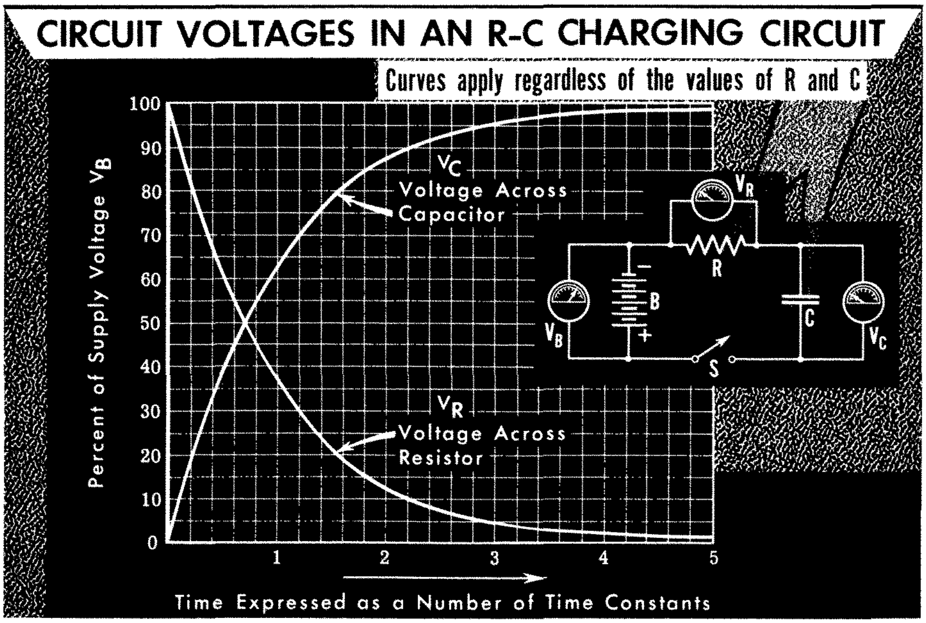
Graphical Representation of the Time Constant



We see a graph of the voltages observed in our charging circuit after closing the switch. Although we measured the passage of time as such, this graph is not plotted directly in terms of time increments, but rather as a function of time constants. There is an excellent reason for this procedure. We have *normalized* our graph, an approach much used in science and engineering. By this technique, we obtain a graph which is universally applicable to R-C networks, no matter what may be the combination of resistance and capacitance. For this reason it was unnecessary to assign values to the resistor and capacitor of our charging circuit; for convenience in reading our stopwatch and voltmeters we merely assumed that the resistance was very high and the capacitance was very large. This combination produced a large time constant so that the capacitor charged up very slowly. However, our graph would remain identical for any other resistance-capacitance combination. This can be more readily understood when it is seen that one time-constant unit may correspond to *any* actual time duration; in circuits with large time constants, one time-constant unit may correspond to many seconds. In circuits with small time constants, one time-constant (unity) may correspond to a small fraction of a second. In both instances however, one time constant is the time required for the capacitor to charge to 63% of its ultimate voltage.

Graphical Representation of the Time Constant (contd.)

In plotting our graphs we first plot in terms of time units as observed on our stopwatch. Next, if we know the values of the resistor and capacitor, we can obtain the time constant and locate this value on our scale of time units. Two time constants then equal 2 times this distance, three time constants equal 3 times the distance of one time constant, and so forth. In the event we do not know the values of resistance and capacitance in the circuit, we find the time constant by projecting a vertical line through the point on the capacitor-charge curve corresponding to 63% of the ultimate capacitor voltage. Then we procede in marking off two, three, four and five time constants as before, that is, we merely ascertain that there are equal distances between adjacent time-constant designations.

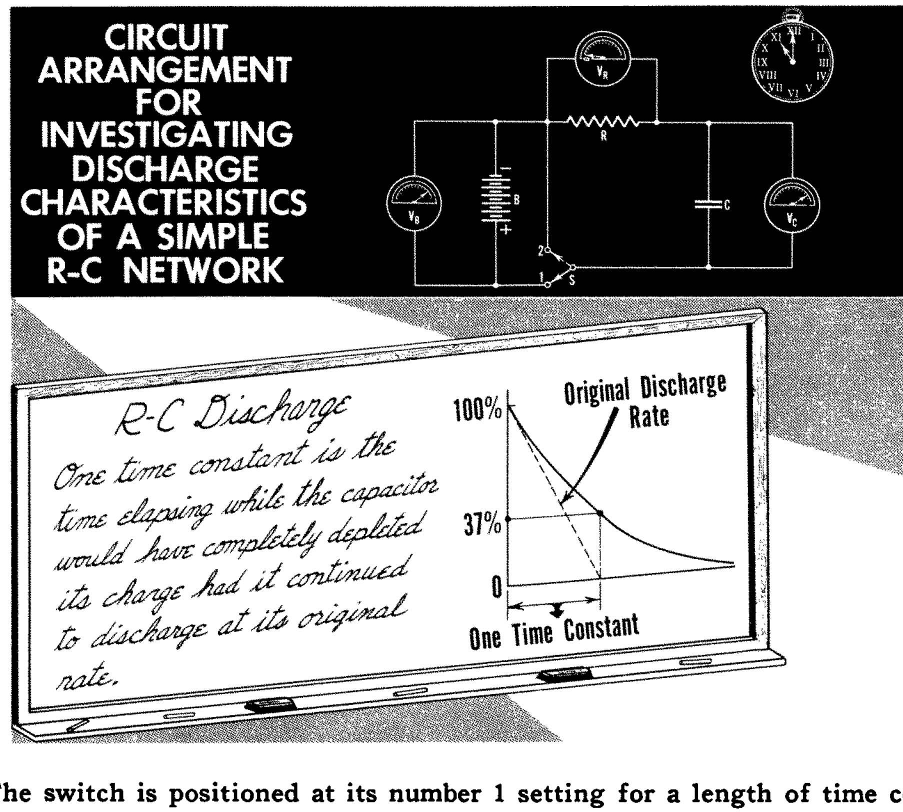


Thinking in terms of time constant is of great value in visualizing circuitry response to pulses. This will be particularly evident when we investigate the emergent waveshapes from low- and high-pass filters when the time constant is changed.

Plotting the voltages in a charging circuit has no practical value beyond fostering a closer acquaintance with the concept of the time constant; we do not require a different plot for different R-C combinations. Any reference book which depicts the graphs of voltages in a charging circuit in terms of the number of elapsed time constants provides for us the universal curves which serve for any R-C combination.

Discharge Characteristics of an R-C Network

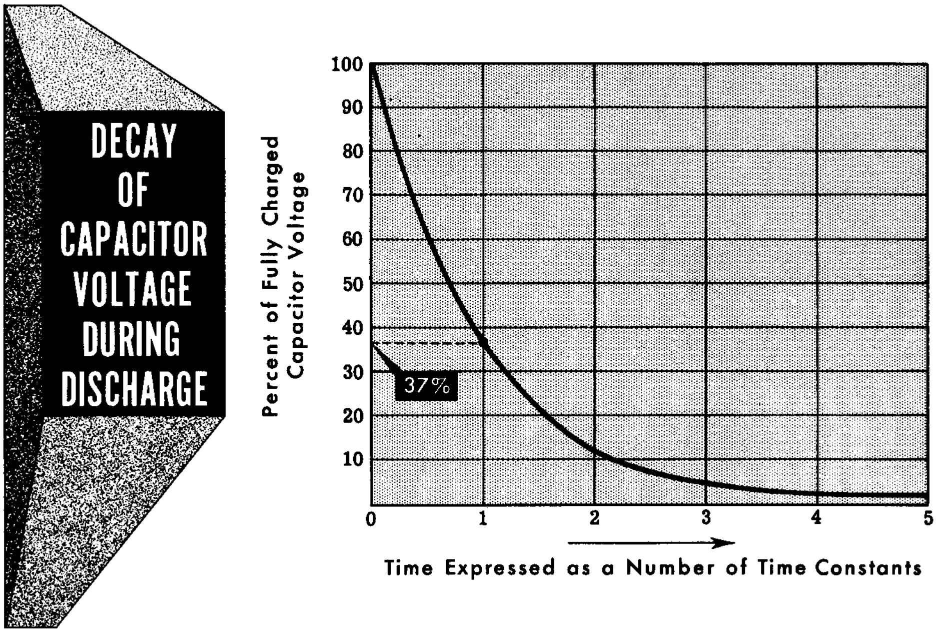
We have investigated some of the important aspects of voltage variations during the charging of a capacitor through a resistor. Let us suppose now that the battery is instantaneously replaced by a direct connection; then the charged capacitor would discharge through the resistor. We could then observe the nature of the voltage variations during discharge. We have been dealing primarily with square or rectangular waves. In discussing the phenomena occuring during the charging of the capacitor, we concerned ourselves with the leading edge and top of a rectangular wave. Now, in order to study what happens as a result of the trailing edge of a rectangular wave, we study its equivalent; the discharge conditions of the R-C network.



The switch is positioned at its number 1 setting for a length of time corresponding to at least 5 time constants. This assures attainment of virtually full charge of the capacitor. Consequently, at the end of this time V_C is equal to the charging source voltage V_B. Next, the switch is positioned at its number 2 setting. Immediately after this, voltmeter readings are recorded at a number of convenient time intervals until V_R and the V_C have ceased changing.

Discharge Characteristics of an R-C Network (contd.)

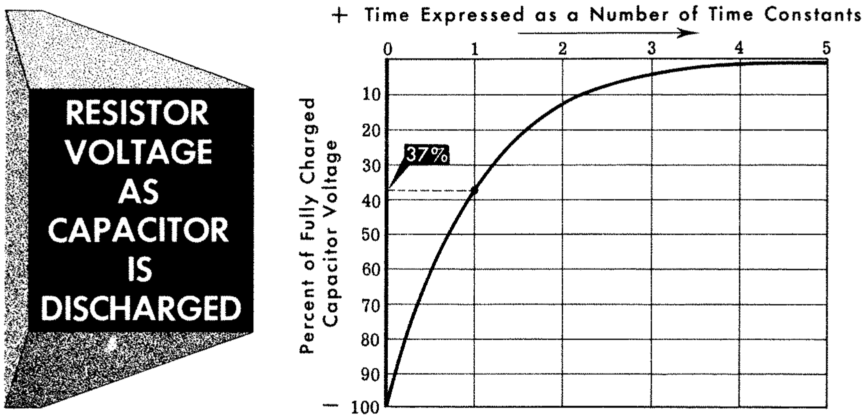
The voltages obtained from reading V_B and V_C during capacitor discharge are plotted with respect to time units. Finally, to render our curves universally applicable to any R-C combination, the time scale is converted from time units to the number of time constants. One time constant in this case is whatever time corresponds to a capacitor voltage 37% of the initial fully charged value. We derive our time constant by correlation with a 37% voltage because we must designate one time constant as the time corresponding to 63% of the initial capacitor-voltage change. We see that this point is, indeed, 63% down from 100% initial capacitor voltage, or 37% up from zero.



An interesting feature of both charge and discharge circuits is that Kirchhoff's law prevails at all times. That is, the sum of the resistor and capacitor voltages always equals the supply voltage. Consequently, if we know any two of these voltages, we can compute or plot the remaining voltage. For the charge circuit, this fact is evident from the curves on page 80. No matter at what time-constant value we add V_C and V_R, the result is always V_B. Similarly for the discharge circuit, we add percent voltages derived from pages 83 and 84 for the same time-constant values. The result is always zero, since the positive percentage obtained from page 83 are exactly cancelled by the negative percentage obtained from page 84. Indeed, the voltage source is zero, for we have replaced the battery with a shorting wire. (This happens when the switch is changed from position 1 to position 2.)

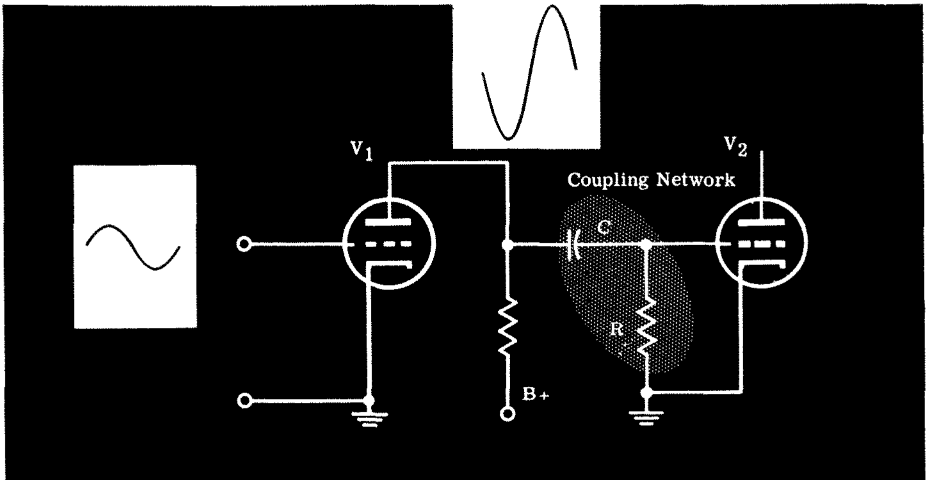
Voltage Variation of R in an R-C Network Discharge

We see a graph of the voltage variation across the resistor during discharge. Note that this curve is of opposite polarity to the curve of page 80 representing resistor voltage during charge. In the one instance, current flows from the battery though the resistor to the capacitor; in the other, current flows out of the capacitor in the direction opposite to that during charge. Consequently, the polarity of the voltmeter leads must be transposed before transferring from switch position 1 to switch position 2 in order to obtain an upscale reading. This is not true of the capacitor voltmeter; the positive and negative plates of the capacitor retain their polarities.



We now will summarize the important characteristics of the simple R-C network impressed with a rectangular wave. First, let us consider the case wherein the value of the resistor is zero. This is not a practically attainable condition because there is always inherent resistance in the capacitor itself. Some of this resistance exists because the dielectric of the capacitor is not perfect. However, we shall not concern ourselves with this resistance because, for most practical purposes, it is possible to construct capacitors with dielectric materials which are very nearly perfect insulators. The resistance inherent in the plates of the capacitor present a different aspect. Each resistance behaves as though it consisted of an external resistor connected in series with the capacitor. Thus, no capacitor can have a zero time constant. For this reason, we often encounter the statement that capacitor voltage cannot change instantaneously. If we connect a battery directly across a capacitor, a relatively rapid charging cycle will occur, particularly if the capacitor is small. Nevertheless, the curve of the charging voltage will be identical with that produced by any physical resistor in conjunction with a capacitor. In this case, the resistance of the charging circuit is the sum of the equivalent battery resistance and the small resistance offered by the capacitor plates.

The Time Constant in Evaluating Sine-Wave Response



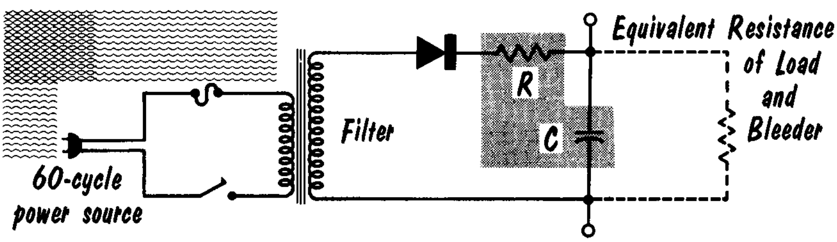
The Low-Frequency Response of the Amplifier is Partly Dependent on the R-C Time Constant of the Coupling Network

Partial Circuit of a Two-Stage Amplifier

The concept of time constant is useful for making evaluations of circuitry response to *sine waves* as well as to pulses. This is simply a manifestation of the equivalence of harmonic and energy-storage analysis. Both analytical methods attain similar conclusions, via different paths. We see a partial schematic of a two-stage audio amplifier. The d-c blocking capacitor C and the grid-return resistor R have the configuration of a high-pass filter which is driven from the signal developed across the plate-load resistor of tube V1. We may now make some useful observations concerning the low-frequency response of the amplifier, providing that there are no limiting factors elsewhere in the amplifier. For C not to discharge appreciably during the time corresponding to one cycle of the frequency involved, the time constant obtained from the product of R and C must be high; C must be a large capacitor and/or R must be a high resistance. If C has the opportunity to discharge appreciably during the time of one sine-wave cycle, the frequency corresponding to such a sine wave will suffer attenuation and a loss of signal level will occur. Consequently, we can say that the time constant R-C must be several times the period of the lowest frequency we desire to pass without considerable fall-off in response. (Of course there will be other low-frequency limitations in an amplifier, such as the loudspeaker. However, simple calculation utilizing time constant has prevented the R-C coupling network from becoming such a limitation.)

The Time-Constant Principle in D-C Power Supplies

Another typical use of the time constant as a means of predicting circuit response to sine waves is illustrated by the R-C filter used in conjunction with a low-current d-c power supply. We know from our study of the harmonic composition of pulses that the half-sine wave produced by the half-wave rectifier consists of a d-c component and numerous harmonics, all multiples of the line frequency, 60 cycles. Our filter will fulfill its intended function if it provides high attenuation for all sine-wave components of the pulse and relatively low attenation for the d-c component. The configuration of the filter is recognized as that of a low-pass R-C filter. R will produce across itself a voltage drop of both the d-c and a-c pulse constituents. The a-c drop is desired, the d-c drop is not. The capacitor acts as a load of lower resistance the higher the harmonic impressed across it; it is, however, an open circuit for the steady-state d-c component. These considerations impel us to strive for a large time constant through the use of a low resistance for R, in conjunction with a very high capacitance for C. The time constant R-C should be approximately 10 or more times the period of the first harmonic (the fundamental) in order to obtain satisfactory filtering for common applications of this type of power supply.

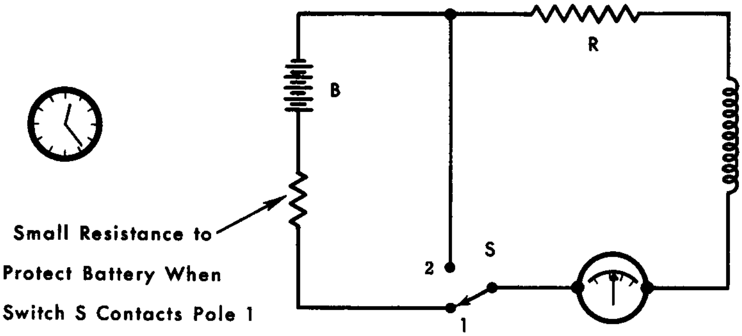


A Simple Power Supply with a Low-Pass R-C Filter

The resistor shown in dotted lines represents the equivalent resistance of the load and bleeder if one is used. In the discussion, it was assumed that the net value of these resistances was high enough to exert negligible effect on C. However, if such parallel resistance is low, it is evident that the time constant of the filter R-C will be effected. During any charging cycle, the maximum voltage that C can charge to will be lowered by virtue of the voltage-dividing action of such resistance with respect to series resistance R. During discharge, the capacitor is provided with a lower resistance path than during charge. This lowered time constant makes it necessary to increase the size of C in order to maintain good filtering action. Thus, it is sometimes necessary to investigate both charge and discharge time constants. If a desired response characteristic stipulates high or low time constants, these stipulations must generally be met by both charge and discharge times.

Comparison of L-R and R-C Networks

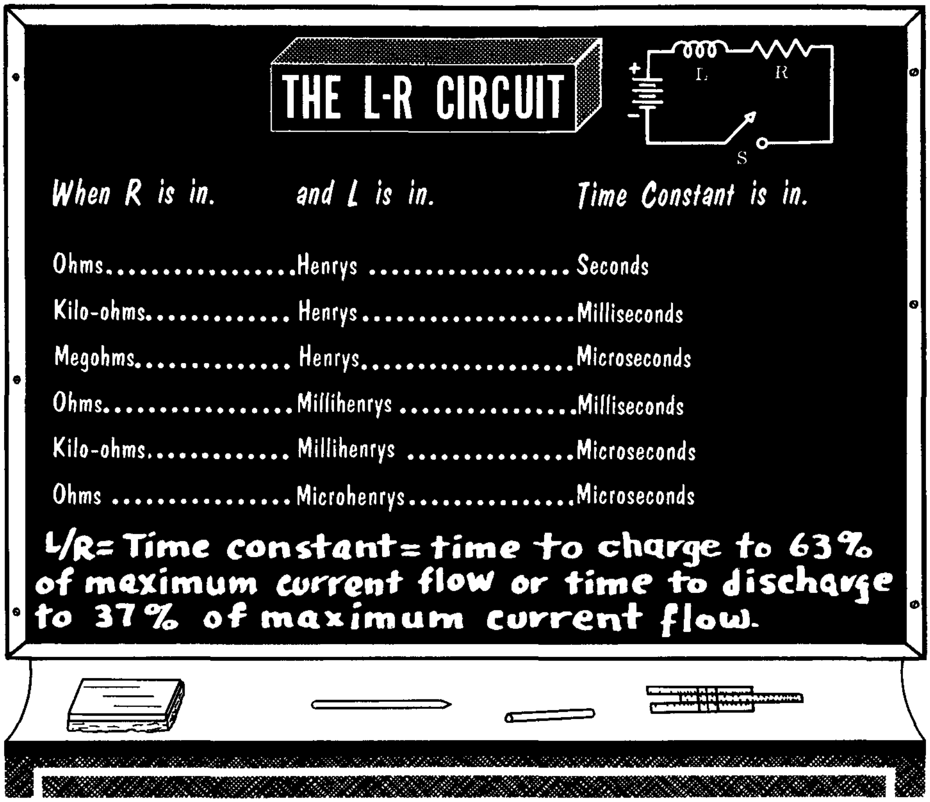
We have discussed inductance-resistance counterparts of resistance-capacitance networks. The fact that a low-pass or a high-pass filter can be made up of a resistor in conjunction with either a capacitor or an inductor would lead us to suspect that the L-R circuit might be accorded the same treatment in terms of charge, discharge, and time constant as the R-C circuit. This is to a large measure true. Energy is stored in the electrostaic field in the capacitor dielectric, it is stored in the magnetic field of an inductor.



Behavior of Current in an L-R Circuit Reveals Energy Storage Phenomena Similar to that of Voltage in the R-C Circuit.

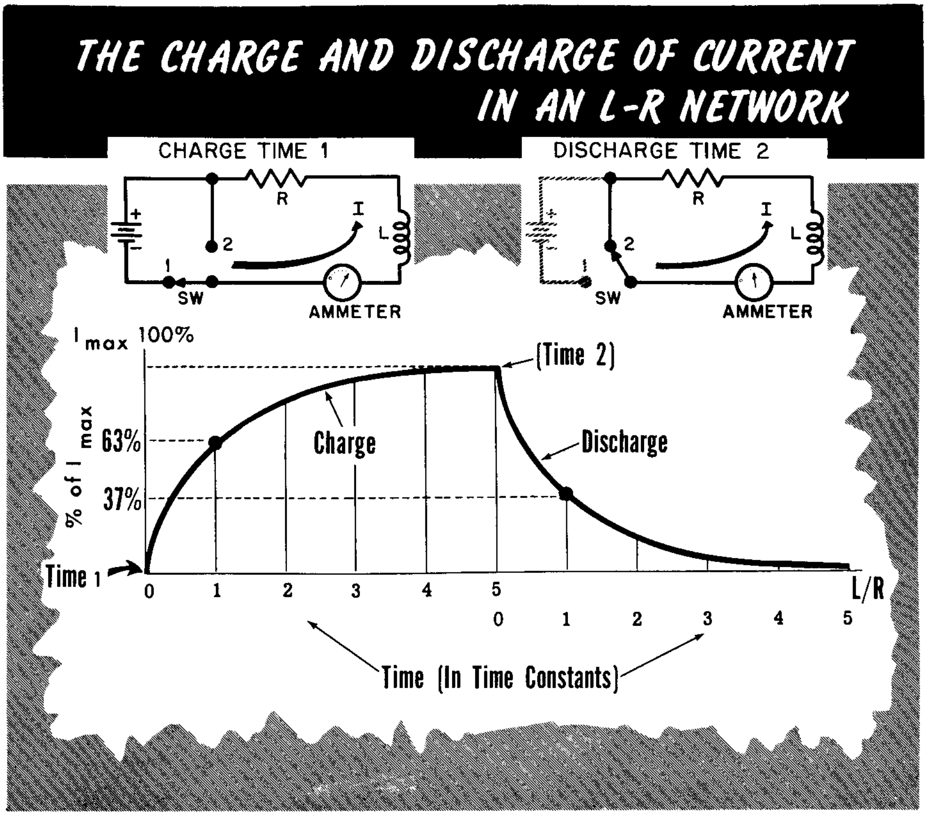
Actually, the arrangement shown is not suitable for making experimental observations because it would be quite difficult to obtain an inductor having the required large time constant to make time and current measurements. Our diagram is, however, symbolic and aids us in recording and plotting data to produce the graph of current versus time. Rather than use a switch in conjunction with a battery, we would employ a square-wave generator. Rather than attempting to read a stop watch, we would use an electronic timing technique such as observation of the charge and discharge transients on an oscilloscope with calibrated timing markers. Also, for laboratory testing, the stored energy of the inductance would largely dissipate itself as an arc when S is changed from position 1 to position 2. This difficulty could be overcome by assuming that S still contacts pole 1 while also contacting pole 2 in the number 2 position. This would, unfortunately, short circuit the battery which would have to be considered expendable. (This latter situation could be circumvented by inserting a low resistance directly in series with the battery.) Evidently, the L-R circuit requires considerations additional to those involved in the R-C circuit.

Inherent Resistance in an Inductor



A previous statement concerning inductive circuits is relevant at this time. It has been mentioned that the inductor is not as pure an element as is, or can be, the capacitor. (Resistance cannot be reduced to the same degree relative to energy storage in the inductor as in the capacitor.) This prevails despite the fact that very large inductance values may be readily attained from inductors. The difficulty we encounter is due to the basic time-constant relationship for L-R circuits. This is expressed by the ratio of inductance to resistance, that is L/R. Unfortunately, practical design considerations dictated by the best available core material and by physical dimensions make it exceedingly difficult to construct an inductor in which L is numerically large compared to R; conversely, R cannot be made relatively small with respect to L. Hence, L/R (the *time constant) cannot under ordinary circumstances be made very large.* Note that the inductor, by virtue of the resistance inherent in its winding is, in itself, an L-R circuit. A physical resistance connected in series with the inductor merely adds to its self-resistance.

Graphic Representation of L-R Charge and Discharge

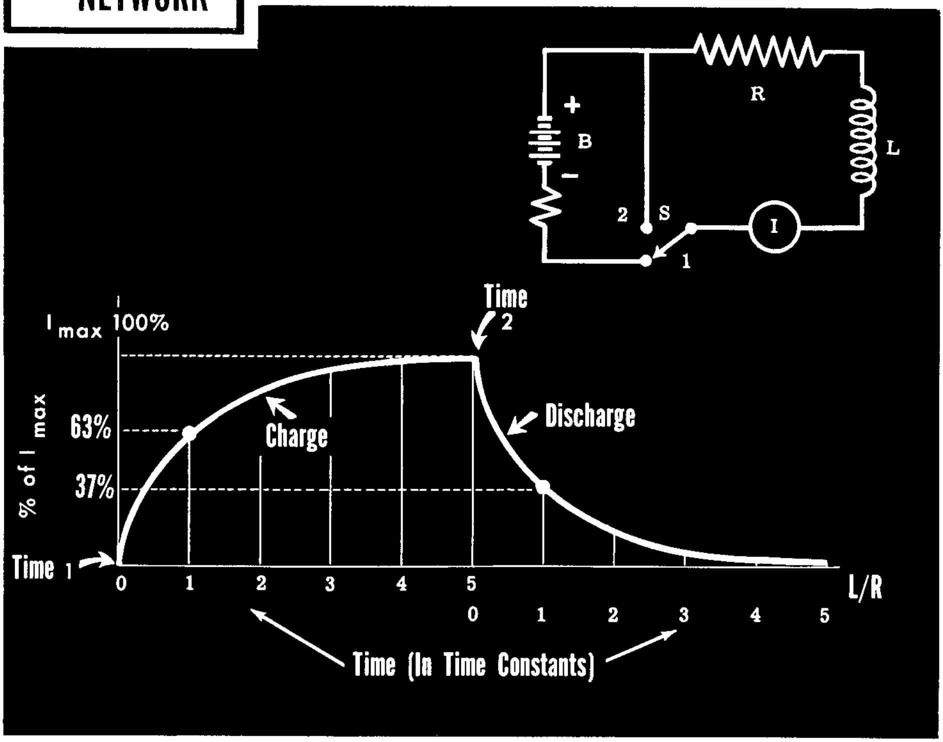


We see the exponential charge and discharge of current in the L-R circuit. We are again considering current through the inductor rather than the voltage across its terminals. As already pointed out, the voltage across the terminals of the inductor would not vary in an exponential manner, which is necessary in order to apply the concept of time constant in the same way as with the R-C circuit. The presence of series resistance does not modify the exponential variation of current other than its effect upon the length of the time constant, which is the opposite from that prevailing in the R-C circuit. (Greater series resistance produces a higher time constant in the R-C circuit, but a lower time constant in the L-R circuit.) Significantly, time constant, once computed, has exactly the same meaning in both circuits. The charge and discharge shown would be obtained if we could read corresponding currents and times quickly and accurately enough with the arrangement on page 87. Note that these curves are replicas of the universal charge and discharge curves of pages 80 and 83 with the exception that the curves now represent percent of maximum current rather than voltage.

Graphic Representation of R-L Charge and Discharge (contd.)

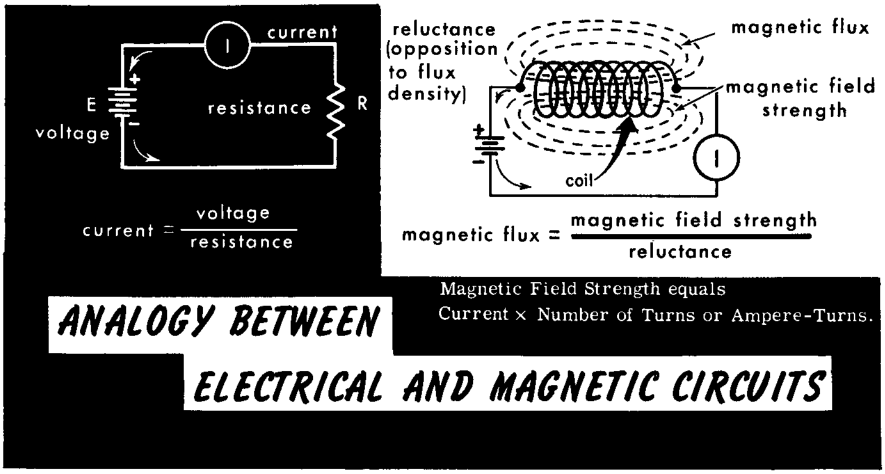
During charge (current rise time) in the inductor, the current follows the same law of rise as the capacitor voltage in the R-C network. During discharge, the current in the inductance follows the same law of decay as the capacitor voltage in the R-C network. At time 1, the switch is placed in its number 1 position and charging commences. At time 2, the switch is in the number 2 position and discharge takes place through the inductor.

THE CHARGE AND DISCHARGE OF CURRENT IN THE L-R NETWORK



The maximum current which can flow in the L-R circuit is the Ohms law value E_B/R. (R represents the sum of the circuit resistance and the resistance of the inductance itself). This is the steady-state current in the circuit, the current which flows following completion of the charging cycle. Electromagnetic induction prevents the currents from establishing its ultimate Ohm's law value when the battery is first connected to the circuit. The counter-emf that is generated is the mechanism responsible for the delay in steady-state current in the L-R circuit.

Analogy of Magnetic and Electrical Terms



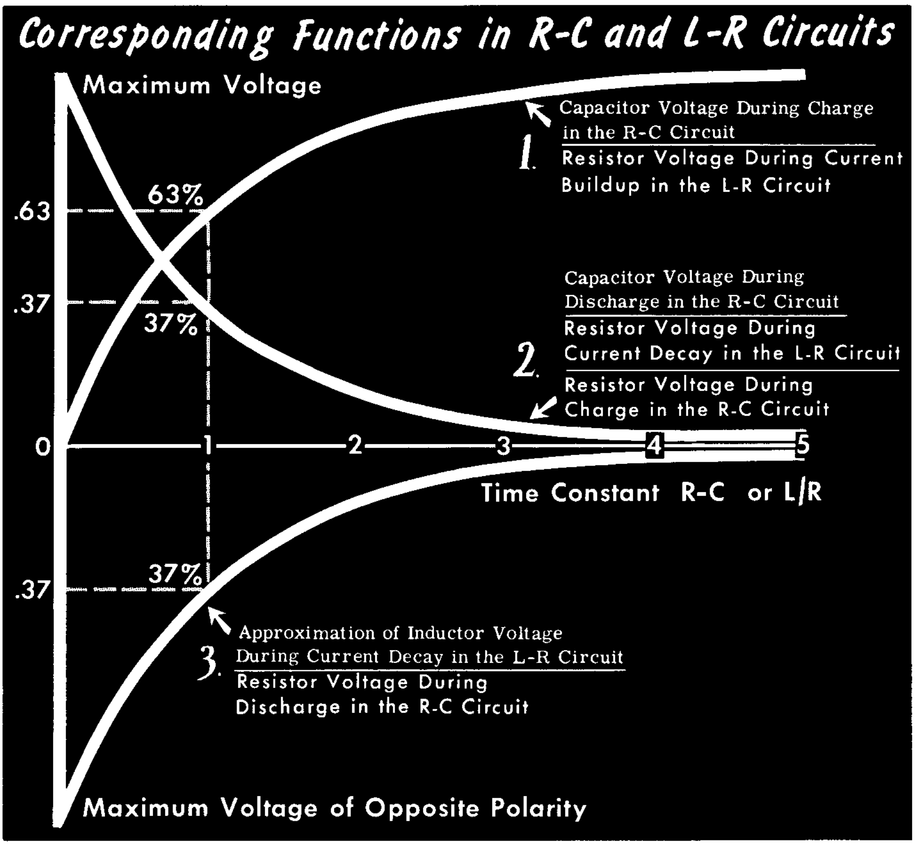
Now it is pertinent to review magnetic concepts involved in electromagnetic induction. It will be recalled, first, that the flow of the electric current is always accompanied by magnetism. Magnetism has two basic measurement aspects, field strength and flux. Field strength is the pressure or driving force which sets up a given flux in a magnetic circuit. How much flux is caused to circulate in a magnetic circuit by a given field strength is governed by the permeability of the substance through which the magnetic flux must pass. This situation is analogous to the electric circuit in which the amount of current which a given voltage can cause to flow in a circuit is governed by the conductivity of the electric circuit elements. In the magnetic circuit, air and all substances which are not magnetized have very low permeabilities, whereas iron, cobalt, nickel and various alloys have relatively high permeabilaties. Reluctance, another term frequently encountered in magnetics, is simply the *reciprocal* of permeability. High permeability means low reluctance and vice versa. It is the same situation encountered in the electric circuit wherein we say that resistance is the reciprocal of conductance; high conductance means low resistance and vice versa. The basic correspondence between the magnetic and the electric circuits are as follows:

magnetic field strength corresponds to *voltage potential or emf*
magnetic flux corresponds to *current*
permeability corresponds to *conductivity*
reluctance corresponds to *resistance*

It is true, by virtue of these correspondences, that an Ohm's law for the magnetic circuit exists. Corresponding to the relationship in the electric circuit in which *voltage/resistance* equals *current,* we have for the magnetic circuit the analogous expression, *magnetic field strength/reluctance* equals *magnetic flux.*

Comparing R-C and R-L Network Curves

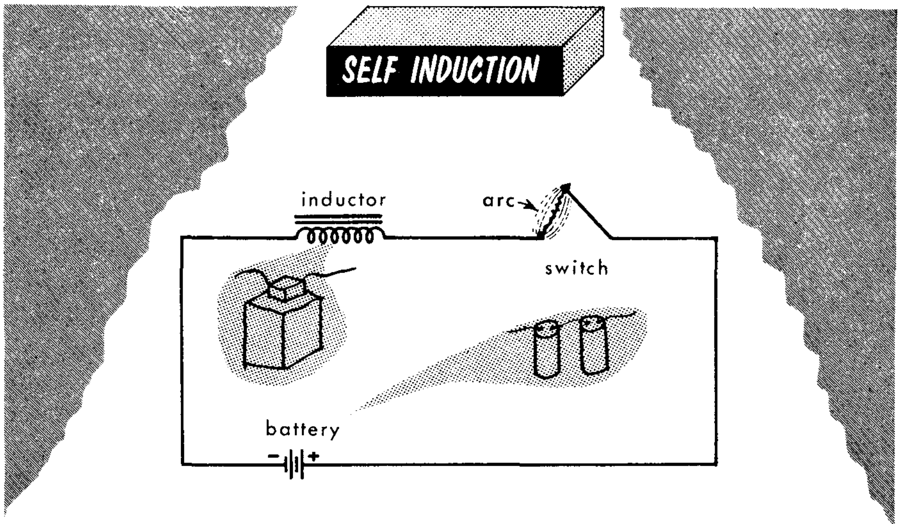
It is interesting to compare time constants in R-C and R-L circuits. (We have already established equivalences of high-pass and low-pass configurations for the two circuits.) The universal curve of capacitor-charging voltage in the R-C circuit is much the same curve as that representing resistor voltage during current buildup (charge) in the L-R circuit. Similarly, capacitor voltage during discharge in the R-C circuit is represented by the same curve depicting resistor voltage during discharge in the L-R circuit. The voltage across the inductor during current buildup approximates the resistor voltage during charge in the R-C circuit. (Inductor resistance prevents these two compared quantities from being identical.) The same approximation applies during *discharge* in the two circuits.



Page 92 shows that three basic curves represent in theory, or approximate in practice, all voltage functions in circuits containing a resistance in series with an energy-storage element, that is, a capacitor or an inductor.

Effect of Magnetic Self-Induction in a Circuit

The magnetic-field strength developed in an inductor is equal to the product of the number of turns in the inductor winding and the current flowing through those turns—*magnetic-field strength* = *number of turns* × *current.*

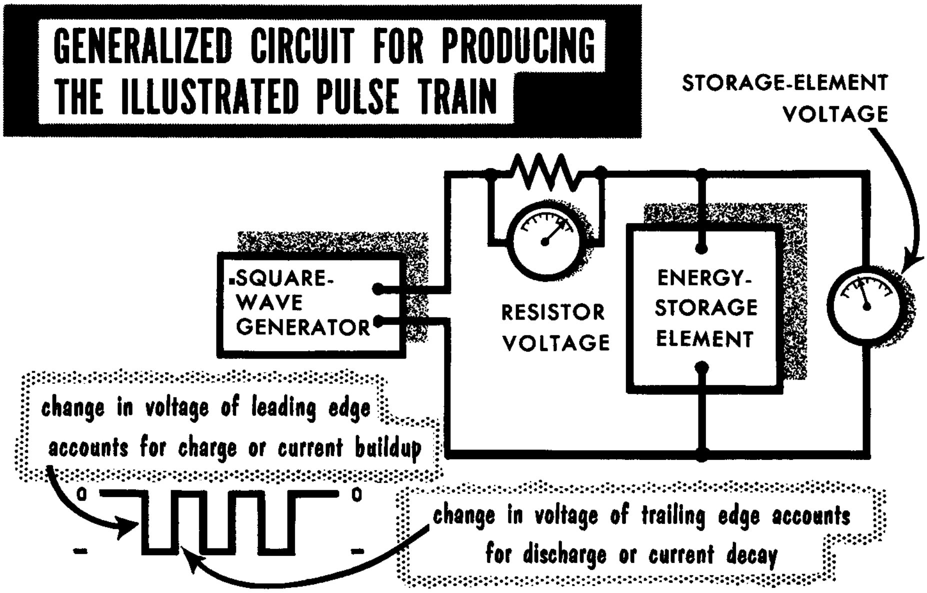


When the switch is opened, the self-induced voltage of the inductor is considerably greater than is the battery voltage

If the current flowing through an inductor is changed in value, the magnetic-field strength will also change. A change in magnetic-field strength, in turn, causes the magnetic flux to change (providing the inductor core material is not magnetically saturated). The change in magnetic flux brought about in this way produces the same result as a change in magnetic flux caused by actual physical movement of a magnet in the vicinity of an inductor, namely a voltage is induced in the inductor. This self-induced voltage is so polarized as to oppose the current change responsible for it. This phenomena, appropriately called *self-induction,* is only evidenced when we try to change the current flowing in the inductor. The more violent the current change, the more pronounced is the opposition to this change. This is why the sudden opening of a switch in an inductive circuit carrying a heavy current is attended by an arc across the switch terminals. Here, the opposition voltage of self induction, generally termed *counter-electromotive force,* is considerably greater than the battery or source voltage.

Effect of Magnetic Self-Induction on a Square Wave

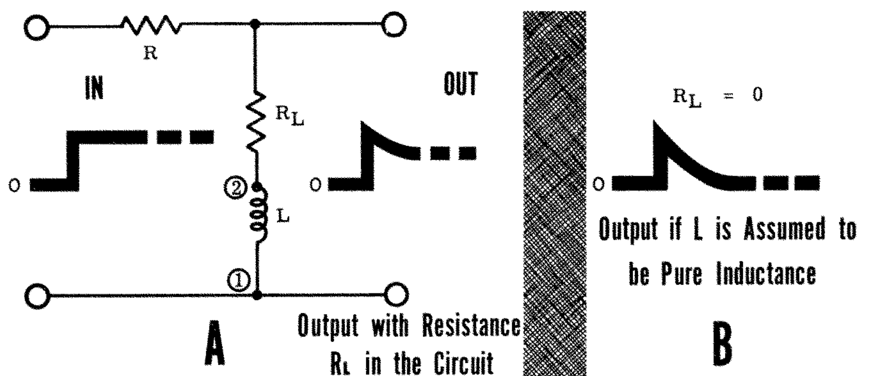
If, instead of a manually operated switch, the current change in an inductive circuit is produced by a square-wave generator, there is no opportunity for the energy of the magnetic field to suddenly dissipate itself as heat, light, and sound in an electric arc. Rather, the current changes are counteracted by the effect of the counter-electromotive force in the only other way the opposition to change can manifest itself, by delaying the rate of change. Because of counter-electromotive force, the maximum source voltage is not immediately available as far as the inductor is concerned, to force maximum current through it.



We now can account for the opposite effects of series resistance on the time constants of R-C and L-R circuits. We decrease the L-R circuit time constant when we increase the series resistance because such resistance reduces the magnitude of the current which, at any time, can flow in the inductor under pressure of battery voltage. If, because of the series resistor, we limit current, or more specifically, the change of current, the self-induced electromotive force will be less than would otherwise be the case. The reduced electromotive force of self-induction bucks the inrushing current less effectively, thereby allowing quicker buildup time. This is shown by the smaller time constant, which is derived from the quotient L/R. Although time constant in the R-C circuit is a product, and although it is a quotient in the L-R circuit, once it is derived the time constant has precisely the same significance in both circuits.

Exponential Variation of R-C and R-L Parameters

Although we have investigated the current transient in L-R circuits, it most frequently happens that *voltage* is the parameter we are primarily interested in. We may therefore think of the voltage across the inductor, rather than the current through it. In so doing, we must realize that the voltage transient is not the exponentially shaped curve we would like to deal with, but is distorted by the effect of the resistance contained in the inductor. We see a true exponential voltage variation due to the inductive component of the inductor and the distorted curve resulting from the effect of the self-resistance of the inductor. Contrary to this situation, the voltage monitored across a physical resistance inserted in series with the inductor is exponential and can be represented by a universal curve plotted in terms of time constants. No matter what the combination of inductance and resistance, the universal curve depicts the number of time constants required for a given change of voltage to occur across the series-connected resistance. The actual number of seconds elapsing for such a change will, however, depend upon the values of the inductance and resistance in the circuit.



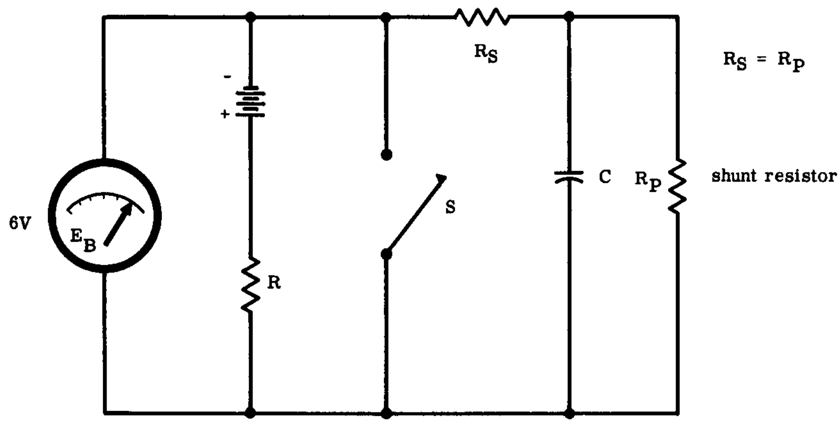
DEGRADATION OF EXPONENTIAL VOLTAGE CHANGE ACROSS INDUCTOR TERMINALS BECAUSE OF THE RESISTANCE CONTAINED IN THE INDUCTOR

The exponential curve is a fundamental mode of change, often encountered as a cause-effect relationship in natural phenomena. In curve 1 on page 92 the rate of voltage increase is inversely proportional to the *stored voltage.* In curves 2 and 3 of the same figure, the rate of voltage decrease is directly proportional to the stored voltage. Both of these statements define exponential curves. It is instructive now to refer back to our hydraulic analogy. As the small tank fills, it exerts more back pressure, thereby diminishing its filling rate.

Effect of Shunt Resistance on R-C Time Constant

Thus far, we have focused our attention upon simple series arrangements of a resistance and a storage element. Parallel resistance connected across an inductor has been discussed as a means of damping shock-excited oscillations, but nothing has been said concerning the effect of such resistance upon the time constant of a circuit comprising a storage element in conjunction with resistance. The effect of resistance shunting the storage element is shown in the figure below. The ordinary R-C low-pass filter consisting of R_s in conjunction with C is modified by resistance R_p. The six-volt battery, resistance R and the switch S, constitute a square-wave generator which can be manually operated at at slow pulse-repetition rate. Observation of charge and discharge cycles are made on an oscilloscope. Resistance R protects the battery when the switch is closed, by limiting the current flow. Other than this, R need not be considered in the operation of the circuit since it is also assumed to be so much lower than R_s that its effect upon time constant is negligible. For the sake of simplicity, we shall assume that R_s and R_p are of equal resistance.

A SHUNT RESISTOR DOES NOT CHANGE THE R-C TIME CONSTANT DURING CHARGING TIME

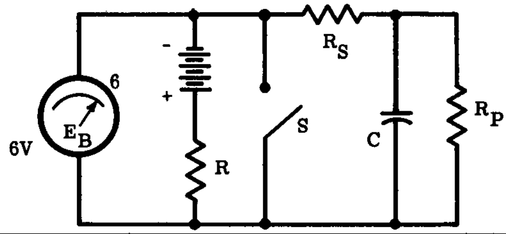


Switch S has been closed for a length of time much greater than any circuit time constant. When we open S, six volts is suddenly available to the network consisting of R_s, C, and R_p. However, due to the voltage-divider action of R_s and R_p, only one-half of the battery voltage is available for C. Since the current flowing into C passes through R_s but not R_p, the time constant during change remains R_s, times C, uninfluenced by the presence of R_p.

Effect of Shunt Resistance on R-C Time Constant (contd.)

After the capacitor voltage has, for practical purposes, attained its maximum charge corresponding to *three volts,* S is opened. The capacitor now discharges through the parallel combination of R_s and R_p. Thus, the time existing for discharge is less than that required for charge. In our example, the discharge time constant is one-half that during charge. This is because the effective resistance resulting from R_s and R_p in parallel is one-half the value of either R_s or R_p. (Recall that these two resistances were assumed to be of equal value in this example.)

Resistance in Parallel with the Energy-Storage Element Reduces Total Voltage Excursion and Makes Charge and Discharge Time Unequal



A

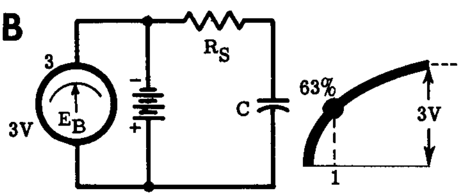
$R_S = R_P$

A Low-Pass R-C Network in Series with R_S, but Shunted by R_P.

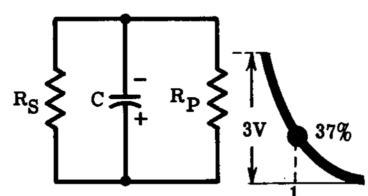
Equivalent of Circuit A when S is Open and C is Charging

Equivalent of Circuit A when S is Closed and C is Discharging

B



C



Charge Time Constant $R_S \times C$

Discharge Time Constant $= \dfrac{R_S \times R_P \times C}{R_S + R_P}$

Similar situations may be readily postulated for other series-parallel combinations. Essentially, they do not differ from one another. The resistance in parallel with the storage element always acts as one arm of a voltage divider, the series-charging resistor constituting the other arm. This voltage-divider action always reduces the voltage excursion of the charge and discharge transients to some fraction of the source voltage. Furthermore, charge and discharge time constants are made unequal by the presence of the resistance shunting the storage element.

QUESTIONS

1. Two identical R-C circuits, each consisting of a capacitor and resistor connected is series with a switch and battery, are energized at the same time. The battery of one R-C circuit has 12 volts, that of the other R-C circuit has 120 volts. In which of these circuits does the capacitor first attain a charge corresponding to one constant (63% of maximum charge)?

2. A charging circuit is composed of a 1-meg resistor in series with a 1 μf capacitor. It is desired to replace the capacitor with a physically smaller 0.1 μf capacitor. How should the resistor be changed to maintain the same time constant?

3. What would be the theoretical objection to defining a time constant as the time required for a capacitor or inductor to charge to maximum values?

4. A capacitor which has been energized in a d-c circuit manifests its energy storage some time later when its terminals are shorted. However, an inductor once removed from its circuit never shows evidence of stored energy when its terminals are short circuited. Is this because practically available inductors do not store sufficient energy to produce a spark? Explain.

5. Which has the greater time constant, an R-C circuit consisting of 1 μf in series with a resistance of 10,000 ohms or an L-R circuit composed of an inductance of 1 henry in series with a total resistance of 100 ohms.

6. What waveshape can result from the combining of the charge-discharge characteristics of capacitors and inductors.

7. How is energy storage related to frequency response?

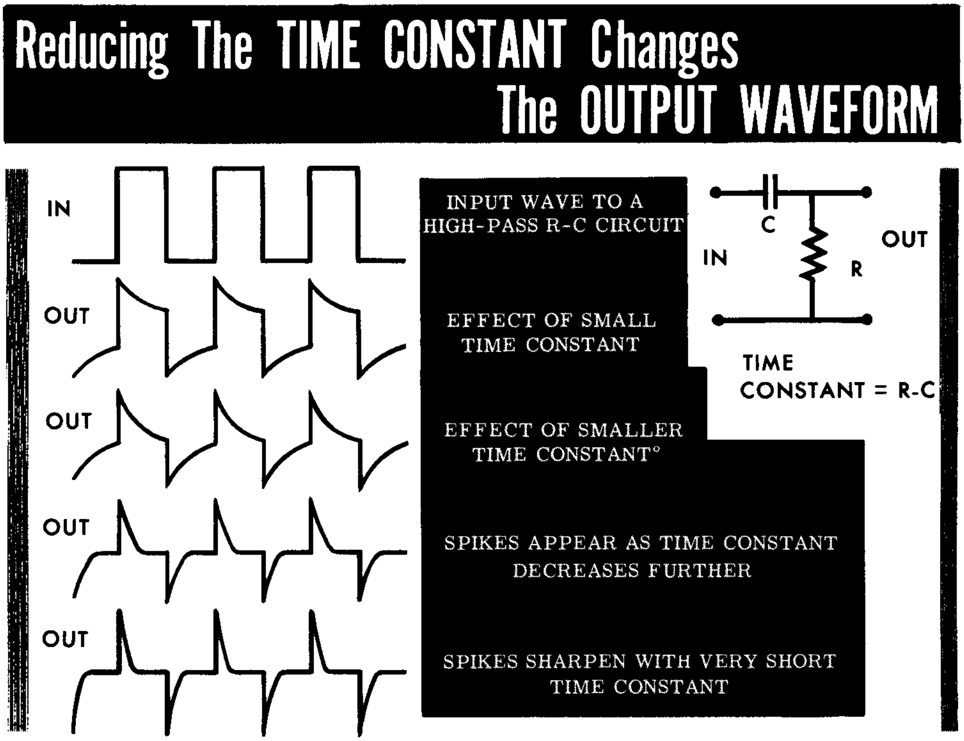
8. What are the principle effects of resistance connected in parallel with a capacitor being charged through a series resistor?

9. In practical electronic circuits would one expect long time constant circuits to be R-C or L-R networks?

10. An a-c square wave is applied to a circuit consisting of a vacuum-tube diode in series with a 1 μf capacitor. What is the time constant during charge, that is, during conduction of the diode, assuming the average resistance offered by the diode is 1000 ohms? What is the time constant for discharge of the capacitor?

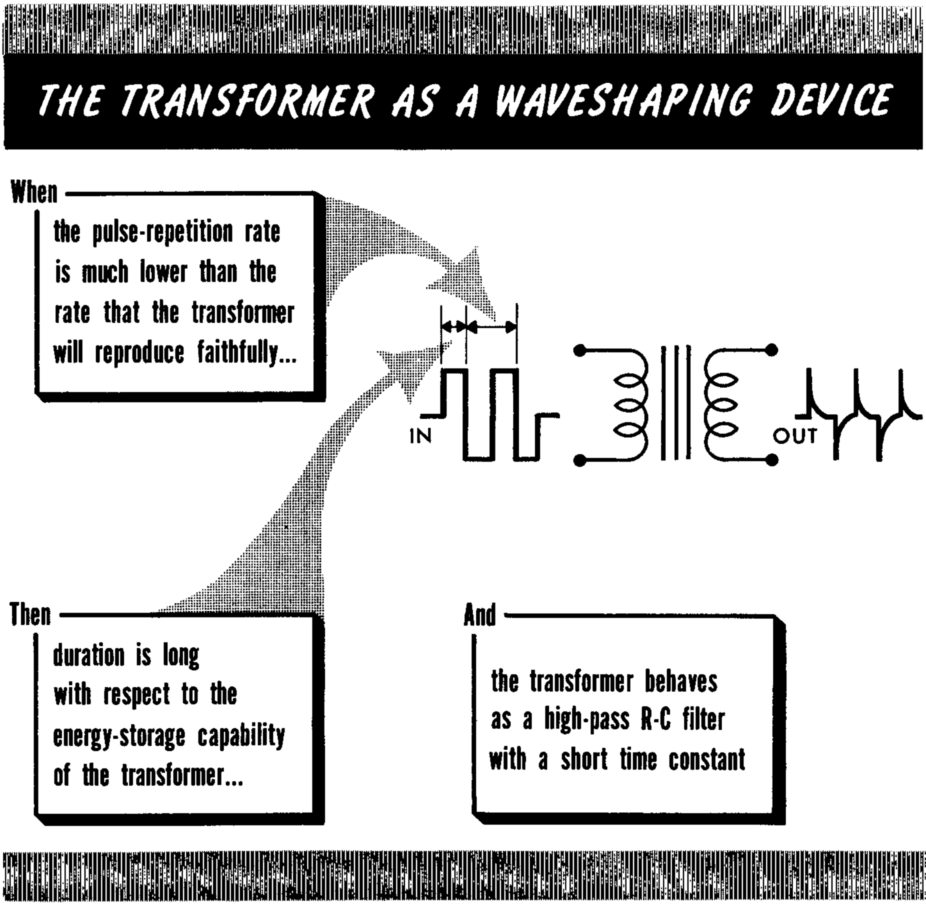
Waveshaping with a High-Pass Filter

We have confined our interest to the significant aspects of waveshape. We have investigated both the Fourier harmonic composition of pulses and pulse-circuit behavior under energy-storage (transient) analysis. Now, we are ready to study some of the more important waveshaping techniques, employing both of these analytical approaches. Both pulse-analysis methods will be applied to practical situations.



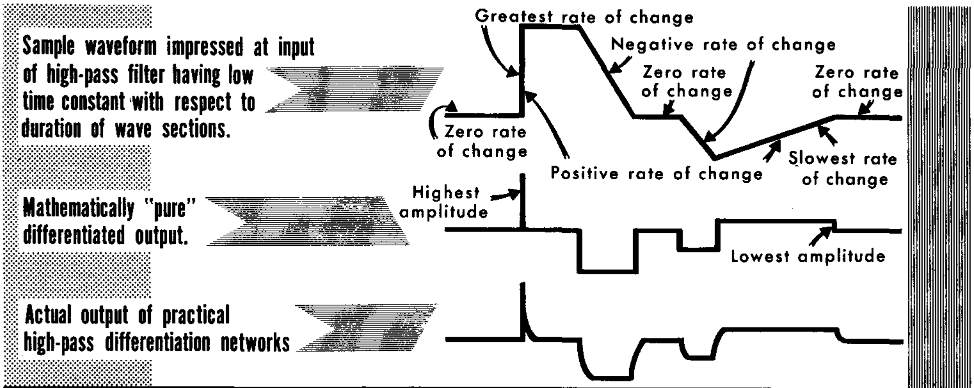
In applications where a sharp spike-like pulse is required, it is common to begin with a square wave having fast rise and decay times. When such a pulse is passed through a high-pass filter which has a small time constant relative to the pulse duration, the emergent pulse is distorted. The smaller the time constant, the less is the reproduction of the horizontal portions of the square wave and the closer is our approach to the desired knife-edge transient. This technique is widely used for circuits requiring synchronization and timing "pips." The L-C high-pass network may be used as well as the R-C network shown, if the tendency toward ringing is damped by a resistor or diode shunted across the inductance. These techniques usually make it more difficult to obtain a clean sharp spike and the R-C circuit is therefore often preferable.

Waveshaping with Specially Designed Transformers



Another technique may provide the type of waveshaping ascribed to the high-pass R-C and L-R circuits. The frequency response of a transformer falls off rapidly below a certain frequency. The low-frequency limit, or *cutoff* frequency of a transformer is governed primarily by its energy-storage capabilities. Transformers with low inductance windings and loose coupling between windings have relatively low energy-storage characteristics and thus cannot reproduce comparatively low frequencies with respect to transformers of converse design parameters. From our knowledge of pulse composition, it is evident that the essential difference between waveforms shown is low-frequency content. The waveform which reproduces only leading and trailing edges of a square wave is relatively devoid of the low frequencies necessary to reproduce the horizontal tops and bottoms of a square waveform.

Waveshaping with Specially Designed Transformers (contd.)

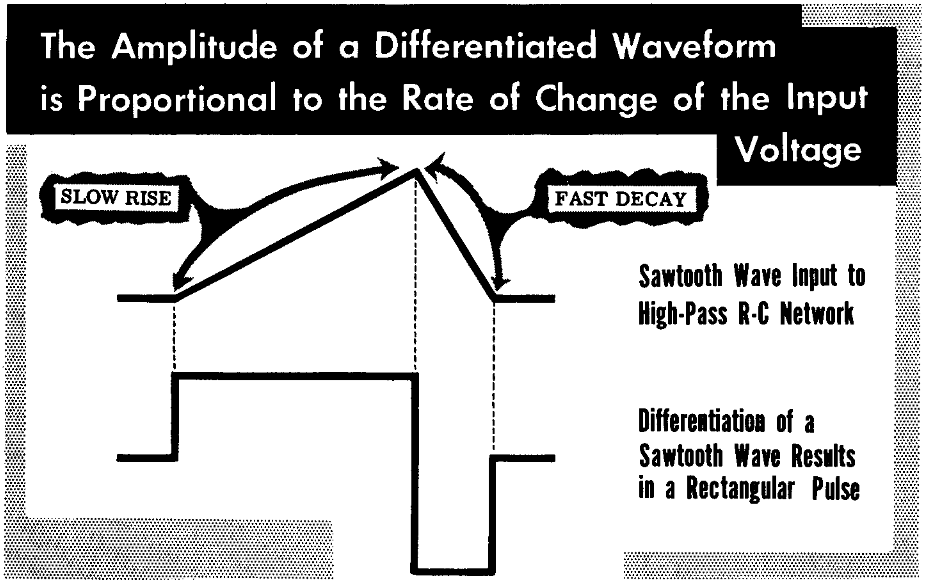


THE PROCESS OF DIFFERENTIATION

The lowest frequency which can be contained in a pulse wavetrain is the fundamental sinusoid, which corresponds to the pulse-repetition rate. The highest frequencies are determined by the rise and decay of the edges, or else by the pulse duration when the duty cycle is extremely low. In order to obtain sharp voltage spikes from the transformer secondary when the primary is excited by a square-current wave, the low-frequency response of the transformer should fall off rapidly below those frequencies required to reproduce the leading and trailing edges of the square wave. The transformer is not simply the L-R circuit with a winding added to the inductor, because the energy-storage capability of the transformer is governed not merely by that of the primary, but also by the inductance of both windings and the degree of coupling between them. The transformer has the desirable practical advantage in that either side of the output circuit can be grounded. Similarly, the secondary voltage spikes can be polarized either way with respect to the current wave in the primary winding. As with the inductor, however, it is generally necessary to impose precautions against ringing. This is accomplished by inserting damping resistors or diodes in the circuits of either or both windings. Note that the input square wave in the case of the inductor and the transformer is the current waveshape needed to obtain voltage spikes at the output. The shape of the voltage wave impressed across the transformer primary winding will vary with the amount of resistance it contains. We see a transformer used as a short time-constant high-pass filter. In order for the transformer to function in this manner, it must have insufficient energy storage to maintain output voltage throughout the duration of the rectangular input pulses. This can be accomplished by limiting the amount of iron comprising the core of the transformer. This does not mean that the operating level is sufficient to produce saturation.

Waveshaping by the Process of Differentiation

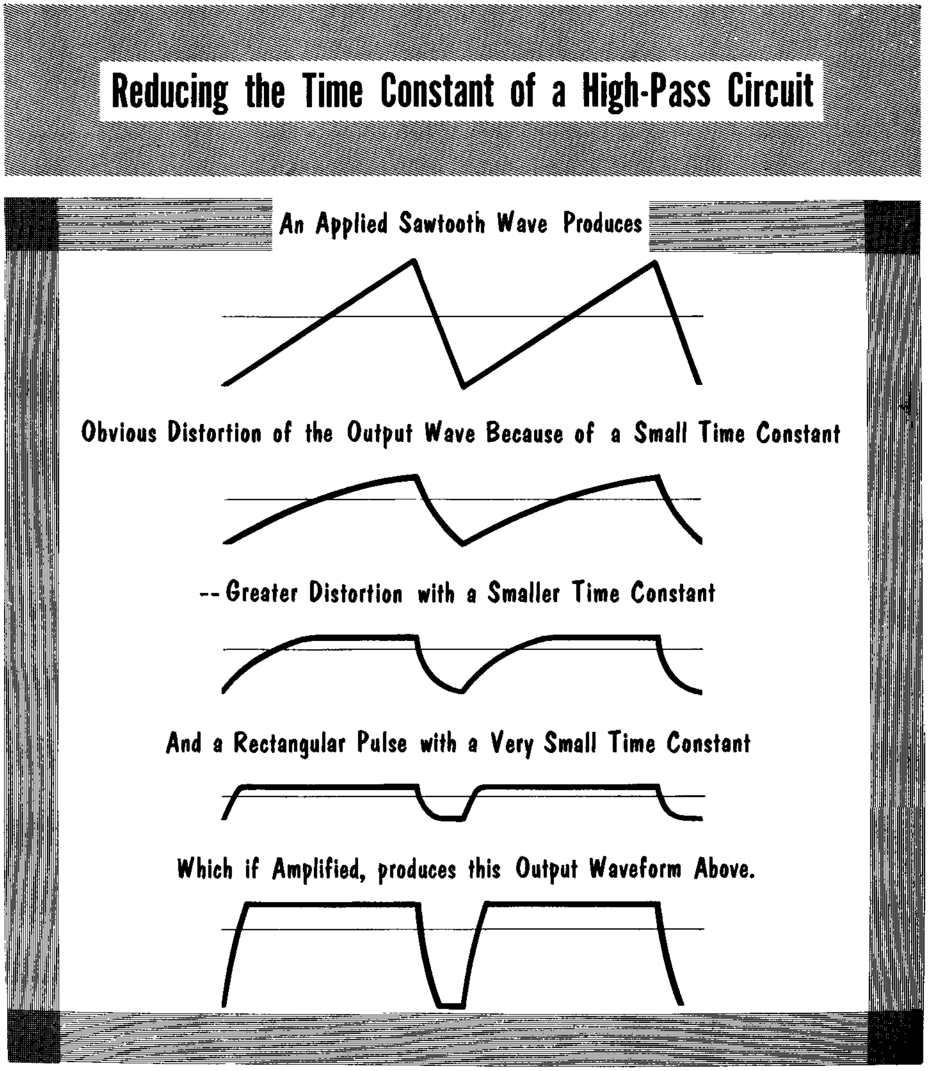
Converting a square wave to a sharp spike is one example of a mathematical process known as differentiation. In differentiation, the amplitude of one quantity is proportional to the rate of change of another quantity. Thus the differential of speed is acceleration. This is so because acceleration is proportional to the rate of change of speed. In high-pass circuits made up of resistance and an energy-storage element, the time constant must be small with respect to pulse duration so that true differentiation can be closely approached. This will become clear in the discussion of the effect of waveshapes other than square waves on the transfer characteristics of the high-pass filter.



The Theoretical Differentiation of a SAWTOOTH

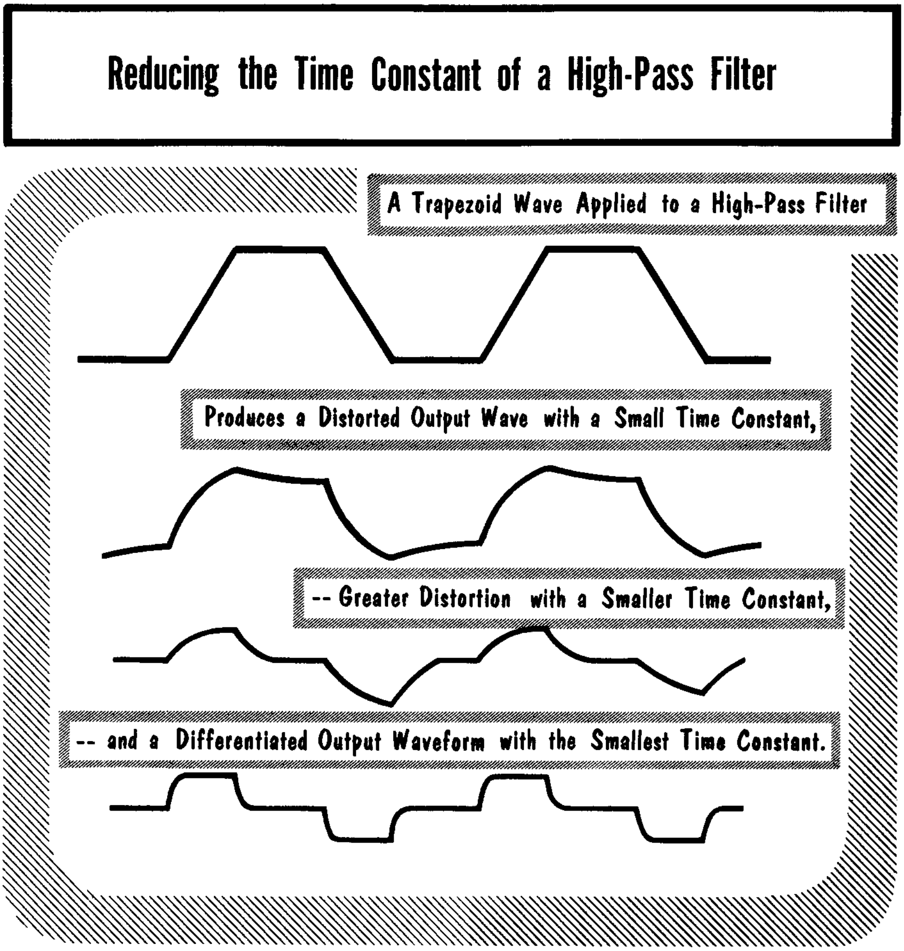
Keeping in mind that differentiation provides an output voltage proportional to the rate of change of input voltage (or current), we can understand the transfer of a sawtooth wave through a high-pass filter with small time constant relative to the leading and trailing edges of the sawtooth. Each edge of the sawtooth represents a constant rate of change of voltage or current with respect to time. Consequently, when we differentiate such a wave, we should expect to obtain sustained levels of the same duration as the leading and trailing edges of the sawtooth. In other words, we convert the sawtooth to rectangular pulses.

Trapezoid Waveform from a Differentiated Sawtooth



In practice, rectangular pulses with vertical sides are unattainable. A near trapezoid is the closest we can approach the rectangular or square wave. We see the improved approximation to the rectangular shape as the time constant of the high-pass filter is reduced. To closely approximate true differentiation, the circuit time constant must be small. This results in considerable loss in peak amplitude. The amplitude is commonly restored by amplifiers.

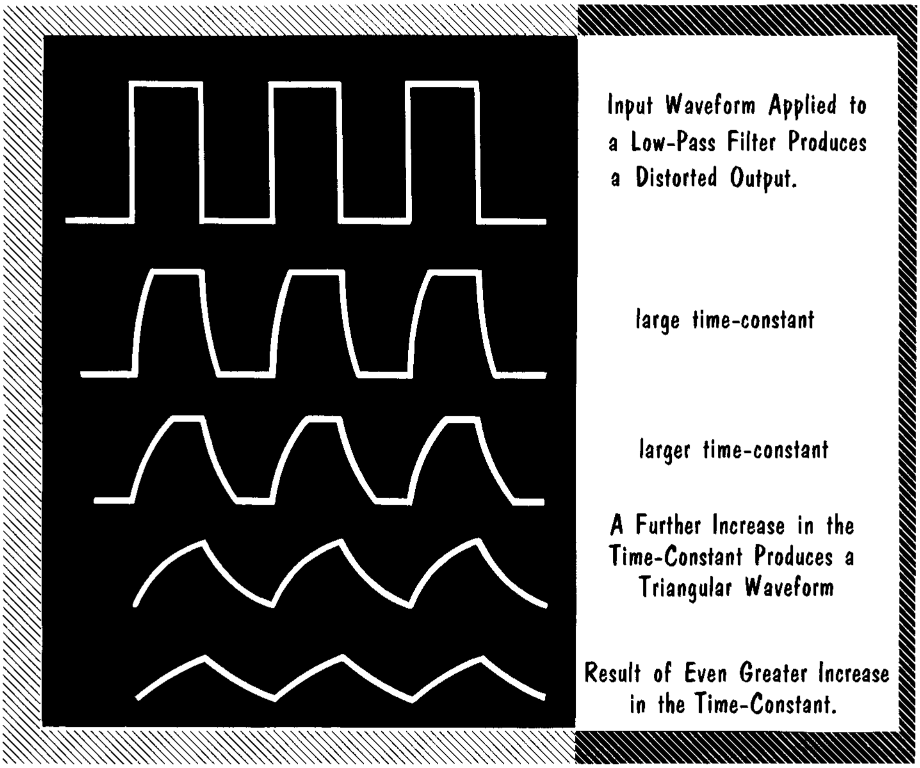
Differentiating the Trapezoidal Input Wave



The trapezoidal input wave is of interest because the "square" or "rectangular" waves generated or used in circuits are actually trapezoids or approximate trapezoids. A true square or rectangular wave is unattainable because the vertical edges would require harmonics extending to infinite frequency, and an infinite number of harmonics. We see the result of decreasing the time constant of the high-pass filter for trapezoid wave input. In the differentiated wave, the tops and bottoms are not those derived from the original trapezoid; they have long since "collapsed" and now form the trailing edges of the differentiated wave. These tops and bottoms are derived from that portion of the rise and decay which correspond to approximately 5 or more time constants.

Integration, the Inverse of Differentiation

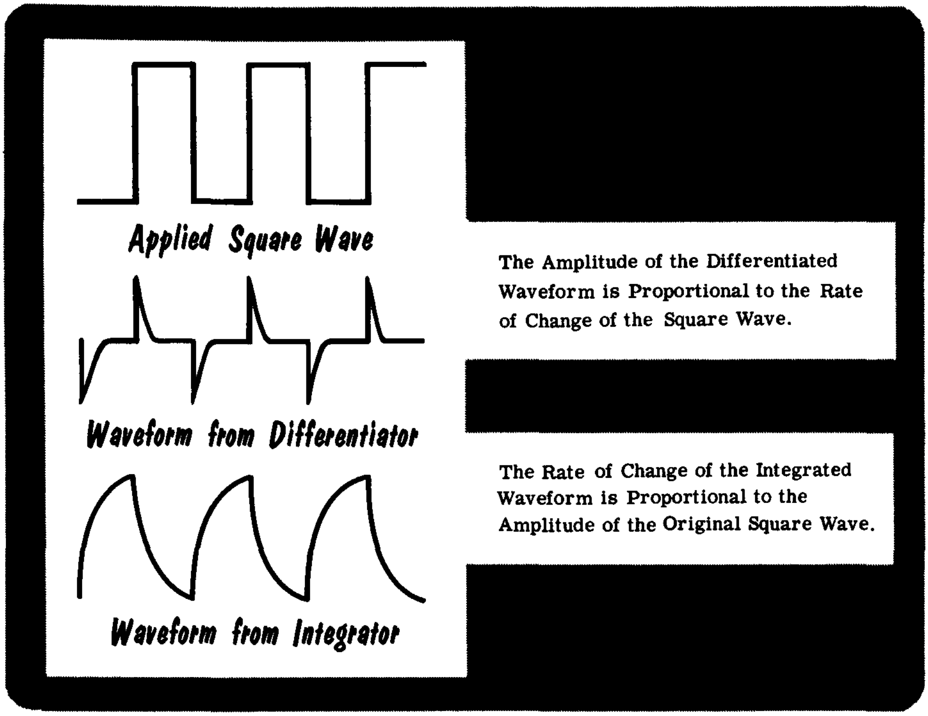
Increasing the Time Constant of a Low-Pass Filter



Our investigation of the differentiating process revealed the same ultimate waveform whether approached from the harmonic composition viewpoint or that of energy storage. The mathematical concept of differentiation was used to correlate the results indicated by these two methods. We will now explore the manner of waveshaping imposed by a reversal of the conditions prevailing for differentiation. For differentiation, we employed a high-pass filter and a small time constant relative to the duration of the impressed pulses. To reverse this situation, we will now deal with low-pass filters with time constants great compared with the duration of the impressed pulses. The low-pass filter may be either of the R-C or L-R variety. We will impress a square wave at the input and investigate the effect of *increasing* the time constant.

Integration, the Inverse of Differentiation (contd.)

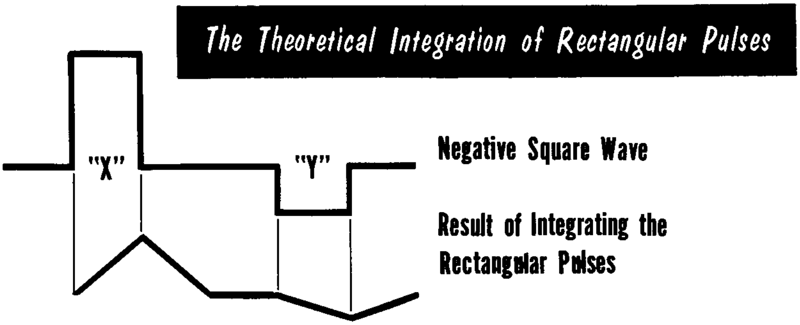
INTEGRATION AND DIFFERENTIATION OF A SQUARE WAVE

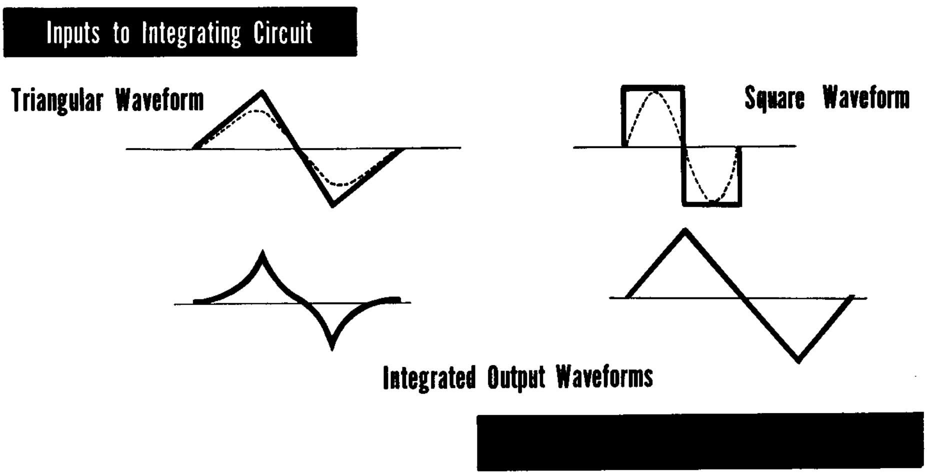


Since the low-pass filter exerts most attenuation for the high frequencies contained in the rise and decay of the square wave, these wave elements suffer distortion. The more the high frequencies are filtered out, the less vertical can be the leading and trailing edges of the resultant wave. From the energy-storage viewpoint, it requires a long time to charge and discharge the capacitor, as is seen in the slow rise and decay of the emergent wave. When the time constant of the low-pass filter is long with respect to the duration of the applied pulses, the resultant waveshape modification is known by the mathematical term, integration, the opposite of differentiation. In differentiation, the amplitude of a derived quantity is proportional to the rate of change of the original quantity. In integration the rate of change of the derived quantity is proportional to the amplitude of the original quantity.

Immunity of the Sine Wave to Integration

We see in the illustration the relationship between the original wave and the integrated wave. The square-wave pulse is positive and has a high amplitude. The integrated wave below it is also positive. Pulse "Y" is negative and of relatively low amplitude. Consequently, the integrated wave below it is also negative and its rise and decay are relatively slow.

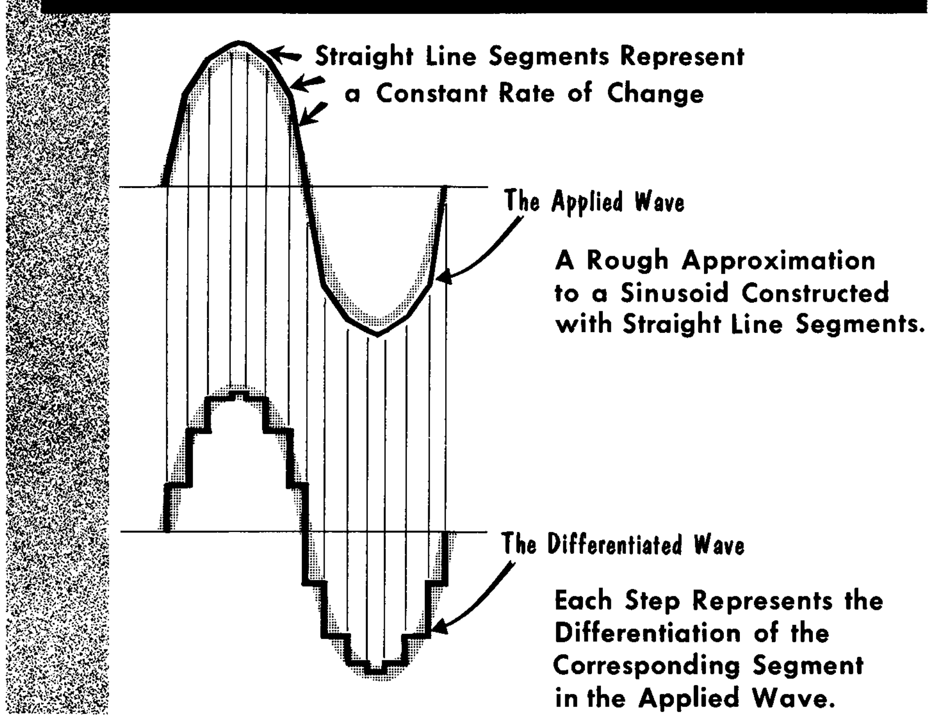




Let us compare the results of integrating *triangular* and *square* waves. The integrated waves shown suggest a waveshape which is unaltered when passing through the low-pass integration circuit. We naturally seek out a waveshape somewhere *between* triangular and square. Such a shape is the *sine wave*. Integration, despite its unique ability to distort other waveshapes, is nevertheless the transfer function of a selective circuit; as such, it has no power to alter the shape of the sine wave. The dotted waves, therefore, can be sine waves.

The Sine Wave Is Also Immune to Differentiation

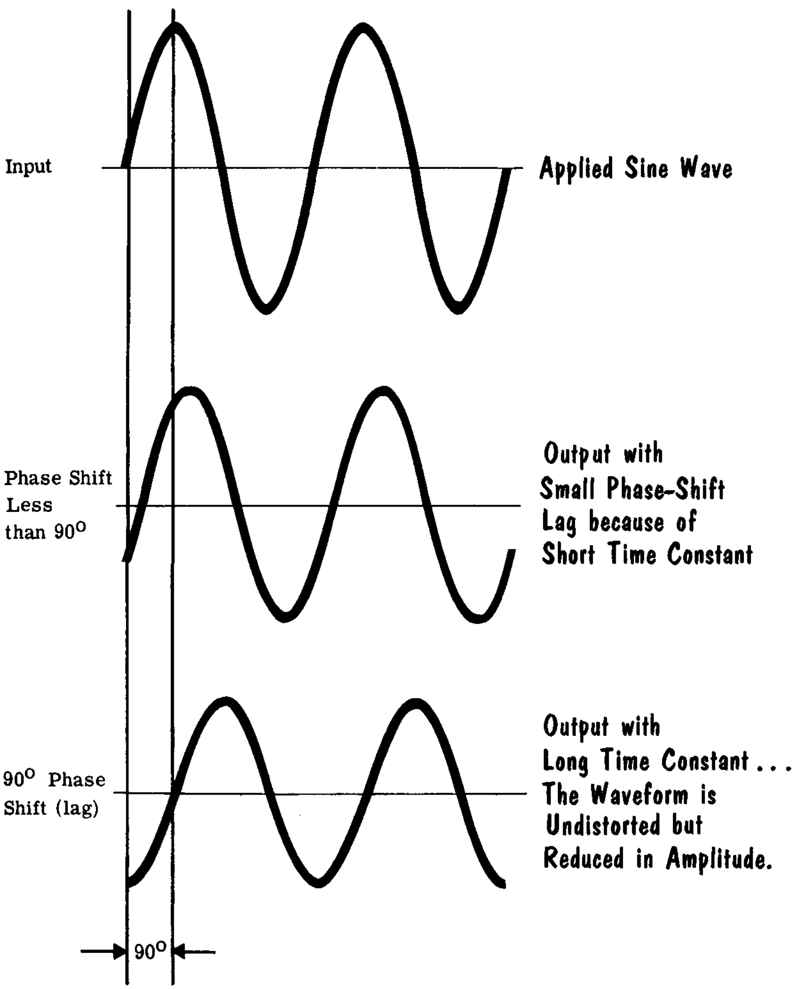
AN EXPERIMENT
SHOWING THAT A SINE WAVE MAY BE PASSED THROUGH A DIFFERENTIATOR CIRCUIT WITHOUT DISTORTION



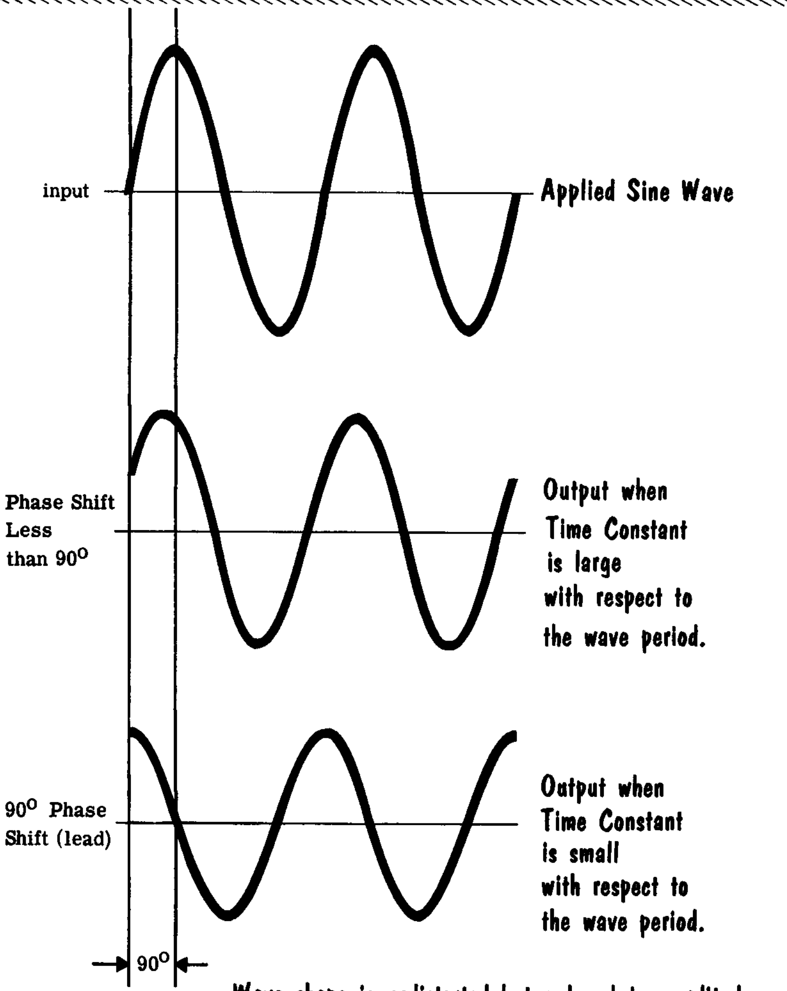
The graph sugests that the sine wave is also immune to distortion by the process *of differentiation* in a high-pass circuit. The segmented waveform is constructed with the aid of an inscribed sine wave. The stepped wave is the differentiated wave. It is constructed by making the amplitude of each step proportional to the slope, or rate of change, of a corresponding part of the segmented waveshape. A smooth line drawn through these steps can approximate the sinusoidal shape. If the segments and steps were made smaller and smaller, both waveshapes would ultimately become exact sine waves: the sine wave enjoys immunity from distortion in all selective circuits containing linear elements. Even with the pronounced effect of the differentiating circuit on the shape of other pulses, the sinusoid slips through unaltered no matter how short the time constant. The graph does not show phase shift.

SINE WAVE PHASE SHIFT DURING INTEGRATION

Which Produces Attenuation and a 90° Phase Shift as a Theoretical Limit.



A SINE WAVE INPUT TO HIGH PASS NETWORK WITH SMALL TIME CONSTANT ATTENUATES THE SIGNAL LEVEL BUT SHIFTS THE PHASE 90° FORWARD AS A THEORETICAL LIMIT

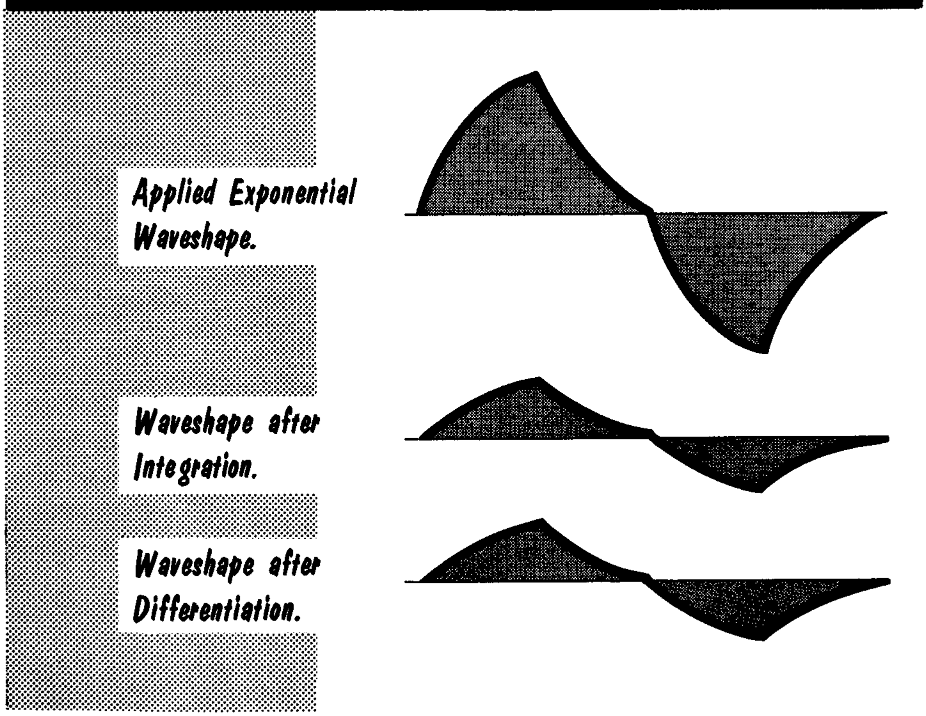


Wave shape is undistorted but reduced in amplitude.

Differentiation and Integration of Exponential Waveforms

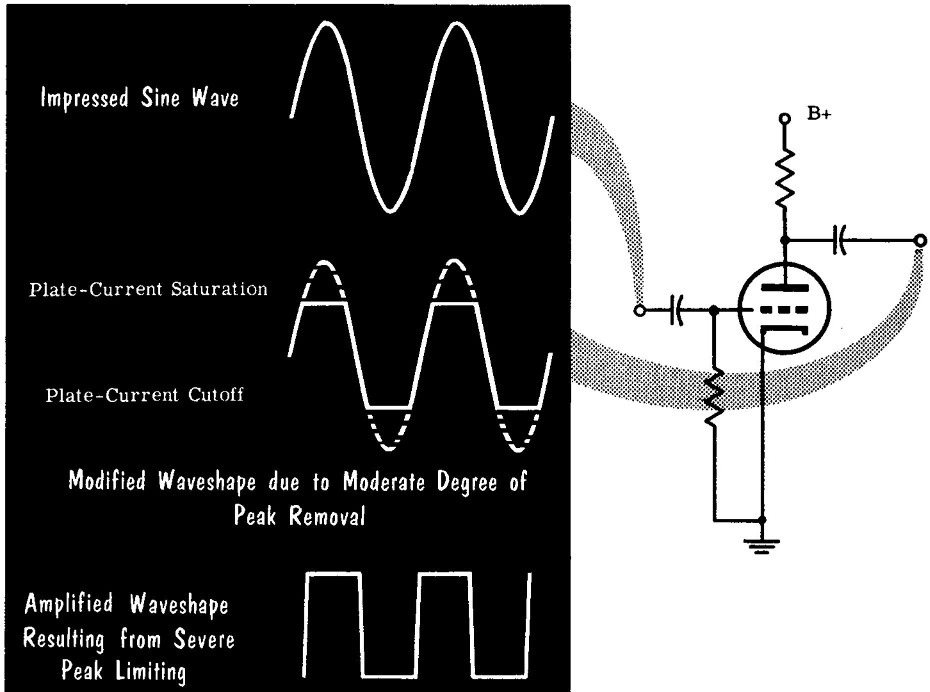
There is *another* waveshape which theoretically is unaltered in shape by integration or differentiation. This is the exponential waveform. It is seldom very pure in shape because the exponential charging and discharging characteristics of storage elements are invariably degraded by the resistances associated with the circuit containing the storage element. That is, a true integrating or differentiating circuit does not really exist. Consequently, for practical electronics, only the sine wave is immune to waveshape modification by integrating, differentiating, or other selective circuits.

Pulses Consisting of Exponential Curves are not Altered in Shape by Integration or Differentiation.



However, a good approximation to the mathematical exponential wave would not be greatly changed by "good" integrating or differentiating networks—R-C or L-R combinations with relatively low resistance. A peculiar property of the exponential wave is that its phase is not shifted by integration or differentiation. Its amplitude is, however, greatly attenuated, as is any other waveshape subjected to integration or differentiation.

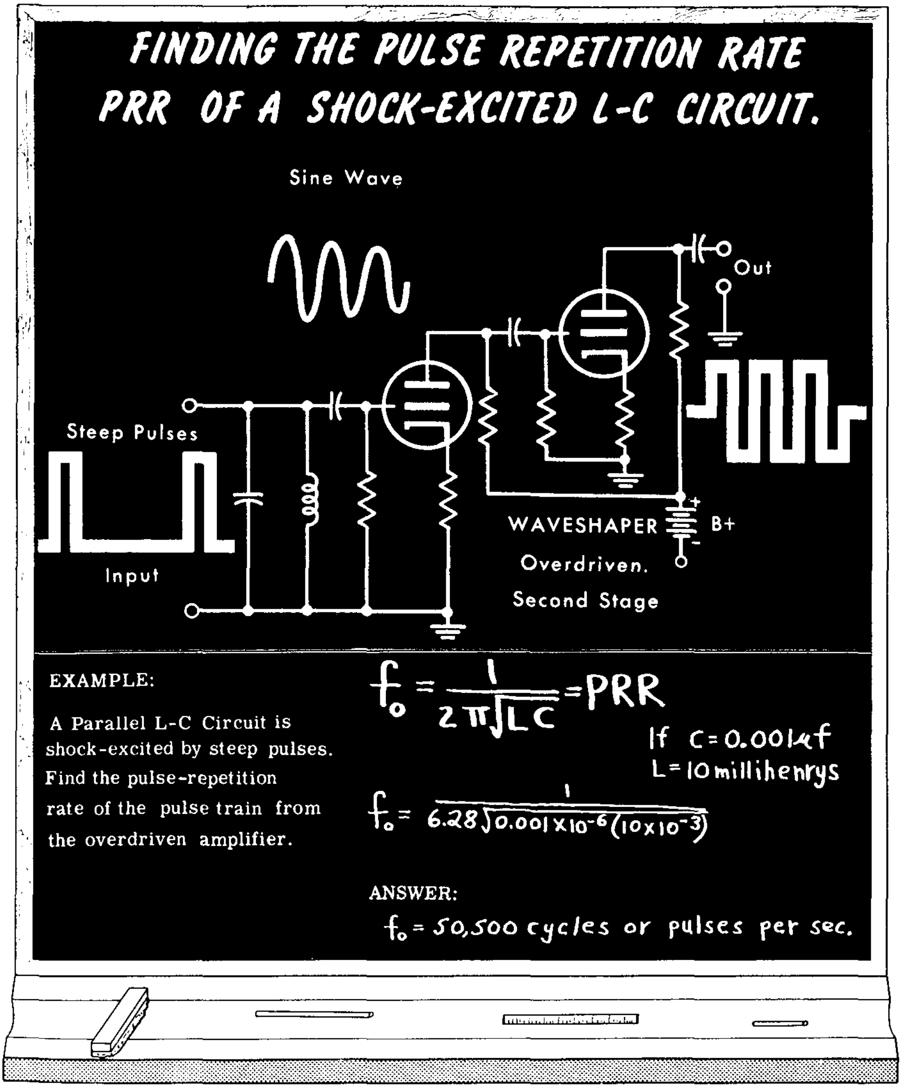
Waveshaping by Nonlinearity



A SINE WAVE SUBJECTED TO PEAK LIMITING CAN BE CONVERTED TO A FAIRLY GOOD APPROXIMATION OF A SQUARE WAVE

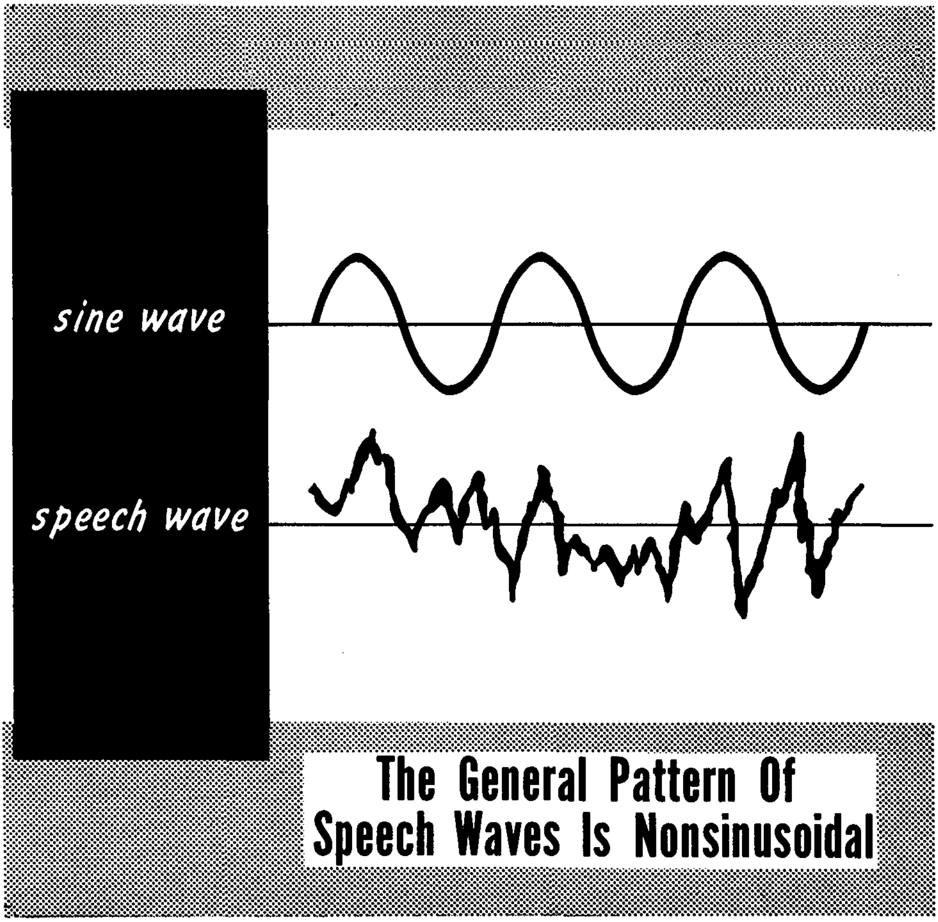
In addition to the waveshaping of passive linear circuits, circuits containing elements which are nonlinear, discontinuous, or which produce pulses under the stimulus of a triggering signal are also widely used for waveshaping. Many of these circuits are more properly treated as pulse generators and will be so discussed later. One very common shaping technique based upon the discontinuous amplitude response of a vacuum tube excited by a high-level signal is shown. The positive excursions of the applied sine wave drive the tube into its plate-current saturation region. The negative excursions of the applied sine wave drive the tube into its plate current cutoff region. As a consequence of these operating conditions, the output-voltage waveform obtained from the plate of the tube has horizontal tops and bottoms. The leading and trailing edges of the output wave reproduce only the relatively small midsection of the applied sinusoid. This clipping technique provides us with a trapezoidal wave which, for many practical purposes, can serve the functions expected of a square wave.

The Repetition Rate of a Pulse Train



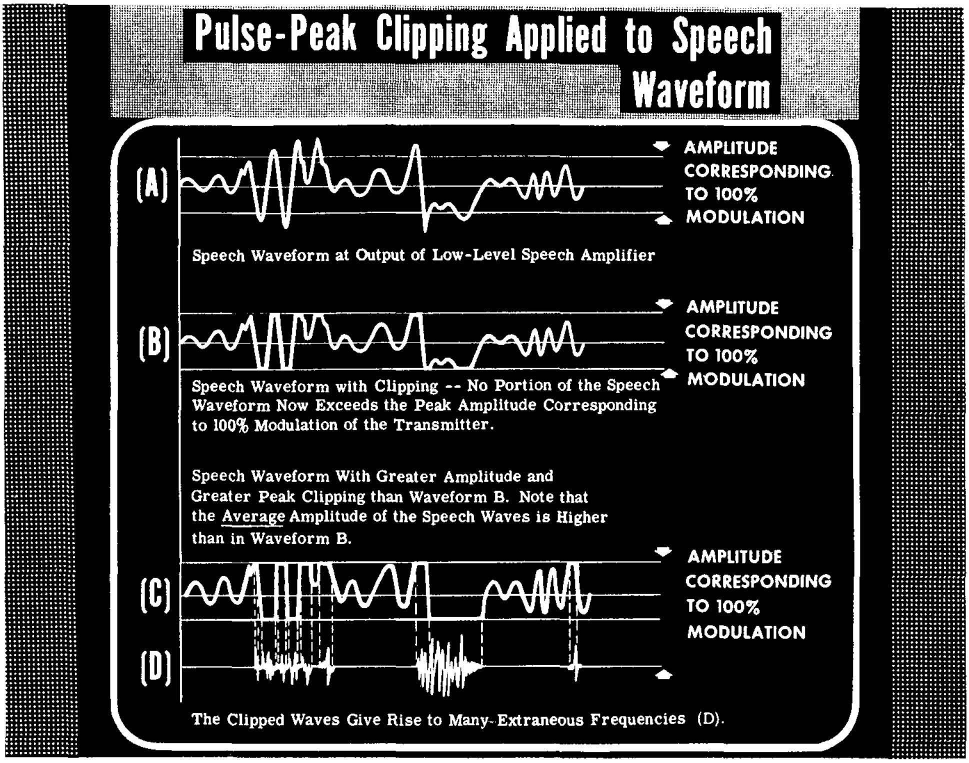
The formula $f_0 = 1/2\pi\sqrt{LC}$ establishes the frequency of the oscillations. This will also be the pulse-repetition rate of the pulse train emerging from the waveshaper. The sine wave from the oscillator tank is damped slightly because of loading produced by the second stage. The damped waveform has no effect on the output pulses, however, because of the amplifying action of the overdriven waveshaper.

The Component Frequencies of Speech



The general pattern of speech waves is nonsinusoidal, and there is a very great variation in both amplitude and frequency. Although there are periodic wavetrains involved, these are interrupted at aperiodic intervals, imparting an overall aperiodic nature to speech waves. The intelligibility of speech is governed more by the lower frequency components than by the higher frequencies. The higher frequencies are necessary for the reproduction of consonents, whereas the lower frequencies convey most of the vowel information. When we speak of low and high frequencies contained in the speech spectrum, we mean the fundamental and the related harmonic frequencies. If we do not reproduce these harmonic overtones, we effect primarily the quality of reproduction; if we retain a fair measure of high-frequency response to accommodate the consonents, the speech wave is considerably modified in form and still conveys intelligibility.

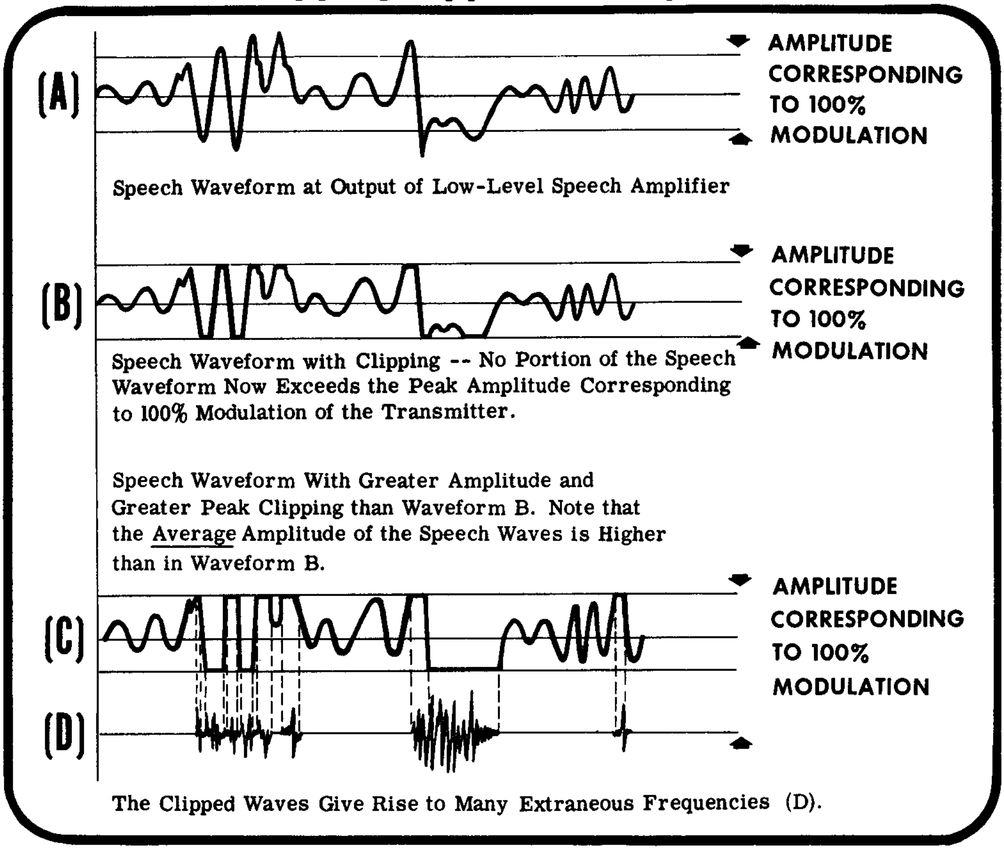
Modification of Speech Frequencies for Broadcasting



The ratio of peak-to-average amplitude in speech waves is quite high. This results in inefficient modulation of transmitters because maximum (100%) modulation is established by the peaks of the speech waveform and the average modulation is relatively low. A higher average modulation level *might* be attained by clipping the speech wave peaks—however, that would cause trouble from the high frequencies generated by clipping, for an abrupt change in waveshape always involves high-frequency components. The high frequencies attendant to clipping would increase the modulation bandwidth in a manner quite similar to that of ordinary overmodulation. We therefore remove these undesired high frequencies with a low-pass filter, resulting in a modified speech waveform which is characterized by much less difference between the amplitudes of what we might designate as the average level, and the peaks. It is surprising how far this process can be carried before serious impairment of intelligibility results. The transmitter then operates at a higher average power output than would be the case if unmodified speech were used for modulation. Another worthwhile feature of this pulse technique is that over- modulation can be avoided by selection of the appropriate clipping level.

Modification of Speech Frequencies for Broadcasting (contd.)

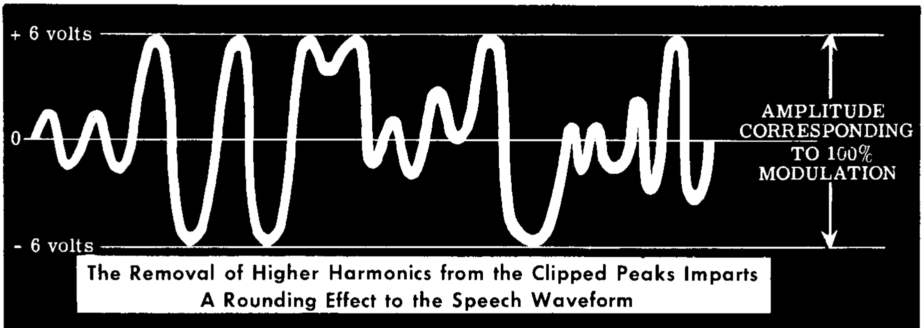
Pulse-Peak Clipping Applied to Speech Waveform



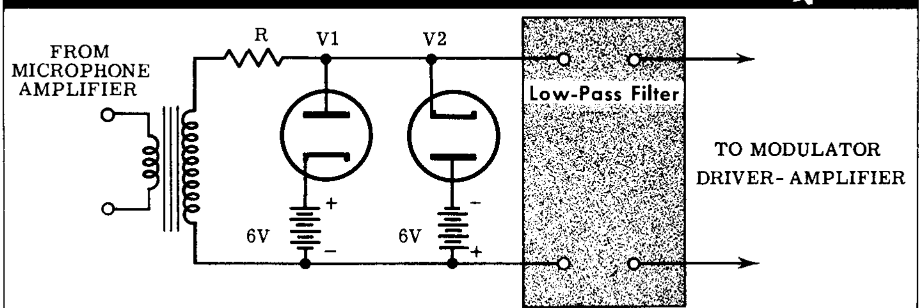
Waveform A illustrates typical speech waves. The peaks of these waves are clipped in waveform B. Clipping occurs at amplitudes determined by circuit parameters; in our particular application, we will clip the waves at positive and negative amplitudes corresponding to 100% modulation of the transmitter. In waveform C we have increased the power level of the speech wave applied to the clipping circuit and clipping is more severe than in waveform diagram B. Note, however, that the average amplitude of the speech waves of C is greater than that of B. Waveform diagram D shows the undesired result of clipping, the generation of high harmonic frequencies, transients, and parasitic oscillations, all having the modulation characteristics of "hash" and "splatter." These, fortunately, can be eliminated by a low-pass filter.

Clipping Speech Waveforms in a Low Pass Filter

We see the effect of passing waveform C (from page 116) through a low-pass filter. Amplitude clipping prevails but the clipped pulses are rounded. The harmonic content of such a waveform is very much lower than that of C. Indeed, the spurious frequencies of waveform D have been virtually removed by the low-pass filter. Although the waveform above is not a true replica of waveform A, we are interested in transmitting intelligible speech, not in providing a hi-fi rendition of music.



EFFECT OF LOW-PASS FILTER ON CLIPPED PEAKS OF SPEECH WAVEFORM

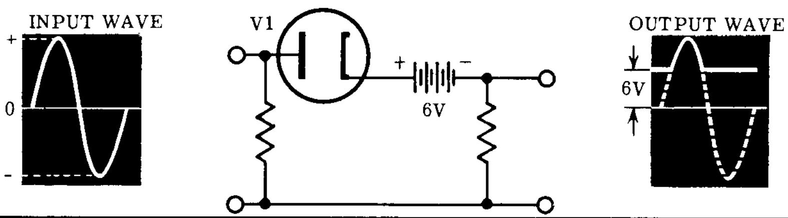


CIRCUIT ARRANGEMENT FOR CLIPPING PEAKS OF SPEECH PULSES

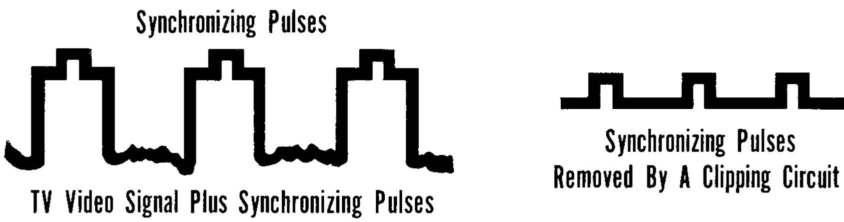
The general circuit arrangement for accomplishing this technique is shown. Positive excursions of the speech wave exceeding 6 volts are removed by the conduction of diode V1. Conduction in this diode is prevented for lower voltages because its cathode is biased 6 volts positive with respect to its plate. In similar fashion, conduction in diode V2 is held off until the negative excursion of the speech wave exceeds the 6-volt back-bias applied to the plate of diode V2. When either of the diodes conducts the resistance is very low compared with the series resistance R. As a consequence, virtually all of the peak amplitude exceeding 6 volts, positive or negative, is developed across R instead of appearing at the output.

Retaining Only Wave Peaks by Clipping

A slightly different arrangement of the clipping-circuit components produces the waveshaping effect as shown. Here, the action provided by the biased diode is opposite that of the previously described clippers; the peak of the waveform is now passed and the remainder rejected. In this circuit, series-connected diode V1 is back-biased from a 6-volt source. Since the cathode of V1 is positive with respect to its plate, V1 is nonconductive until the positive excursion of the input waveform exceeds 6 volts, making the plate positive with respect to the cathode. Consequently, the output wave is that portion of the input waveform which has a positive amplitude greater than 6 volts. If the terminal functions are interchanged (the input waveform applied to the output terminals and the output wave derived from the input terminals), the output wave is reversed in polarity. Operation of the circuit in this manner retains the negative wave peaks and rejects the remainder of the applied wave because the negative excursion of the applied wave must now exceed 6 volts negative in order to project the diode into its conductive region.



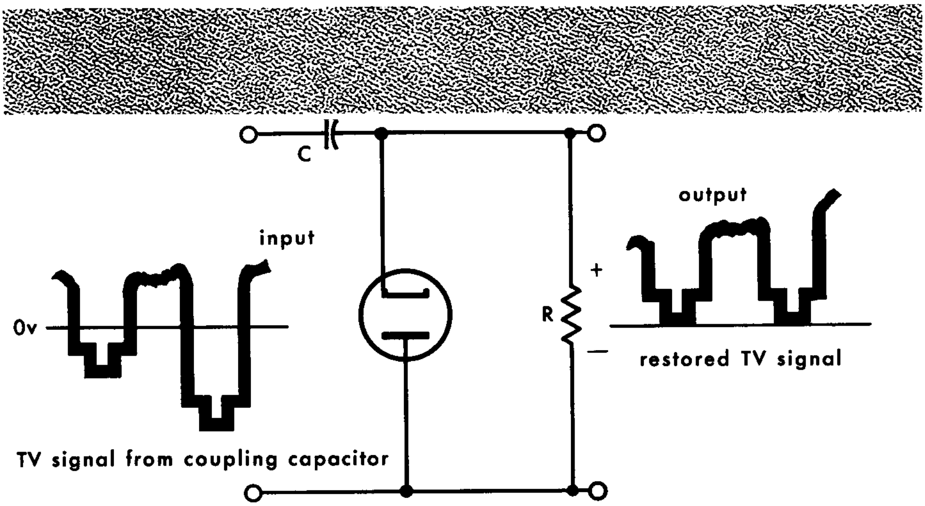
A CLIPPING CIRCUIT WHICH RETAINS ONLY THE POSITIVE PEAK OF A WAVE



REMOVAL OF TV SYNCHRONIZING PULSES FROM THE VIDEO SIGNAL

We see the removal of synchronizing pulses from the video signal in a television receiver by means of a clipping technique. Clamping, damping, demodulation, and clipping are techniques which are, or can be, accomplished by the unidirectional conduction process of rectification. Rectification in all of its variations is, therefore, an important waveshaping technique.

D-C Restoration in Pulse Trains

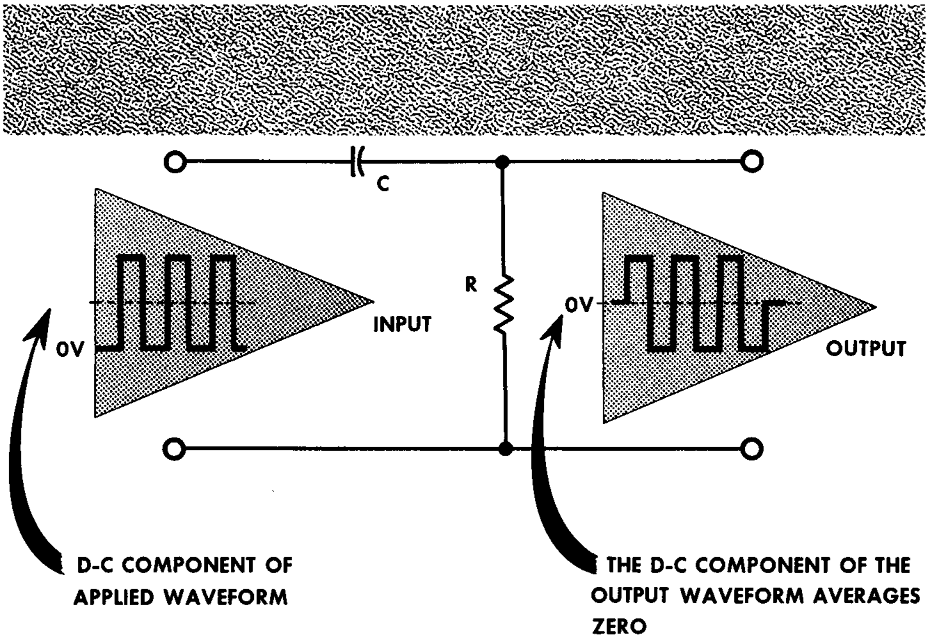


D-C Restorer Re-inserts The D-C Component Which Has Been Lost Through Capacitive Coupling

A very useful pulse function is that of d-c restoration. We have noted that the high-pass filter configuration does not pass the d-c component of a waveform if one is present. The interstage coupling networks in vacuum-tube amplifiers generally have the configuration of the high-pass filter, even though the elements are usually chosen to satisfy design requirements other than those involving the selective properties of a high-pass filter. However, the fact that the d-c component is not passed is of serious consequences for certain applications. This would not be true in audio amplifiers because the d-c component of a pulsetrain carries no useful audio information. In television-video amplifiers, however, picture brightness is provided by the d-c component. In order to re-establish a d-c component in the video signal, a diode is shunted across the output of the R-C coupling network. The diode conducts during the excursion of one pulse polarity, but is nonconductive to the opposite pulse polarity. As a consequence of this switching action of the diode, the output waveform is not permitted to seek excursions corresponding to an average d-c voltage of zero. Rather, one polarity becomes the fixed reference for the other: this is effectively the reinsertion of the d-c component in the pulsetrain.

Loss of the D-C Component in Coupling Circuitry

We see a circuit in which no special attempt has been made to modify the transfer characteristics of the R-C coupling circuit. The time constant of the coupling circuit is sufficiently large to provide good reproduction of the square wave, but the action of the capacitor causes a symmetrical wave to be delivered at the output. The average d-c value of such a wave is zero.

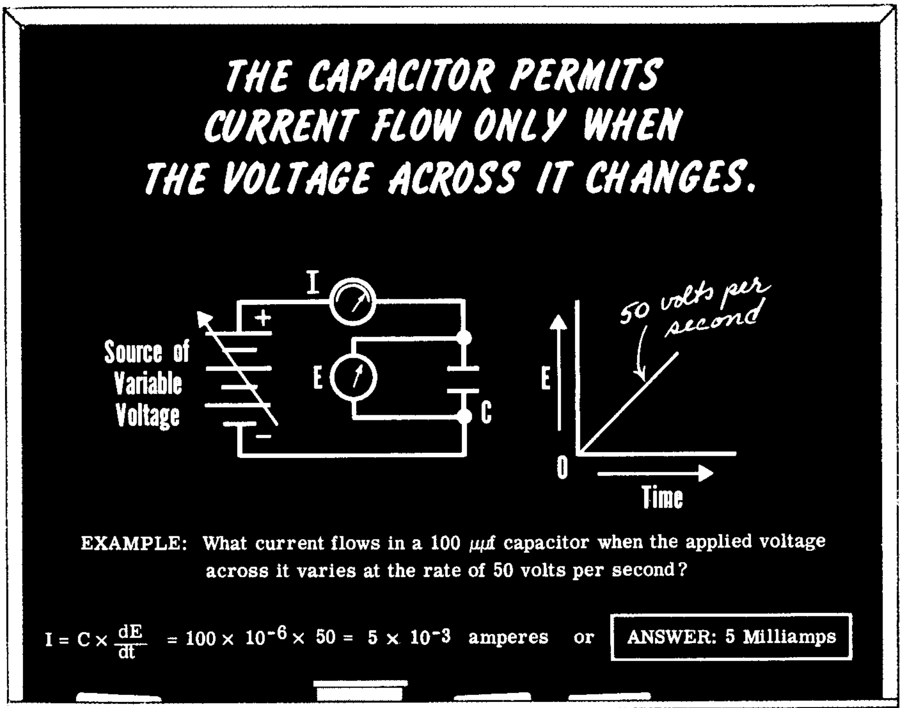


THE D-C COMPONENT IS LOST WHEN A WAVEFORM IS PASSED THROUGH A CAPACITOR

This demonstrates that a capacitor will not pass current at constant level. It will only pass current undergoing a change in level. The waveforms shown would be monitored by an oscilloscope after the circuit had been energized by the square-wave source; there is no intended correspondence between the first pulse drawn for the input with the first pulse shown at the output. The output wave is simply the monitored waveform one would observe by connecting an oscilloscope to the operating circuit.

Factors Effecting Capacitor-Charging Current

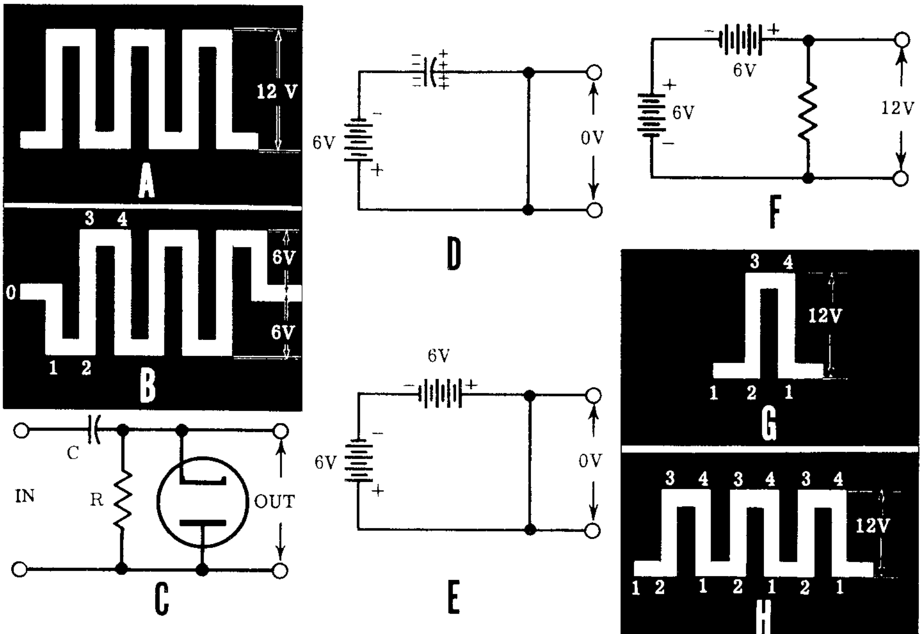
The amount of charging current associated with a capacitor depends partly on the applied voltage source and the time that this source is active. The relationship is expressed by the formula $I = C \times dE/dt$ where I equals the charging current in amperes, C is the capacitance of the capacitor in farads and dE/dt represents the change of the applied voltage over a period of time (volts per second in this case). When dE/dt equals zero, I also equals zero. This shows that no current can flow through a capacitor as a result of a d-c voltage impressed across it. The voltage must change.



Current flows in a circuit containing a capacitor because, when a voltage is applied, a capacitor charges until its operating voltage is reached. Then, if applied voltage decreases, the capacitor will discharge and the current flow in the opposite direction.

Let us assume now that we may obtain a capacitor able to store an infinite amount of charge. In other words, we may apply to this capacitor a voltage that increases continuously at a constant rate. We can find out what current flows in the simple circuit containing this capacitor in series with a variable d-c source whose output voltage changes continuously at the steady rate of 50 volts per second.

Operation of a D-C Restoration Circuit

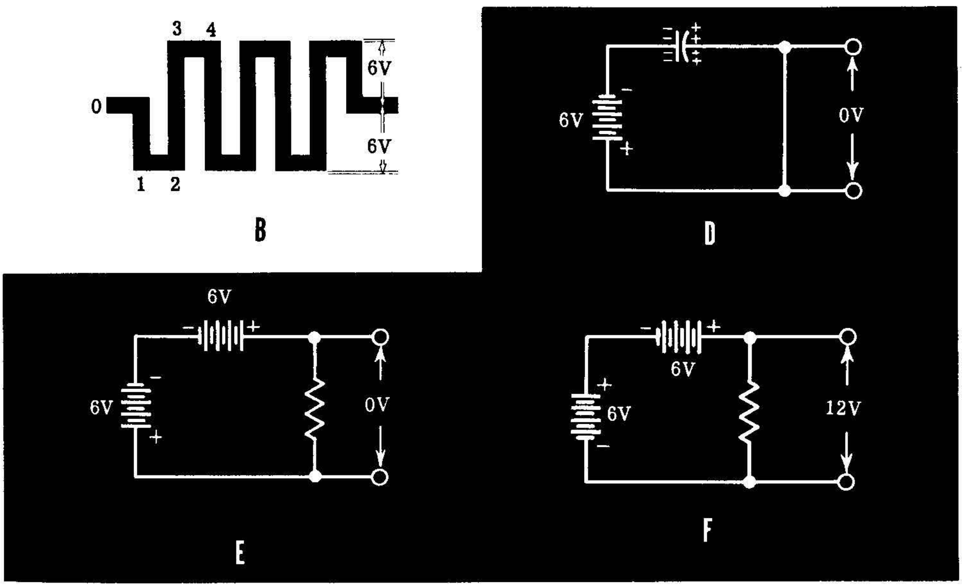


EQUIVALENT CIRCUITS SHOWING HOW A DIODE RESTORES THE D-C COMPONENT WHICH HAS BEEN REMOVED FROM A PULSE TRAIN BY A CAPACITOR

We see a step-by-step analysis of the operation of the d-c restoration circuit. Waveforms A and B are respectively the input and output waveforms of the coupling network before the diode shown in C is connected. (Waveform B is the steady-state ouput of the R-C circuit; there is no need to assume synchronization between elements of waveforms A and B.) During the time designated 1-2, waveform B is negative; during time interval 3-4, waveform B is positive. Assuming the diode is connected as depicted in C let us investigate the modified circuit operation produced. During time interval 1-2, the cathode of the diode is negative with respect to its anode. This polarity condition causes the diode to conduct. We will assume the diode behaves as an ideal element and has zero resistance during conduction. Circuit D represents circuit operation prevailing while the diode conducts. The capacitor charges to the source potential. The charge time is very short due to the assumed zero resistance of the conducting diode. (The source resistance and effective series resistance of the capacitor can be dismissed as being negligibly small.)

Operation of a D-C Restoration Circuit (contd.)

We see a circuit equivalent to the conditions existing after the capacitor has attained full charge. In E we have replaced the capacitor of D with a battery having a voltage equal to that of the charged capacitor, and therefore equal to that of the source. The relative polarity of the two batteries depicted in E which prevails during time interval 1-2 of waveform B is the essence of the *reinsertion* principle. The output voltage is zero due to the short circuit provided by the conducting diode, but no current is drawn from the series-connected batteries because they are polarized to produce current flow in opposite directions. Since the batteries are of identical voltage, exact cancellation takes place and the net current flow is zero.

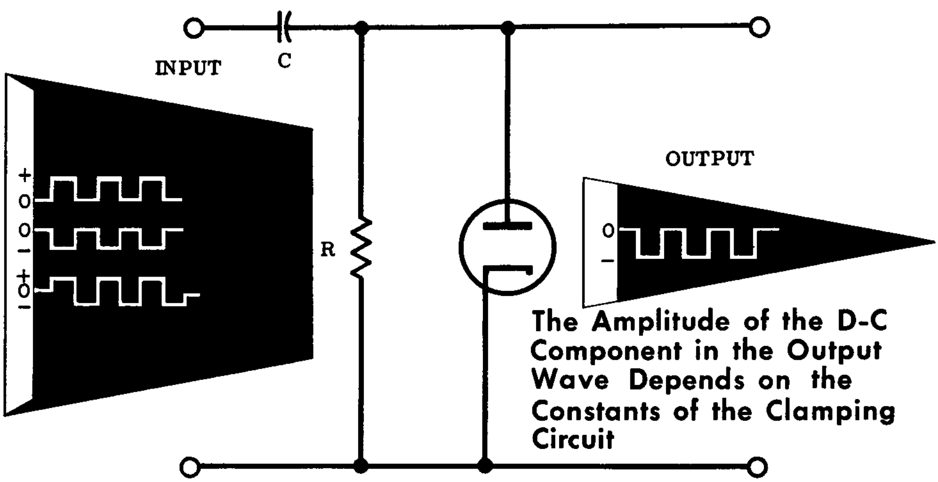


EQUIVALENT CIRCUIT AFTER THE CAPACITOR OF THE D-C RESTORER HAS BEEN FULLY CHARGED.

Now we will consider the circuitry action over time interval 3-4 on waveform B. Our equivalent-source battery has abruptly reversed its polarity, but nothing (ideally) has been done to the charged capacitor. Consequently, the equivalent circuit of F shows the source battery reversed in polarity with respect to its previous connection in E. The other battery, which represents the charged capacitor, remains connected. The batteries are now connected in series *aiding*. The sum of their voltages (two times the source voltage) now appears across the output resistor. The diode is not shown, its cathode is now positive with respect to its anode. It is therefore nonconductive, and is effectively out of the circuit.

Clamping, Another Name for D-C Restoration

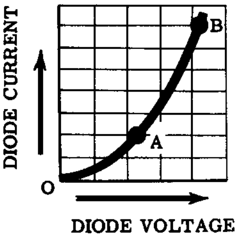
Waveform G, page 122, is the output voltage, and the numbers associated with it correspond in time to the numerical time designations on waveform B. In waveform G the output was zero during time interval 1-2. During time interval 3-4 the output was a positive voltage of twice the amplitude of the positive excursions of waveform B. Waveform H is the repetitive version of waveform G. After time interval 3-4 the circuit operation repeats itself. Waveform H again contains the d-c component originally present in waveform A. Therefore, the diode has been instrumental in restoring or reinserting the d-c component which otherwise would have been rejected by the capacitor.



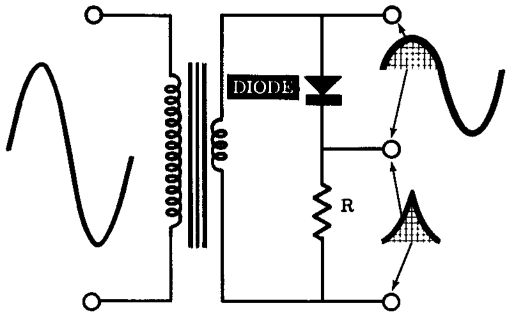
Diode Connection for Clamping the Positive Waveform Level.

This technique is also known as *clamping:* the diode *clamps* one polarity of the applied waveform at a fixed level which then becomes the reference, or base-line, for the wave excursion of opposite polarity. If we reverse the diode connection in the circuit of C, page 122, the positive rather than the negative level is clamped and we obtain the results shown here. The steady-state output wave of this type of circuit is determined by the diode connection as far as the d-c component is concerned; it is of no consequence whether the input wave has a positive, negative, or zero d-c component.

Diode as a Waveshaper



Forward-Conduction Characteristic of a Nonlinear Diode



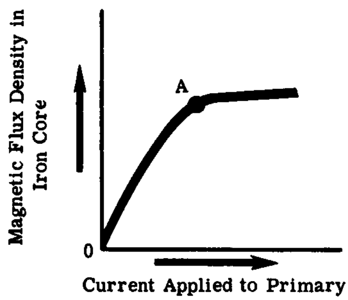
Circuit for Producing Modified Waveshapes

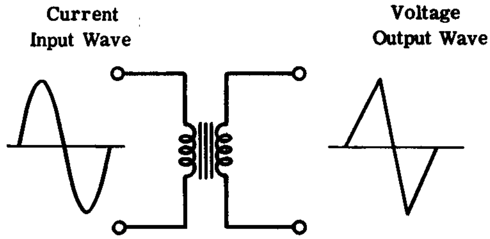
WAVESHAPE MODIFICATION DUE TO NONLINEARITY OF SEMI-CONDUCTOR DIODE

Nonlinear elements may be utilized in various ways to modify waveshape. When we speak of a circuit element as being "nonlinear," we mean that the voltage-current relationship in such an element deviates from the Ohms law relationship, that is, current through the element is not proportional to the voltage applied to the element. When such proportionality does not exist, output voltage is also not proportional to input voltage. An output voltage of a simple two-terminal nonlinear element is readily derived across a very low resistance inserted in series with the element. We see a waveshaping circuit making use of the nonlinear forward conduction characteristic of a point-contact germanium diode. Although this circuit has the configuration of the ordinary rectifying circuit, the operation is different in two respects. First, the resistor has a very low value compared with the load resistor which would ordinarily be used in a conventional rectifying application. Secondly, the amplitude of the applied waveform operates the diode over the most curved portion of its characteristic, which prevails throughout the region O-A of the Figure. (If we were interested in rectification only for the purpose of deriving a unidirectional waveform or for recovery of the d-c component, we could impress a higher amplitude wave to operate the diode between O and point B of its forward conduction characteristic. Also, under such circumstances, the load resistor would generally be high enough to substantially swamp out the nonlinear diode characteristics.) Of course, even the more conventional use of such a diode as a rectifier in which the prime objective is the removal of one or the other polarity of a wave is, in itself, a waveshaping technique.

The Saturable Reactor

Inductors and transformers become nonlinear elements when their iron cores are unintentionally or deliberately overly magnetized. We see the general form of the curve representing the relationship between primary current of an unloaded transformer and the magnetic flux density produced in the core. (For our purpose, we may assume that hysteresis is negligible and that the curve retraces itself.) Ordinary transformer operation is restricted to the region defined by O-A. Point A is known as the *knee* of





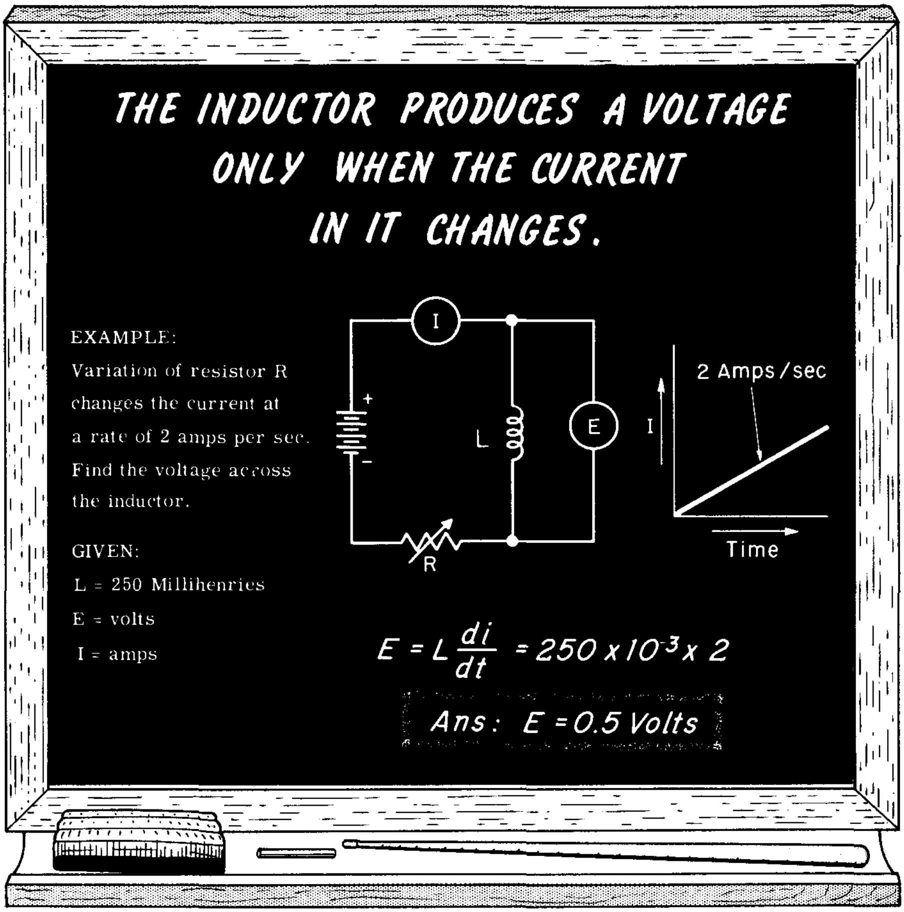
Typical Effect of Magnetic Saturation on a Sine Wave

WAVESHAPE MODIFICATION BY MEANS OF MAGNETIC SATURATION

the magnetization curve. Operation at primary currents higher than that corresponding to the knee saturates the core and very little increase in flux density results. An important feature of this curve is that it also implies the change in inductance occurring when operation is extended past the knee and into the region of saturation. The inductance of a winding such as the transformer primary is proportional to the slope of the magnetization curve. Thus, the inductance corresponding to operation over the region O-A is substantially constant in value. However, the inductance resulting from operation in the saturation region is negligible because the slope of the magnetization curve in this region is almost zero, that is, almost horizontal. The decreased inductance is accompanied by diminished counter emf, which in turn allows a sudden inrush of primary current. The inrush of current cannot induce a secondary voltage of appreciable energy content because the low inductance does not permit much electrical energy to be transferred to the core as magnetic energy, from which the secondary obtains its electrical energy. However, the current inrush in the vicinity of point A causes an abrupt change in magnetic flux density. This manifests itself as a high induced voltage in the secondary winding. This high-amplitude short-duration voltage exerts the illustrated peaking effect upon a sine wave. With square waves, the effect is even more pronounced and a high potential can be generated in this fashion.

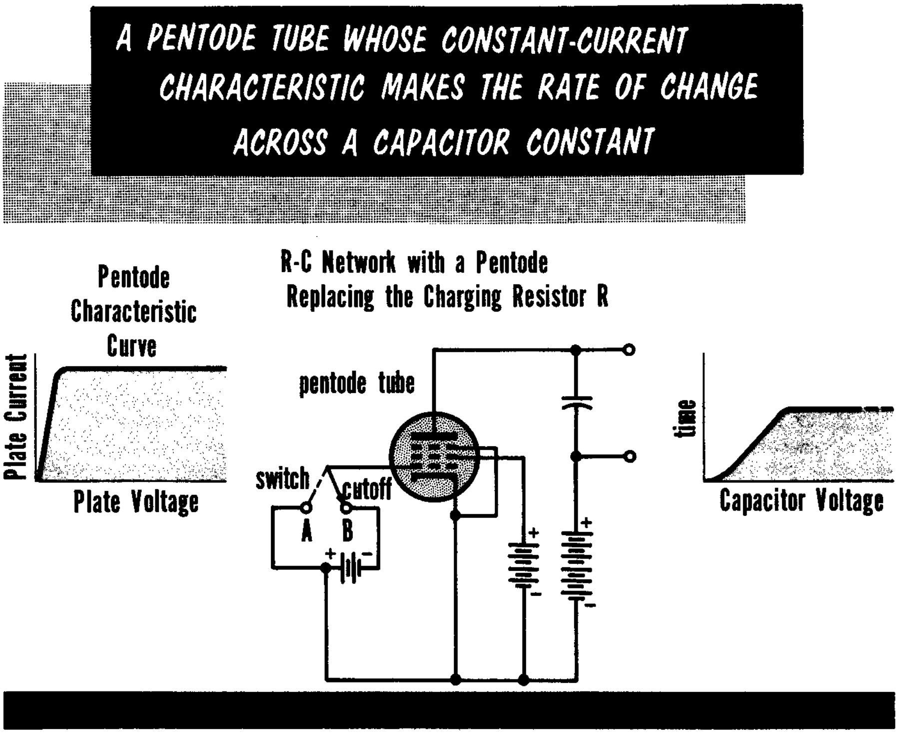
Current Flow Through an Inductor

Assume that this theoretical inductor contains no inherent resistance. The formula E = L di/dt indicates that a rate of change of current is necessary for a voltage to develop across the inductor. A steady current produces no voltage across the inductor because di/dt becomes zero.



In the formula E = L di/dt, E is equal to the voltage produced across the terminals of the inductor, in volts; L is equal to the inductance of the inductor, in henrys; and di/dt is equal to the rate of change of current through the inductor, in amperes per second. In this example we are not interested in the voltage drop which, in practical inductors, exists across the inductor's terminals by virtue of the inherent resistance of the winding. Rather, we wish to investigate the voltage that is induced electromagnetically in the inductor.

Nonlinear Characteristic of a Pentode Tube



An important kind of nonlinearity is provided over a substantial portion of the plate-voltage plate-current operating characteristic of a pentode tube.

A typical curve depicting plate current as a function of plate voltage is shown. Note that the pentode acts as a constant-current generator; except over a restricted region of low-plate voltages, the current is virtually independent of the plate voltage. The charging voltage across a capacitor is an exponentially shaped curve. This is so because of the current flowing into the capacitor during charge varies exponentially. If we substitute our pentode tube for the charging resistor of the capacitor-charging circuit, the pentode does not permit current change during the charging period of the capacitor. As a consequence of the constant charging rate enforced by the pentode, the voltage across the capacitor rises at a linear rate. The circuit shown demonstrates this phenomena. The capacitor is large, so an oscilloscope connected across it provides an observable straight-line trace. When switch S is at its B position, the pentode is cutoff and no current flows to the capacitor. When this switch is placed in its A position, the control-grid cutoff bias is removed and the pentode acts as a high resistance with the special property that the current flowing through it is constant.

QUESTIONS

1. Means are generally employed to slow the rise and decay of the dots and dashes used in radio-telegraphy. Explain the reason for this.

2. A narrow bandpass filter is used to transfer telegraph signals from the line to the receiver in carrier-frequency telegraphy. What effect does this have on the allowable speed of the telegraph pulses?

3. A 1 mc square wave is used to eavluate the high-frequency response of a radar video amplifier which should provide nearly flat response to about 7 mc. What qualities should be evident in the emergent waveform?

4. A 60-cycle square wave is applied to the input of a hi-fi amplifier. The tops and bottoms of the waveform monitored across a dummy load connected to the output transformer are virtually horizontal. Nevertheless, listening tests indicate the need for better low-frequency response. Discuss this situation and suggest the trouble.

5. The oscilloscopic display of a sharply differentiated square wave shows a pulse with considerably greater duration and decay than is desired. What is a likely cause for this, assuming that the rise and decay of the impressed square wave is fast enough and that the components of the differentiating circuit are properly chosen.

6. A high-pass filter with frequency cutoff at 3000 cycles is subjected to a laboratory test for attenuation characteristics. The filter is composed of several ferrite inductors and associated capacitors. It is observed that when the frequency of an impressed sinusoidal signal is in the vicinity of 3500 cycles there is observable distortion in the output signal. Comment on this situation and suggest an improved measurement technique.

7. Although exceptions are encountered, it is generally better to accomplish differentiation by means of an R-C circuit rather than an L-R circuit. Explain why this is so.

8. It is desired to increase the sharpness of the spikes obtained from an R-C differentiator circuit. Amplitude considerations preclude modification of either the capacitor or the resistor. Explain what must be done to accomplish this.

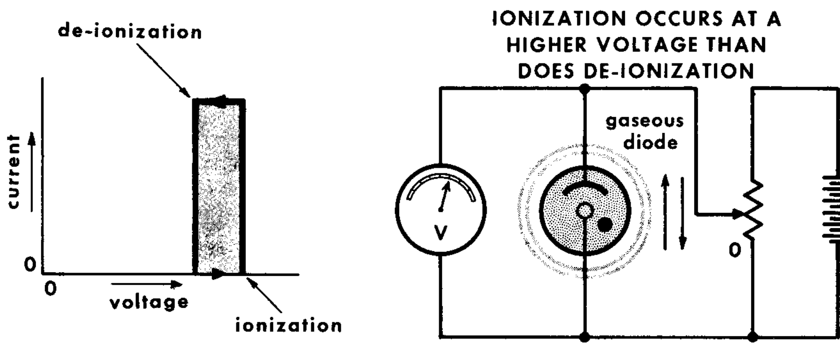
9. List three ways in which more pronounced integration may be obtained from resistors and capacitors connected to provide this function. Assume the incoming signal is a square wave having fixed characteristics.

10. A simple R-C filter is to be designed for a low-current drain half-wave d-c power supply operating from a 60-cycle source. What would normally be the first consideration in calculating R and C values?

Pulse Generators

It is not easy to make a clear-cut separation between waveshapers and pulse generators. In a sense, the shaping of a pulse constitutes its generation. Thus, the triode clipper shown on page 112 generates the near-rectangular waveform. There are instances where we would more naturally label a pulse technique as a *shaping* rather than a *generating* function. For example, the waveshape modification produced by passive R-C and R-L circuits would fall into this classification. We would, on the other hand, be inclined to view the operation of an over-driven vacuum-tube oscillator as pulse generation. We will discuss pulse techniques which lean more towards the concept to generation than shaping. There will, however, be cases of overlap with respect to the two pulse functions.

THE IONIZATION AND DE-IONIZATION VOLTAGES OF A GASEOUS DIODE



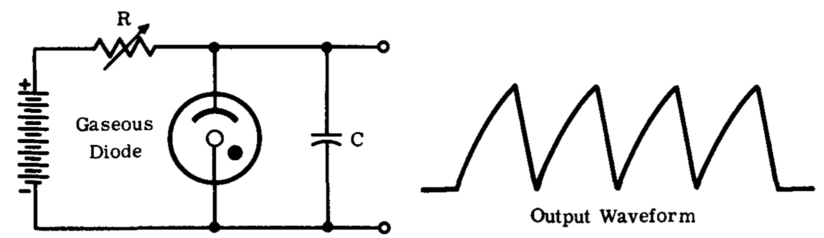
Probably the simplest pulse generator is the *relaxation* oscillator which makes use of the voltage hysteresis involved in the ionization and de-ionization of a gaseous diode such as a neon bulb. We see that the ionization, or "firing" voltage of a gaseous diode is higher than the voltage at which ionization is extinguished. This phenomena is readily demonstrated by the circuit arrangement shown. The potentiometer is slowly advanced from its zero-voltage position and the increasing voltage may be observed on voltmeter V. At a certain voltage, the neon bulb ionizes. This can be seen from the visible glow of the bulb.

Let us assume the voltmeter reading was made just prior to the firing of the neon bulb. Now we will reverse the rotation of the potentiometer to reduce the voltage across the bulb. Upon doing so, we note that we may pass through the voltage corresponding to firing, but the bulb remains ionized. As we continue to decrease the voltage, a value is attained at which the glow in the bulb abruptly ceases. The voltage recorded just prior to this event is the *de-ionization voltage.*

The Gaseous Diode Sawtooth Generator

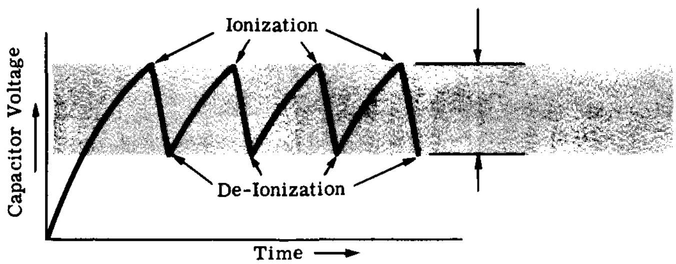
Let us now connect a gaseous diode across the capacitor of an R-C charging circuit. The voltage source is sufficiently high to initiate ionization in the diode. This generally requires a minimum of about 70 volts, depending upon the gas, the pressure, and other factors associated with the gaseous diode.

the GASEOUS DIODE behaves as a VOLTAGE-ACTUATED SWITCH



THE SIMPLE GASEOUS-DIODE SAWTOOTH GENERATOR

the PEAK-TO-PEAK AMPLITUDE of the GENERATED SAWTOOTH is determined by the DIFFERENCE between the IONIZATION and DE-IONIZATION VOLTAGE LEVELS



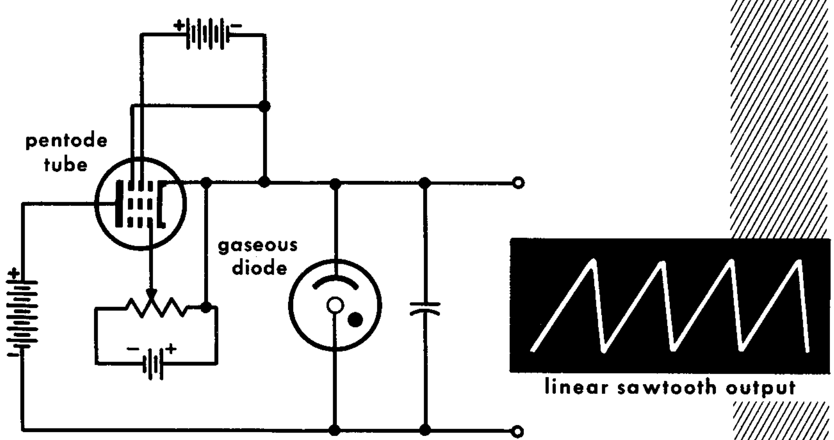
GENERATION OF SAWTOOTH WAVEFORMS BY GASEOUS-DIODE RELAXATION OSCILLATOR

The capacitor charges until the voltage across it is equal to the ionization voltage of the gaseous diode. When this voltage is attained, the gaseous diode ionizes, initiating a high rate of discharge in the capacitor. This action deprives the gaseous diode of its ionization voltage and it consequently de-ionizes. The de-ionized diode is effectively an open circuit. As a result, the capacitor again undergoes a charging cycle. This continues until the capacitor again charges to the ionization voltage of the gaseous diode, whereupon the cycle repeats. Note that this mode of operation is dependent upon the fact that ionization and de-ionization occur at different voltages.

The Pentode Tube in a Relaxation Oscillator

The pulse-repetition rate that can be generated by this type of pulse generator is limited by the speed at which the gas atoms are capable of de-ionizing. Depending again upon the design of the gaseous diode, the upper limit is between 10 and 20 kilocycles. However, the waveform is rich in harmonics.

A constant current charges the capacitor, resulting in a linear-voltage rise across the capacitor.



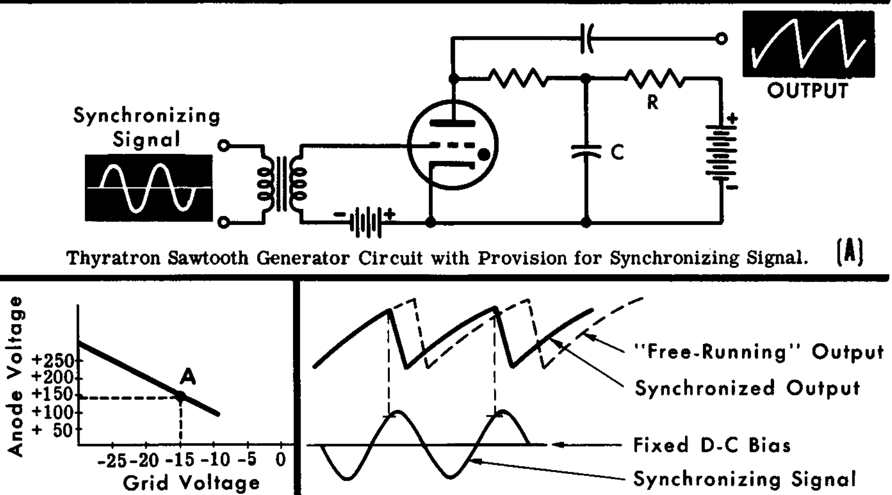
SUBSTITUTING a PENTODE for a CHARGING RESISTOR IMPROVES the WAVESHAPE of a GASEOUS-DIODE RELAXATION OSCILLATOR

A worthwhile improvement, particularly for sweep-circuit applications, can be imparted to the relaxation oscillator by substituting a pentode tube for the charging resistor. The pentode causes the output waveform to have a much more linear rise than is the case with the circuit shown on page 131.

The Thyratron Relaxation Oscillator

A more practical relaxation oscillator utilizes a thyratron rather than a simple two-electrode gaseous tube. The thyratron ionization voltage can be controlled by the potential impressed upon a third electrode, the grid.

The Principles of Oscillation and Synchronization of Thyratron Sawtooth Generator



Thyratron Sawtooth Generator Circuit with Provision for Synchronizing Signal. (A)

Plate Voltage Required for Ionization with Different Control Grid Voltages. (B)

Synchronization of Sawtooth Frequency by Injected Sine-Wave Synchronization Signal. (C)

Although cold-cathode tubes with starter or grid electrodes exist, the gaseous tube which is called a thyratron has a thermo-emissive cathode similar to ordinary vacuum tubes. The grid voltage required to produce ionization at different plate voltages is shown. As far as the action of the cathode-plate circuit is concerned, the thyratron behaves as a switch in the same manner as does the simple two-electrode gaseous tube. The main advantage of the thyratron is that it lends itself much better to synchronization than does the gaseous-diode oscillator. Another thyratron feature is that, with copious electron emission from its cathode, it is more immune to the effects of ambient temperature, radiant energy, and electrostatic fields than is the simple gaseous diode. These influences often cause premature ionization in the gaseous diode, thereby degrading the stability of the generated pulse-repetition rate. In the thyratron, the ionization voltage is governed by the fixed grid bias if the circuit is operating as a free-running relaxation oscillator, or the instantaneous grid voltage if the circuit is synchronized. As in the case of the gaseous-diode relaxation oscillator, the charging resistance R can be replaced with a pentode tube in order to linearize the rise of the generated sawtooth. The small resistor R protects the thyratron from high surge currents.

Synchronizing the Relaxation Oscillator

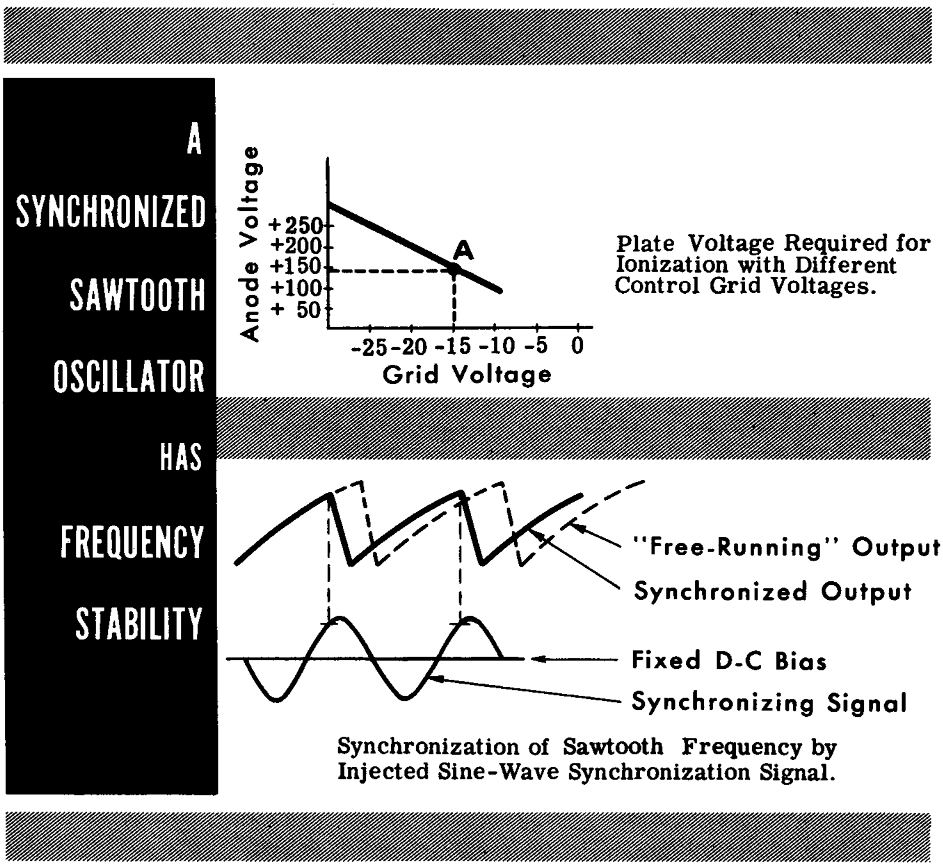


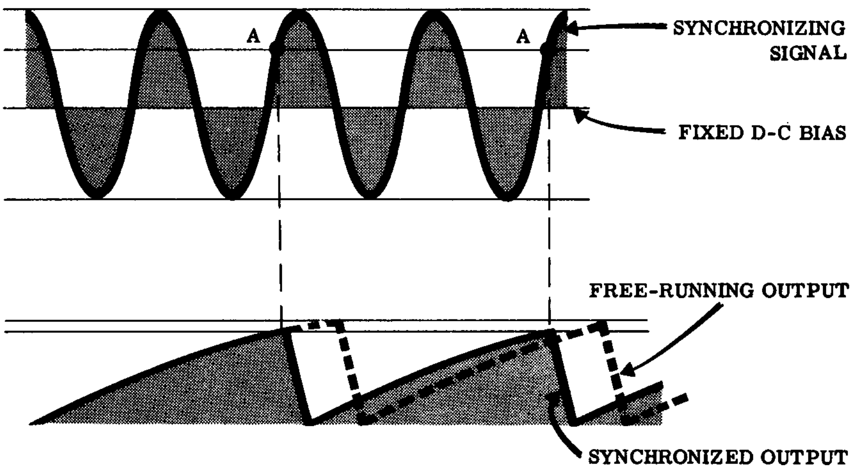
Plate Voltage Required for Ionization with Different Control Grid Voltages.

Synchronization of Sawtooth Frequency by Injected Sine-Wave Synchronization Signal.

The principle underlying synchronization of the pulse-repetition rate is illustrated. The dotted extension of the capacitor-charging voltage depicts operation without the injection of a synchronizing signal. When a synchronizing signal of frequency slightly higher than the free-running pulse-repetition rate of the thyratron relaxation oscillator and of suitable amplitude is applied to the grid-cathode circuit, the thyratron ionizes earlier in the capacitor-charging cycle than would otherwise be the case. The exact time at which the thyratron fires is determined by corresponding plate and grid voltages as is exemplified by the dotted lines. The thyratron is not triggered into ionization at voltages below the instantaneous grid potential of point A because the plate voltage is not yet high enough to produce the condition indicated by the intersecting dotted lines. Under synchronization, the frequency stability of the thyratron relaxation oscillator is very nearly that of the source supplying the synchronizing signal.

Synchronization with Harmonics of the Sawtooth

Synchronization of the Thyratron Relaxation Oscillator by a Signal Twice the Frequency of the Generated Sawtooth

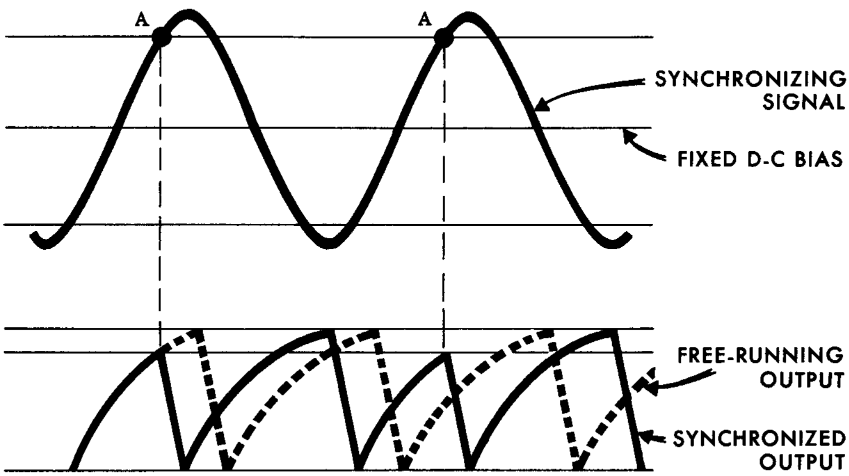


Alternate Cycles of the Synchronizing Signal Cause Premature Triggering of the Thyratron

Synchronization can also be accomplished with synchronizing signal frequencies which are actually harmonics or submultiples of the pulse-repetition rate of the thyratron relaxation oscillator. We see synchronization by a synchronizing signal frequency which is twice that of the generated sawtooth. In similar fashion, the sawtooth repetition rate is locked to a synchronizing frequency only one-half that of the generated sawtooth on page 136. Synchronizing action is basically the same regardless of the synchronizing frequency. In all cases, the synchronized sawtooth must be periodically terminated at an earlier time than would result under free-running operation. Synchronizing stability is less as the synchronizing signal is raised to higher harmonics of the generated sawtooth. The reason for this is that the individual cycles of the synchronizing signal become so close together that it becomes possible for more than one cycle to be the one which, during its positive rise, will trigger off the thyratron. Such a situation is brought about or agitated by random effects and circuit transients.

Synchronization with Harmonics of the Sawtooth (contd.)

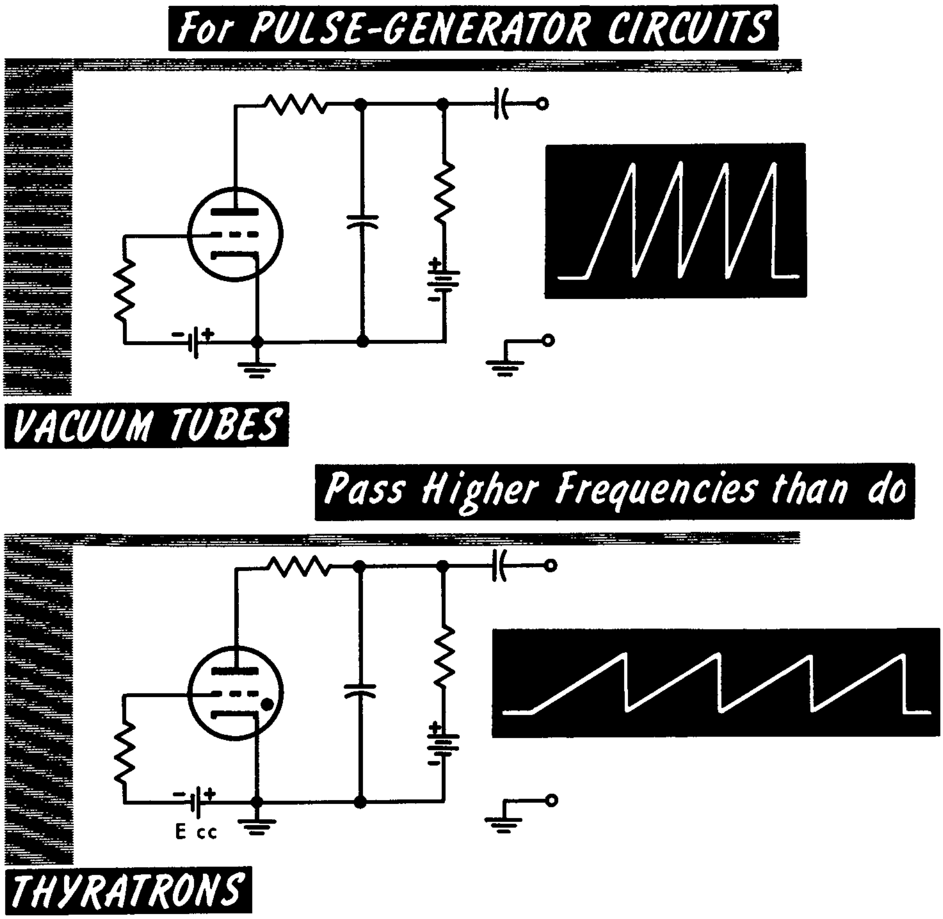
Synchronization of the Thyratron Relaxation Oscillator...



by a Signal with Half the Frequency of the Generated Sawtooth

Synchronizing stability suffers as a submultiple synchronizing frequency becomes a smaller fraction of the generated sawtooth. The figure shows that synchronization by a submultiple frequency does not trigger every sawtooth cycle. The less often triggering occurs, the more time the relaxation oscillator has to behave as free-running oscillator. Note that the individual sawteeth are not identical in amplitude or duration during submultiple synchronization. The synchronized sawtooth cycles are of shorter duration than those unaffected by the synchronization signal. The generated wave is, therefore, a train of nonidentical pulses.

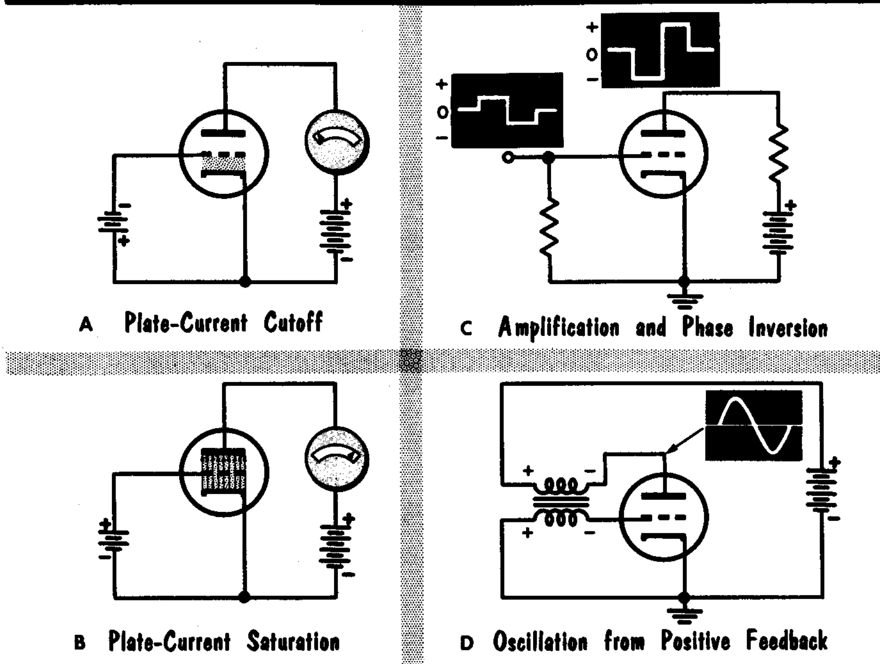
Vacuum-Tube Substitute for a Thyratron



Vacuum tubes are inherently better in some respects than thyratrons in pulse-generator circuits. The high-frequency limit imposed by gas de-ionization time does not exist in vacuum tubes. Another advantage of vacuum tubes is that the grid retains control over the plate current at all times. (In the thyratron, the grid loses control of plate current once ionization is initiated.) These differences permit greater flexibility of circuit design and steeper waves to be generated in vacuum-tube circuits than in thyratron circuits. On the other hand, vacuum-tube pulse generators are generally relaxation oscillators as are thyratron pulse generators; that is, the time constants of R-C networks operate in conjunction with the switching characteristics of the tubes in such a way that the capacitors are periodically charged and discharged.

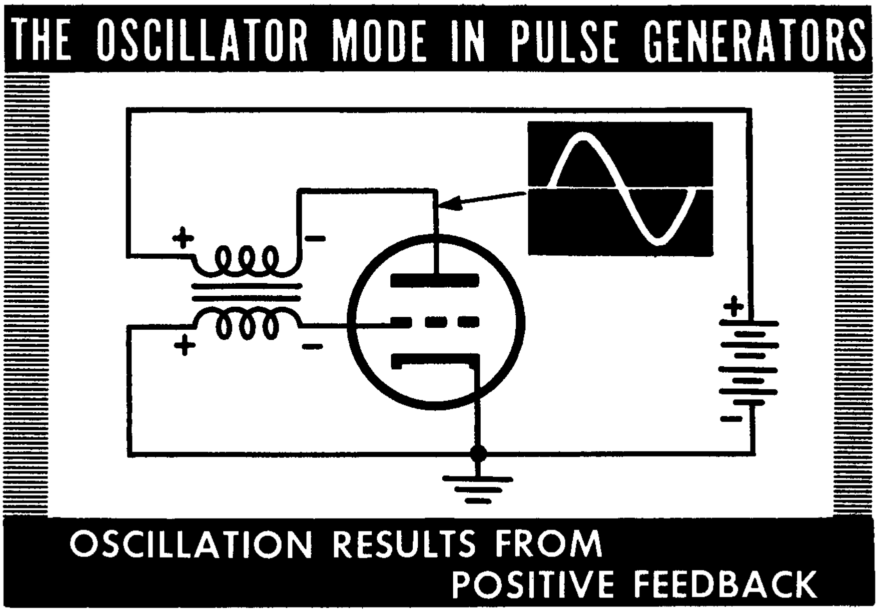
Vacuum-Tube Substitute for a Thyratron (contd.)

THE FOUR OPERATIONAL MODES OF VACUUM TUBES IMPORTANT IN PULSE GENERATORS



There are four operating modes of vacuum tubes which are particularly relevant in vacuum-tube pulse generators. Illustrated in circuit A is plate current cutoff due to a voltage making the grid sufficiently negative with respect to the cathode. The circuit shown in B illustrates the opposite phenomena, plate-current saturation, which results when the grid is sufficiently positive with respect to the cathode. Note that these two operative states represent changes in the conductive state of the tube. Indeed, the transition from one conductive state to the other can generally be considered as a switching action in pulse-generator circuits. The third important vacuum-tube characteristic is the phase or polarity reversal which occurs as the signal is transferred through the tube. Thus, in figure C, plate voltage is at its most negative value when the signal impressed at the grid undergoes the positive portion of its excursion; conversely plate voltage is at its most positive value when the grid signal is most negative. This diagram also depicts the fact that the tube amplifies; it delivers a signal from its plate higher in level than that impressed at the grid.

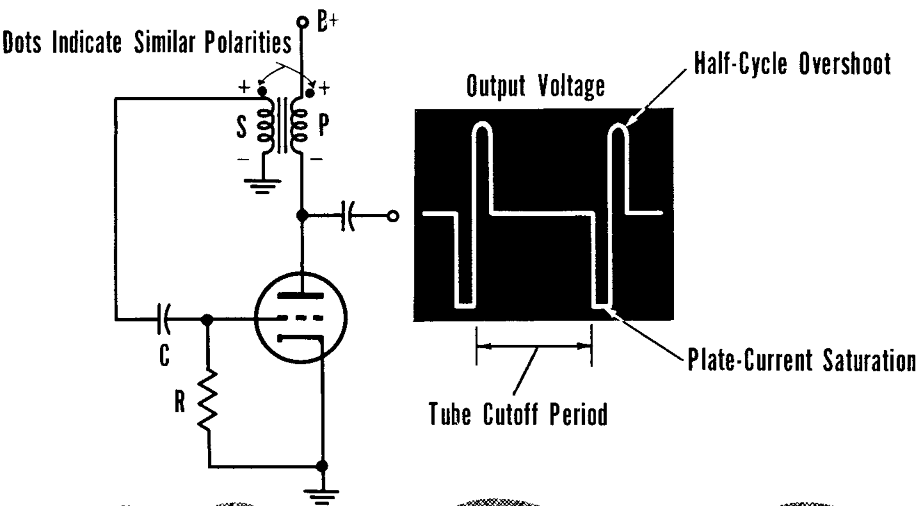
The Vacuum Tube as an Oscillator



The important implication of phase reversal and amplification is shown by circuit D, above. In this circuit a transformer is used to effect a second-phase inversion so that a portion of the plate signal is returned to the grid circuit at a polarity to reinforce the original grid signal. A cumulative or regenerative process ensues until the tube breaks into an oscillatory state, functioning as an alternating-current generator. With regard to this particular circuit, it is natural to ask from what source the original grid signal came, since the generated alternating current did not exist prior to oscillation. There are always input signals in practical oscillators; these derive from thermal agitation of electrons in components, random emmision of electrons from the cathode, power source fluctuations, and the switching transients occurring when the oscillator is turned on. Any of these are adequate to initiate the commulative buildup in amplitude by virtue of the tube's amplification. Once the buildup starts, the frequency of the oscillation is determined by circuit constants. Due to nonlinearity of the tube when the signal becomes large, the rate of buildup slows down until an equilibrium is attained and a constant-amplitude output results. If the transformer coupling is great, sufficient energy is fed back to project the operation of the tube into its cutoff and saturation regions, and we have the essentials of a pulse generator. In many pulse generators, an additional tube is employed, rather than a transformer, to produce the phase conditions required for oscillation.

The Operation of a Blocking Oscillator

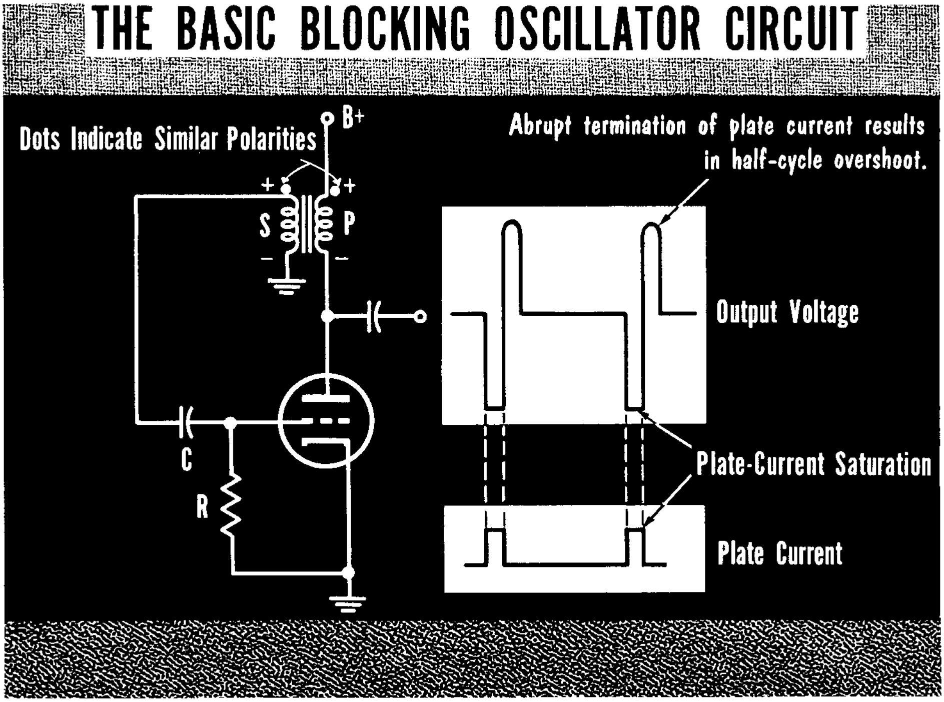
THE BASIC BLOCKING OSCILLATOR CIRCUIT



We see the basic form of the much-used *blocking oscillator.* Except for the R-C combination in the grid circuit, this oscillator resembles circuit D, page 138. Suppose that the buildup of an oscillation cycle has begun; plate current is increasing and the phasing of the transformer connections is such that the grid is being driven increasingly *positive.* The grid and cathode constitute a diode which is driven into its conductive region by the feedback voltage delivered by the transfomer. As a consequence of the diode conduction, the grid side of the capacitor acquires a negative charge with respect to the transformer-side of the capacitor. It so happens, however, as long as the transformer provides a rapidly increasing voltage, current will flow through the capacitor to the grid and the grid will be made increasingly positive relative to the cathode. This process is regenerative, for as the positive grid voltage rises, the resultant plate-current increase produces transformer-coupled feedback which further enhances the rising grid voltage. The amplification in the tube and the close coupling provided by the transformer provide very rapid buildup. Surprisingly, however, this will not culminate in continuous oscillation at a frequency determined by the L-C constants of the transformer.

The Operation of a Blocking Oscillator (contd.)

The extremely rapid rise in the plate current of the oscillator quickly brings the operation of the tube to its plate-current saturation region. When this happens, transformer action ceases since no voltage is induced in the transformer secondary when the current through the primary is of constant value. (Frequently, transformer action terminates from the combined effects of plate-current saturation and transformer-core saturation.) The disappearance of the positive voltage source which, prior to plate-current saturation had been charging the capacitor, leaves the capacitor charged with sufficient voltage to abruptly bias the tube to plate-current cutoff, preventing the start of continuous oscillation.

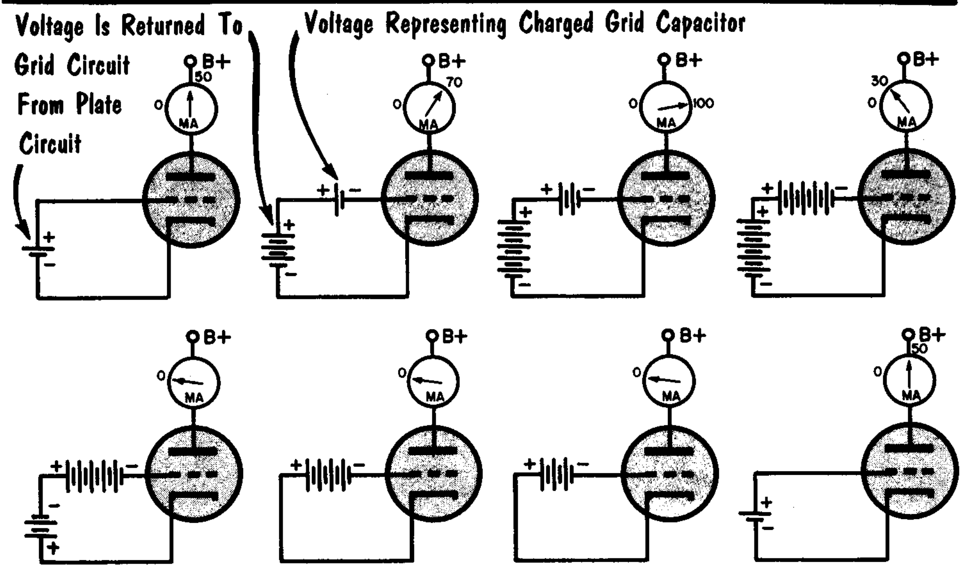


The abrupt termination of plate current causes the generation of a half-cycle overshoot in the transformer primary as indicated in the output waveform. Remember that, although the capacitor charged up rapidly through the relatively low resistance provided by grid-cathode conduction, discharge involves a very much longer period. This is because the discharge path is through R which is a high resistance. The blocking oscillator remains quiescent until the charge in capacitor C has depleted sufficiently to remove the cutoff bias voltage applied to the grid. When this state is attained, a new buildup cycle commences and the sequence of events repeats.

The Operation of a Blocking Oscillator (contd.)

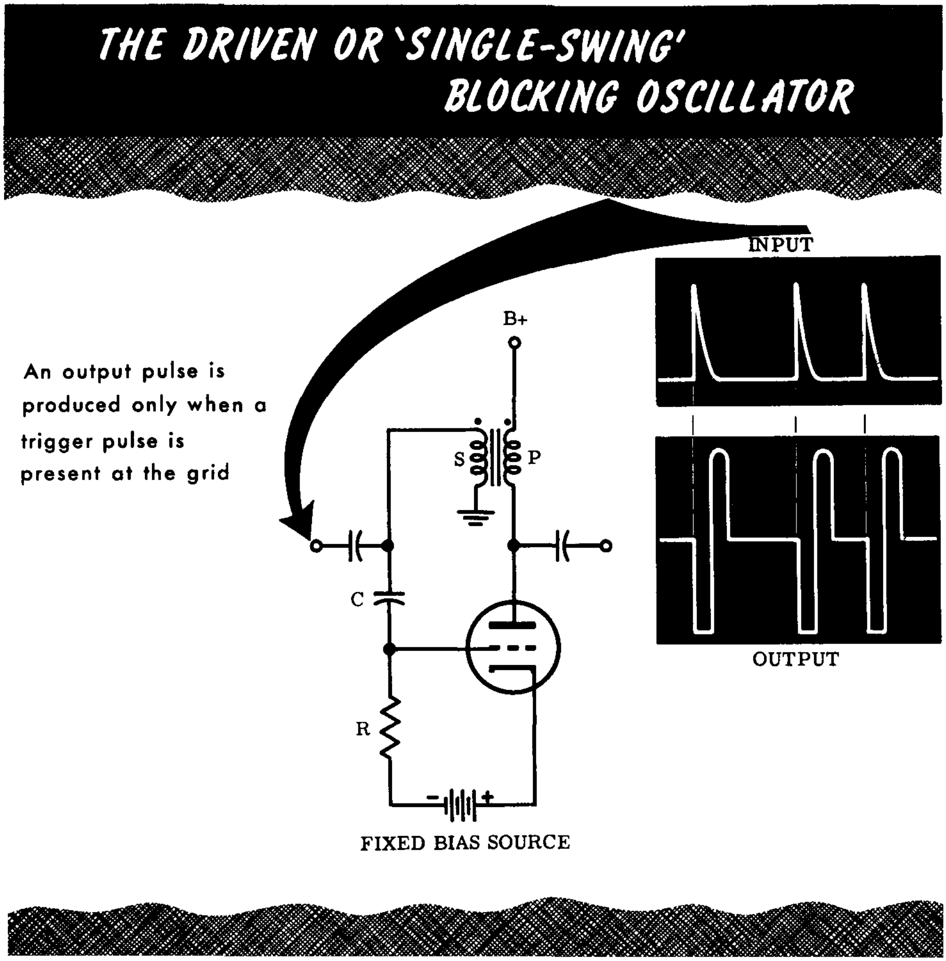
The pulse-repetition rate of the blocking oscillator is governed by the R-C time constant and not primarily by an L-C tank circuit, characteristics of a relaxation oscillators. It should be appreciated that more is involved than the mere configuration of the circuit, for uninterrupted sine waves, pulsed sinusoidal wavetrains, or distorted sine waves, can also be generated by this circuit. Among the conditions for blocking-oscillator action are tight electromagnetic coupling and a long grid-circuit time constant. The latter stipulation is generally provided by a larger capacitor and a higher resistance than is used for continuous oscillations. Reducing the grid-circuit time constant raises the pulse-repetition rate, but eventually a point is reached where the undissipated energy storage of the transformer causes the circuit to break into continuous oscillation. Other factors being equal, higher pulse-repetition rates become possible as the natural oscillation frequency of the transformer secondary and associated circuitry is increased.

EQUIVALENT CIRCUITS showing GRID VOLTAGE and PLATE CURRENT CONDITIONS in the BLOCKING OSCILLATOR



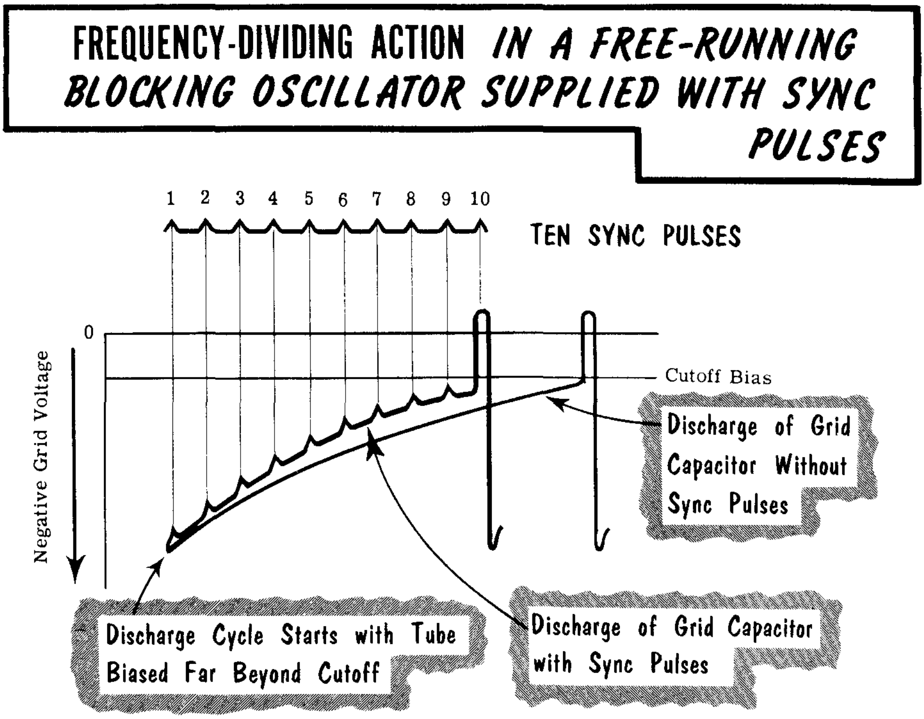
The operation of the blocking oscillator may be better visualized by contemplating the equivalent circuits shown. In these circuits, the grid capacitor is represented by a battery which during plate-current buildup opposes current flow. This flow is produced by another battery symbolizing the feedback voltage delivered to the grid circuit by the transformer secondary. The key to blocking-oscillator action is to be found in the relative polarities and amplitudes of the two batteries.

The Driven Blocking Oscillator



The blocking oscillator just described is free-running, that is, it automatically generates pulses and determines its own pulse-repetition rate. The variation of circuit shown here cannot of its own accord produce pulses because the grid is maintained by battery by a bias higher than cutoff. If, however, the cutoff bias is momentarily overcome by a high-amplitude positive pulse introduced in the grid circuit, cumulative buildup will be initiated in a manner not unlike that resulting from circuit-noise voltages in the free-running blocking oscillator. However, after this driven or "single-shot" blocking oscillator turns itself off, it will not generate a subsequent pulse until again provoked by a positive trigger voltage delivered to its grid from an external source.

Triggering a Blocking Oscillator from a Sine Wave Source

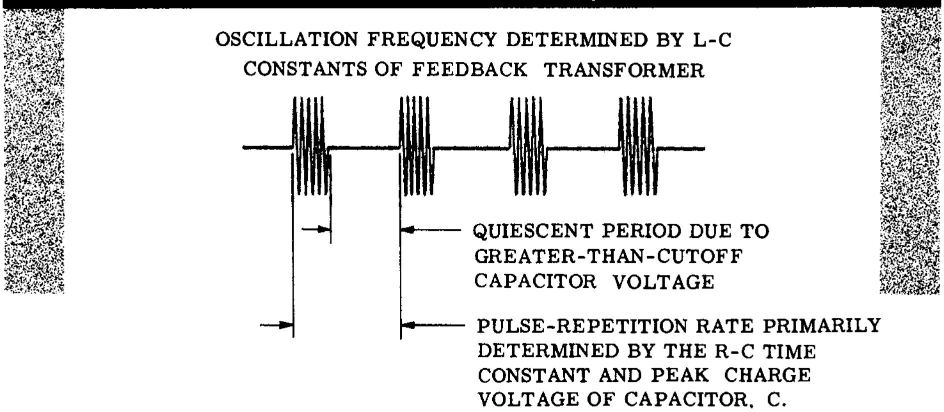


The driven blocking oscillator may also be operated from a sine-wave source such as a crystal oscillator. If the exciting frequency is approximately a submultiple of the pulse-repetition rate generated without the fixed bias, synchronized frequency-division occurs. For frequency-division, it is generally better to synchronize with steep short-duration pulses than with sine waves. This is particularly true when the dividing factor is greater than six or seven. Frequency-division beyond 10 becomes increasingly susceptible to premature triggering from circuit transients. We see the principle involved in producing tenfold division of the synchronizing signal. Since the tenth synchronization pulse projects the tube into its operating region sooner than would otherwise be the case, it is necessary that the frequency of the sync signal be slightly greater than the free-running pulse-repetition rate of the blocking oscillator. The principle of frequency-division applies in much the same way to both the driven blocking oscillator and to the free-running variety. The major difference is that, other factors being equal, the driven blocking oscillator requires a synchronization signal of greater amplitude than does the free-running oscillator. The nine pulses prior to the "firing" pulse increase the discharge rate of the capacitor in the blocking oscillator.

The Squegging Oscillator

By reducing the amount of positive feedback, another useful operational mode is obtainable from the basic blocking-oscillator circuit. Let us suppose that this change is accomplished by using fewer turns on the secondary (grid-circuit winding) of the feedback transformer T1. The plate current is not driven to saturation although the grid does conduct during positive peaks of the fed-back voltage derived from the secondary of T1. It now requires several oscillatory cycles for the charge in capacitor C1 to attain a voltage sufficiently high to project the operation of the tube into its plate-current cutoff region. However, when this voltage is reached, the oscillations cease and the circuit remains quiescent until the charge stored in grid capacitor C1 leaks off through the grid return resistor. The cycle then repeats.

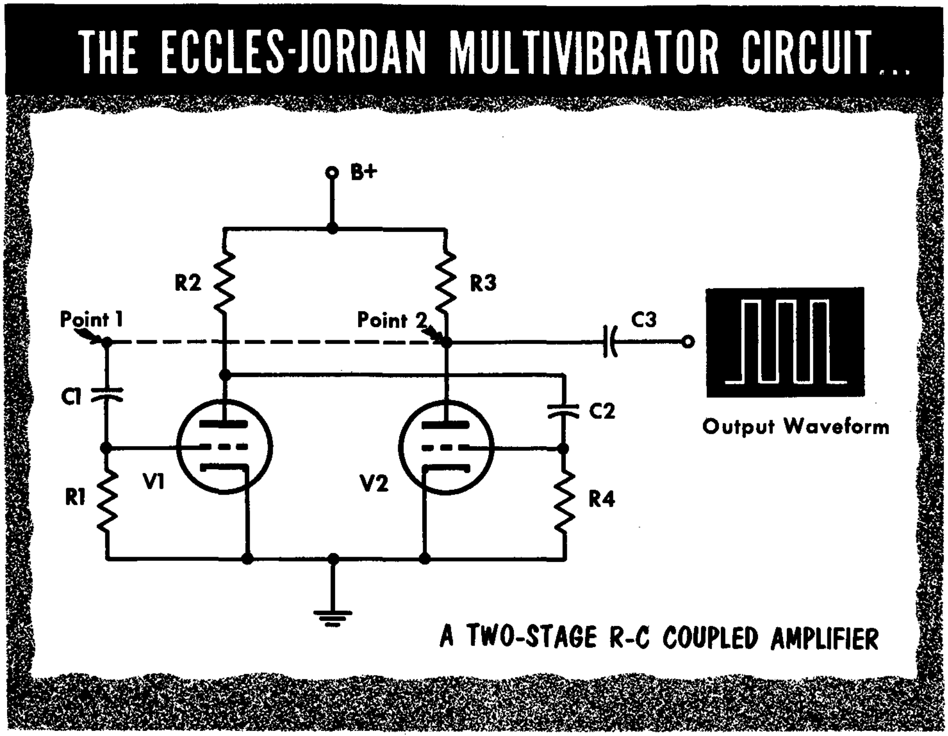
PULSED WAVETRAIN PRODUCED BY A SQUEGGING OSCILLATOR



Operation is Similar to the Blocking Oscillator, but has Different L-C and R-C Time Constants

The output from a blocking oscillator operating in this manner consists of a periodically pulsed wavetrain of high-frequency oscillations. The pulsing repetition rate is governed by the time constant of the grid capacitor in conjunction with the grid return resistor, and also by d-c operating voltages and tube parameters. The frequency of the oscillations within the pulses is determined by the tank circuit represented by the inductances and capacitances associated with the transformer. This mode of operation is known as *squegging*. A blocking oscillator performing in this manner is often referred to as a squegging oscillator. The squegging oscillator can be made to operate as a single-shot device by the application of suitable fixed negative bias in a manner similar to that shown for the single-shot blocking oscillator on page 143. The trigger pulses actuating the single-shot squegging oscillator must be spaced at somewhat greater intervals than that corresponding to the number of oscillatory cycles generated within an active pulse.

Pulse Generation by Means of the Multivibrator



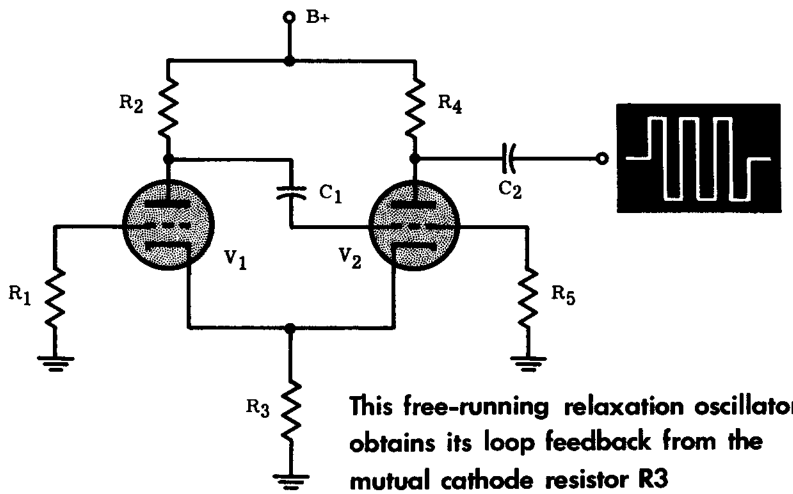
Except for the blocking oscillator, most vacuum-tube pulse generators employ two tubes. The circuit configuration takes a number of forms, but they all are variations of two basic arrangements, the Eccles-Jordan multivibrator and the cathode-coupled multivibrator. In the Eccles-Jordan multivibrator, the circuit configuration is essentially that of a two-stage R-C coupled amplifier with the output returned through a coupling capacitor to the input. One tube can be considered an amplifier and the other a phase reverser, although either tube can be considered to serve either of these functions. This viewpoint is useful in establishing a common denominator with the blocking oscillator, for one tube can be thought of as substituting for the blocking-oscillator feedback transformer. As in the blocking oscillator, the feedback factor in multivibrators greatly exceeds that merely necessary to cause oscillation. Consequently, each tube is alternately driven to plate-current saturation and plate-current cutoff. The output waveform derived from one of the plates displays the clipping action of these two circuit conditions and is, accordingly, nearly rectangular in shape. The values of the plate-load resistors shown in the Eccles-Jordan multivibrator are such that the tubes draw saturation current when their grid voltages are zero.

The Cathode-Coupled Multivibrator

The cathode-coupled multivibrator differs from the Eccles-Jordan circuit in that the feedback tube is connected as a cathode follower. A cathode follower does not reverse phase as does the grounded-cathode amplifier.

Therefore, the output of the second stage cannot be returned to the grid of the first stage as is done in the Eccles-Jordan multivibrator, for then we would not have the proper feedback conditions to produce oscillation. However, we can take advantage of the fact that a signal of a given polarity impressed at the grid of a tube is equivalent, as far as direction of plate-current change is concerned, to an *oppositely* polarized signal applied to the cathode. Since the cathode-follower tube does not provide the polarity inversion needed for positive feedback to the grid of the first tube, we return the feedback signal to the cathode of the first tube. In essence, the cathode-coupled multivibrator, the Eccles-Jordan multivibrator, and the blocking oscillator represent three different feedback-circuitry techniques.

THE BASIC CIRCUIT OF THE CATHODE--COUPLED MULTIVIBRATOR

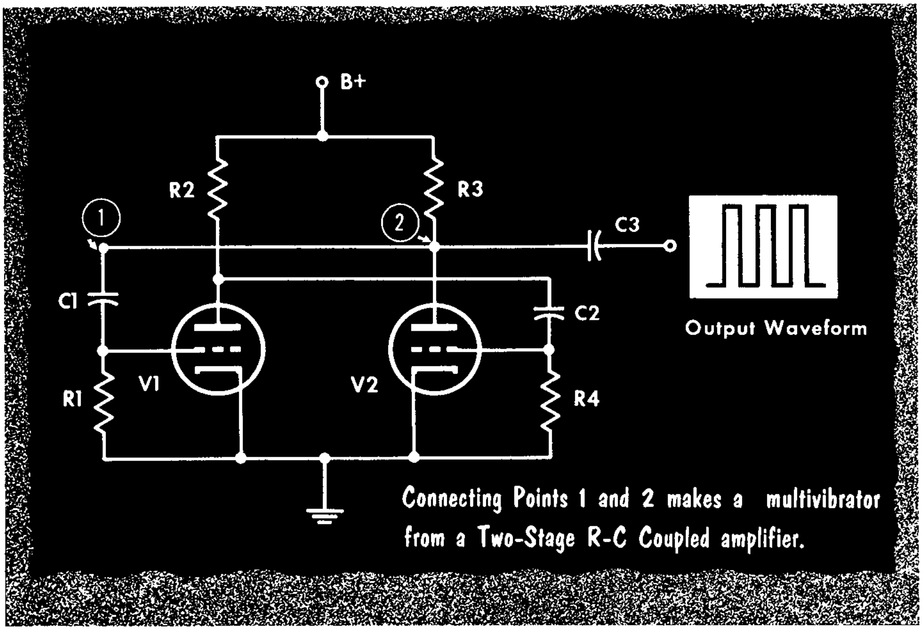


This free-running relaxation oscillator obtains its loop feedback from the mutual cathode resistor R3

They all produce an overly excited oscillator in which the amplitude of grid signals greatly exceeds the limits required to confine the operation of the tubes to their linear regions. Both the Eccles-Jordan multivibrator and the cathode-coupled multivibrator may be biased to provide single-shot action in which pulses are generated only under provocation of an input trigger pulse supplied from an external source.

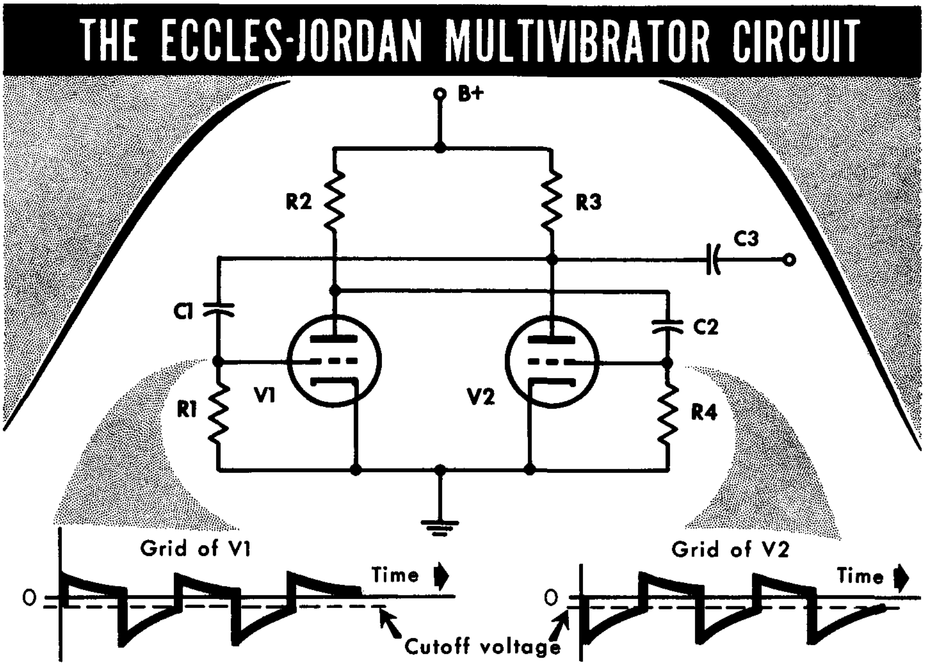
Operation of the Eccles-Jordan Multivibrator

THE ECCLES-JORDAN MULTIVIBRATOR CIRCUIT



The oscillatory action of the Eccles-Jordan multivibrator commences in similar fashion to most other vacuum-tube oscillators. Page 146 shows the effect of a minute positive transient impressed at the grid of tube V1. Such a transient may originate from a variety of circuit disturbances; thermal noise, shifting plate-current balance between the two tubes, nonuniform thermionic emission, or power-supply fluctuations. In any event, the positive grid potential is amplified and inverted in polarity by tube V1. The amplified pulse is derived from the plate of tube V1 and transferred, as a pulse of negative bias, through coupling capacitor C2 to the grid of tube V2. The plate current of tube V2 is thereby decreased and is accompanied by an increase in plate voltage due to the smaller voltage drop developed across plate-load resistor R3. This plate-voltage jump is returned through coupling capacitor C1 as a pulse of positive bias to the grid of tube V1. Note that this sequence of events is regenerative; the original signal, that is, the small positive transient appearing at the grid of tube V1, is reinforced by the signal fed back from tube V2. As a consequence of the circuit operation thus far considered, tube V1 has become the conducting, or *on* tube, whereas tube V2 has become the nonconducting, or *off* tube.

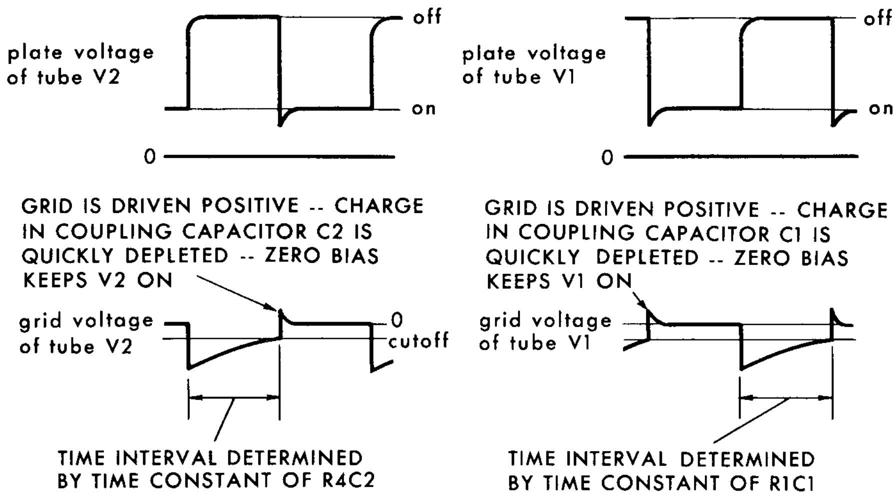
Operation of the Eccles-Jordan Multivibrator (contd.)



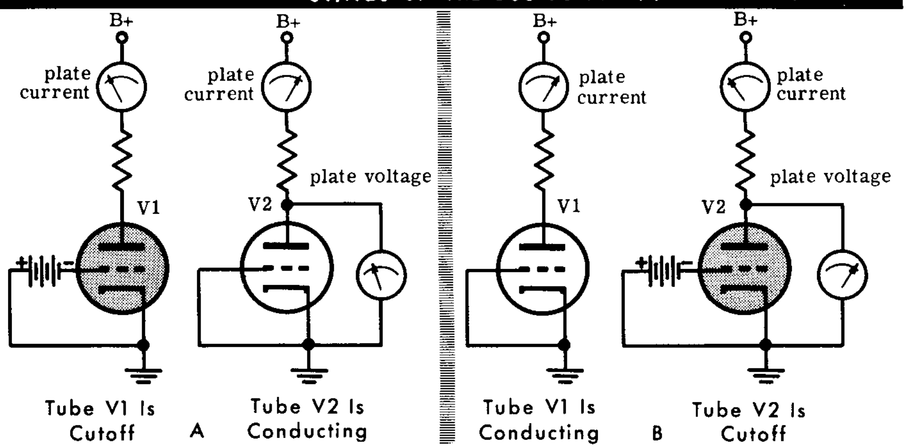
Tube V2 was switched to its *off* state by the decrease in plate voltage of tube V1. This decrease in voltage was communicated through the coupling capacitor C2 as a pulse of negative bias to the grid of tube V2. The charge accrued by capacitor C2 then leaks off through grid-return resistor R4. For an interval of time, however, the stored voltage of the charge in capacitor C2 maintains tube V2 in its *off* state. During this time, tube V1 remains in its *on* state, not because of charge stored in capacitor C1, but simply because the tubes are conductive when zero or near zero grid bias exists. (The charge stored in capacitor C1 was quickly depleted by the relatively low-resistance path provided by the positive grid with its attendant grid current.) When the charge in capacitor C2 finally becomes insufficient to maintain tube V2 in its cutoff condition, tube V2 conducts and the resulting drop in plate voltage is transferred through capacitor C1 to the grid of tube V1, cutting off plate current in that tube. Also, capacitor C1 accumulates a charge sufficient to maintain tube V1 in its *off* state until depletion of the charge through grid-return resistor R1 reduces the stored voltage below cutoff value. During this time, tube V2 remains in its *on* state by virtue of zero, or near zero grid voltage. Thus, the two tubes periodically alternate conductive states at a rate governed by voltages associated with R-C time constants. Furthermore, the switching transitions are regenerative and are therefore very rapid.

Waveforms and Equivalent Circuits of the Multivibrator

WAVEFORMS OF THE FREE-RUNNING ECCLES-JORDAN MULTIVIBRATOR



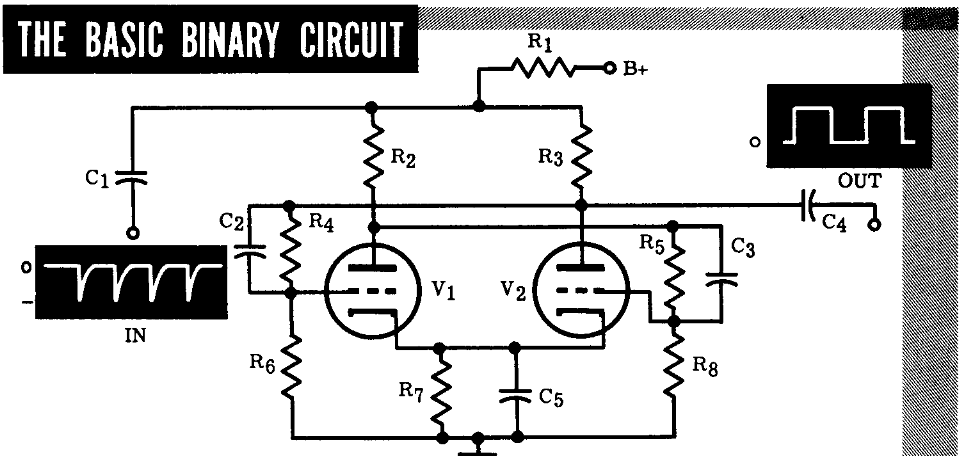
EQUIVALENT CIRCUITS OF THE CONDUCTIVE STATES OF THE ECCLES-JORDAN MULTIVIBRATOR



The waveform diagrams of the Eccles-Jordan multivibrator corresponding to the described sequence of events are shown, as are the two conductive states of the circuit. In these circuits, the charged coupling capacitor which holds one of the tubes at cutoff is represented by a battery. Tube V2 in the circuit diagram is assumed to be the output tube; that is, the output waveform is derived from the plate of this tube.

The Binary or Bi-Stable Multivibrator

The binary circuit shown is a modification of the Eccles-Jordan multivibrator which performs a unique switching operation. The additional resistors R4 and R5 are connected across the plate-grid coupling capacitors. As a consequence of these resistors fixed biases are supplied to the grids of tubes V1 and V2. These fixed biases prevent free-running operation; whichever is the *on* tube reinforces the alternate tube in the *off* state. Conversely, the *off* tube keeps the alternate tube in its *on* conductive state. Therefore the circuit is passive, without externally derived trigger pulses. It has, theoretically, an equal chance of being in one or the other of its two possible conductive states. Because of a third resistor, R1, the trigger pulses are applied symmetrically to both tubes.



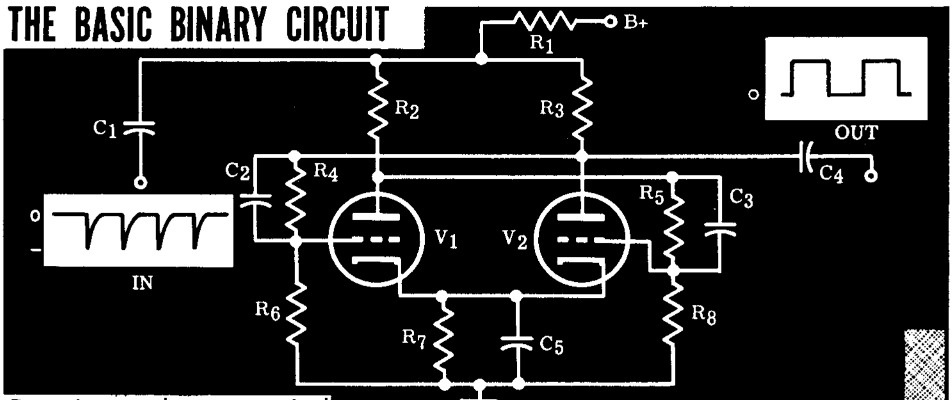
Only the grid of the ON or CONDUCTING tube is affected by negative trigger pulses

Suppose that tube V2 is *on* and tube V1 is *off*. A negative trigger pulse will be passed through capacitor C1, then through resistor R3 to the plate of tube V2. This tube, being in its conductive state, will not be effected by the negative trigger appearing as its plate because its plate voltage already is at the most negative of its two possible voltages. Furthermore, the pulse will be considerably attenuated by the shunting effect of the low plate-cathode resistance offered by V2 in its conductive state. Therefore, only a relatively weak pulse will be transferred through coupling capacitor C2 to the grid of tube V1, where it will have an insignificant effect in reinforcing the *off* state of tube V1. Thus far, we have not stimulated a disturbance in the equilibrium state of the binary. Consider, however, the effect of the negative trigger pulse which has simultaneously been distributed through plate-load resistor R2 to the plate of tube V1. The plate voltage of this tube will be quite depressed because it offers no shunting effect ir its *off* state.

The Binary or Bi-Stable Multivibrator (contd.)

The drop in V1 plate voltage is communicated through coupling capacitor C3 as a pulse of negative bias to the grid of tube V2. This causes a drop in the plate current of tube V2 and an attendant plate-voltage rise. The plate-voltage rise is communicated through coupling capacitor C2 as a pulse of positive grid bias to the grid of tube V1, where the resultant plate current increase is accompanied by a drop in plate voltage. Thus, a regenerative switching action has been initiated by the incoming negative trigger pulse. The switching action culminates with the binary-conduction state opposite to that which prevailed prior to triggering by the negative pulse; tube V1 is now the *on* tube, whereas tube V2 is now the *off* tube. The advent of a second negative trigger pulse reverses this conduction state, returning the binary to its original state with tube V1 *off* and tube V1 *on*. (Mutual cathode resistor R7 is bypassed by capacitor C5 so that this resistor does not provide regenerative coupling between the two tubes. This resistor limits the plate currents of the tubes during their *on* states to safe values. Also, following a switching transition, this resistor, carrying the conduction current of one tube, helps bias the alternate tube to cutoff.)

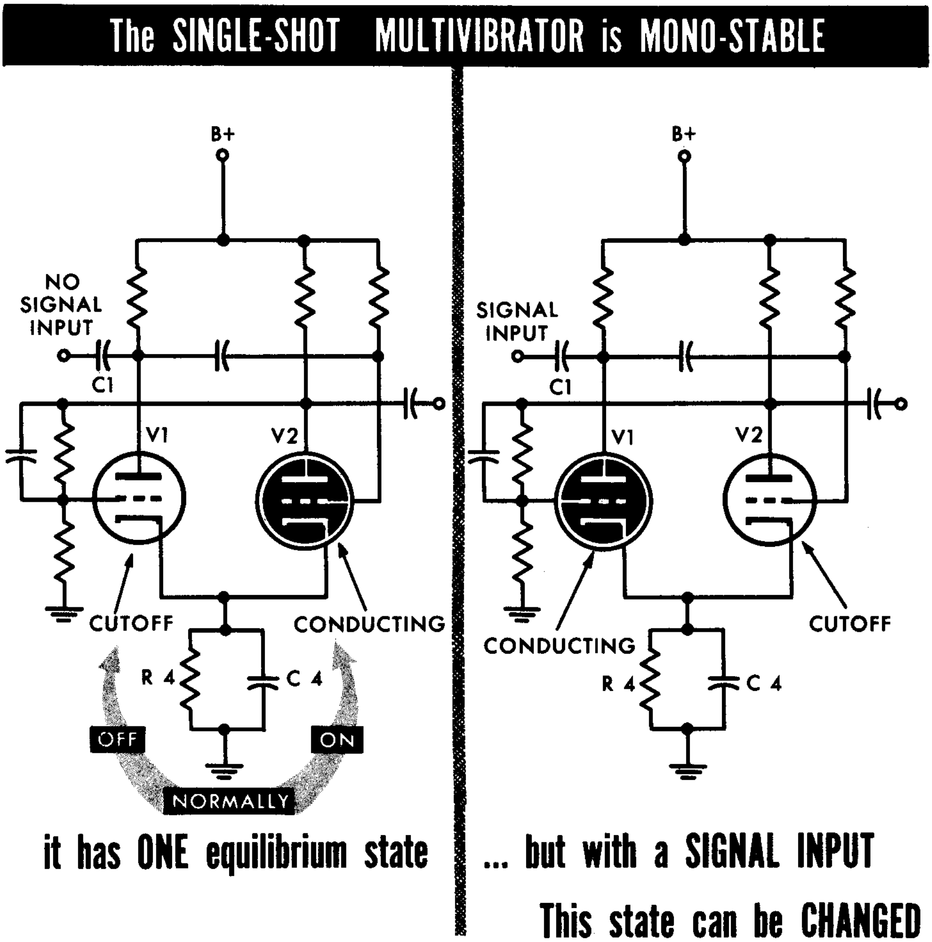
THE BASIC BINARY CIRCUIT



Two trigger pulses are required to make the circuit go through a complete multivibrator cycle.

The significant operational feature of the binary is that two trigger pulses are required to cause the circuit to undergo one complete multivibrator cycle. That is, the binary is a frequency-halver. Consequently, two cascaded binary circuits will perform frequency-division by a factor of four; three cascaded binaries will divide the pulse-repetition rate of the incoming trigger pulses by eight, and so on. This circuit is unique among relaxation-oscillator or multivibrator-frequency dividers in that no critical time constant is involved. A binary will divide by two whether the pulse-repetition rate of the trigger pulses is 10 pulses per second, 100 pulses per second, or 10,000 pulses per second. Furthermore, the binary is *bi-stable;* it will remain in either conduction state until triggered.

The Single-Shot or Mono-Stable Multivibrator

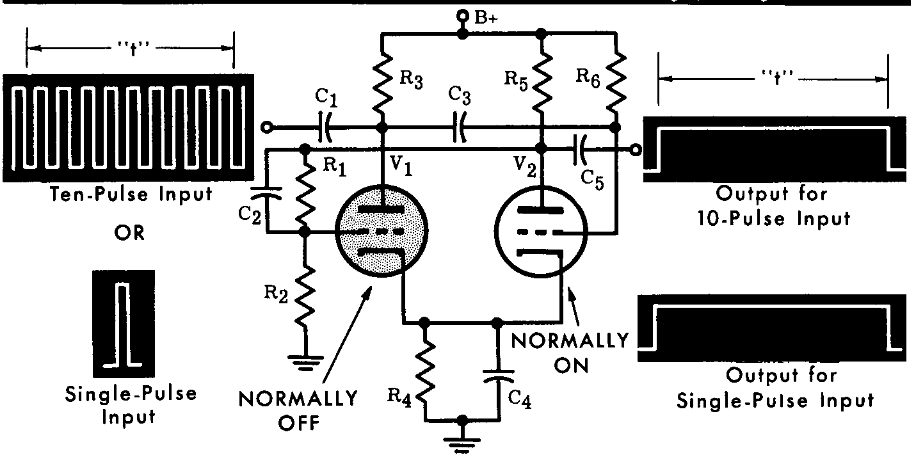


By means of a different biasing provision and signal-injection technique, another useful circuit may be derived from the basic Eccles-Jordan multivibrator. Such a circuit is the single-shot multivibrator or univibrator. The salient feature of this arrangement is that it is mono-stable; of its own accord, it prefers one equilibrium state to the alternate state. With no signal impressed at the input terminal (capacitor C1) tube V2 is in the conductive state and tube V1 is cut off. This circuit appears to be also a derivitive of the cathode-coupled multivibrator by mutual cathode resistor R4. However, the cathode resistor is bypassed by capacitor C4, so it does not constitute a feedback path during switching transitions. The same situation prevails as in the binary circuit, as concerns the function of the cathode resistor.

The Single-Shot Multivibrator or Univibrator

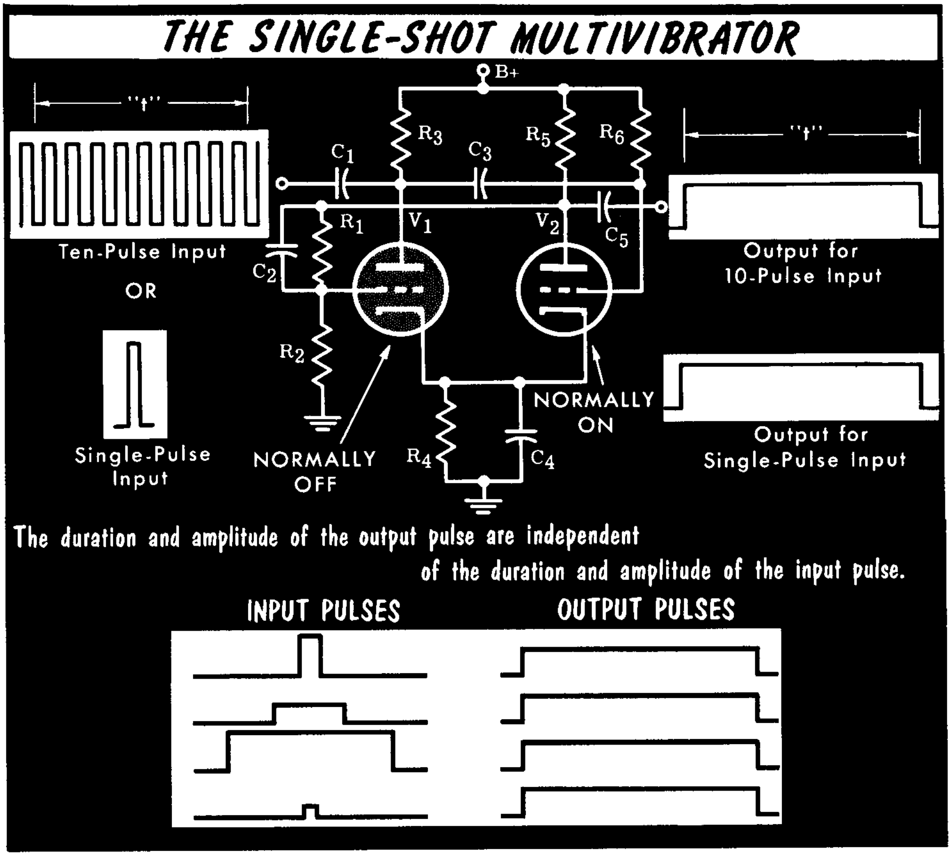
We see the single-shot multivibrator circuit as both a frequency divider and a single-shot responder which delivers a single output cycle when triggered by a single input cycle. In the latter operation, tube V2 is *on* and tube V1 is *off*, partially because of positive cathode bias developed by the conduction current of tube V2 flowing through mutual cathode resistor R4. Tube V1 is maintained in its *off* state also by tube V2 plate voltage being at the most negative (least positive) of its two possible values. Consequently, the portion of tube V2 plate voltage which appears as grid bias at tube V1 is also at its most negative value. (The grid bias applied to tube V1 is determined by the voltage-divider network composed of resistors R1 and R2.) Tube V2 remains strongly in conduction due to the connection of its grid return resistor, R6, to the positive side of the power supply.

THE SINGLE-SHOT MULTIVIBRATOR



The positive excursion of the input pulse merely urges tube V2 toward its already existing conductive state. Also, no effect is produced by the presence of the positive excursion of the input pulse at the plate of tube V1. The negative excursion of the input pulse depresses the plate voltage of tube V1 and appears as a pulse of negative bias at the grid of tube V2. This decreases the plate current of tube V2, and the attendant rise in plate voltage is communicated through crossover capacitor C2 as a pulse of positive bias at the grid of tube V1. Tube V1 is projected into its plate-current conduction region with an accompanying drop in plate voltage. The drop in tube V1 plate voltage is transferred through capacitor C3 as a pulse of negative bias to the grid of tube V2, repeating the sequence of events. This repetition of triggering events constitues regeneration. A very rapid switching transition ensues, culminating with tube V1 in its *on* (conductive) state, and tube V2 in it *off* (plate-current cutoff) state.

The Single-Shot Multivibrator or Univibrator (contd.)

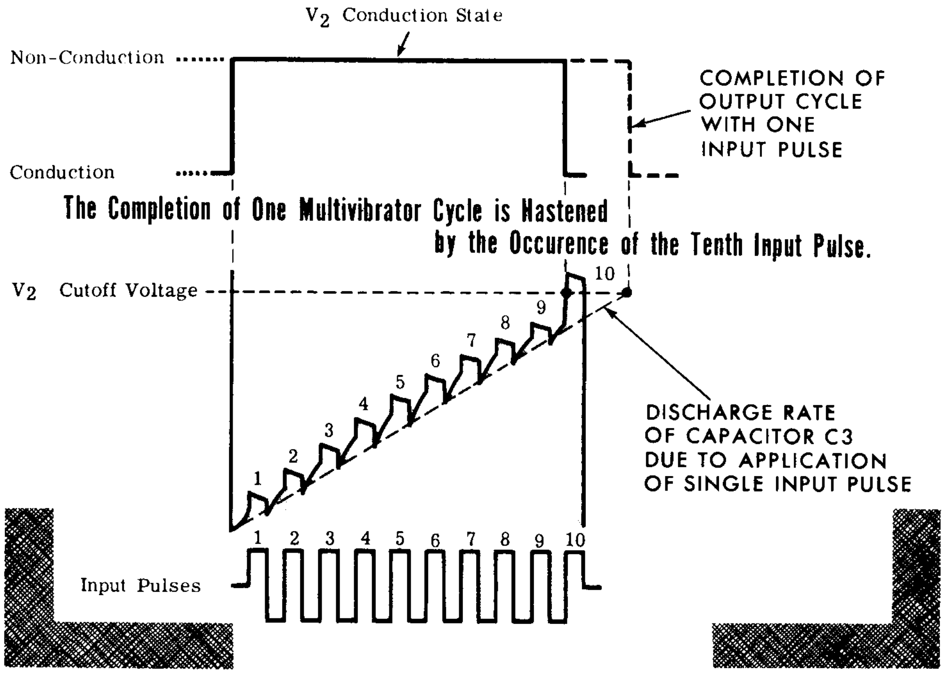


When tube V1 switched from its cutoff to its conductive state, the resultant plate-voltage drop not only appeared as a negative grid bias pulse at tube V2, but also charged capacitor C3 so that the grid of tube V2 was maintained at cutoff for some time after. The grid of tube V2 remains more negative than the voltage corresponding to cutoff until the charge stored in capacitor C3 depletes itself through resistor R6. When this occurs, tube V2 becomes conductive and initiates a regenerative switching action in the direction opposite to the transition provoked by the input trigger pulse. This switching action is very rapid and culminates with the univibrator restored to its original conductive state (tube V1 *off;* tube V2 *on*). During operation in either conductive state, mutual cathode resistor R4 enables the *on* tube to help cutoff the *off* tube. During regenerative switching, feedback occurs through cross-over capacitors C2 and C3. Capacitor C4 maintains constant voltage across mutual cathode resistor R4 long enough to prevent R4 from becoming a feedback path, as in the cathode-coupled multivibrator.

The Single-Shot Multivibrator as a Frequency Divider

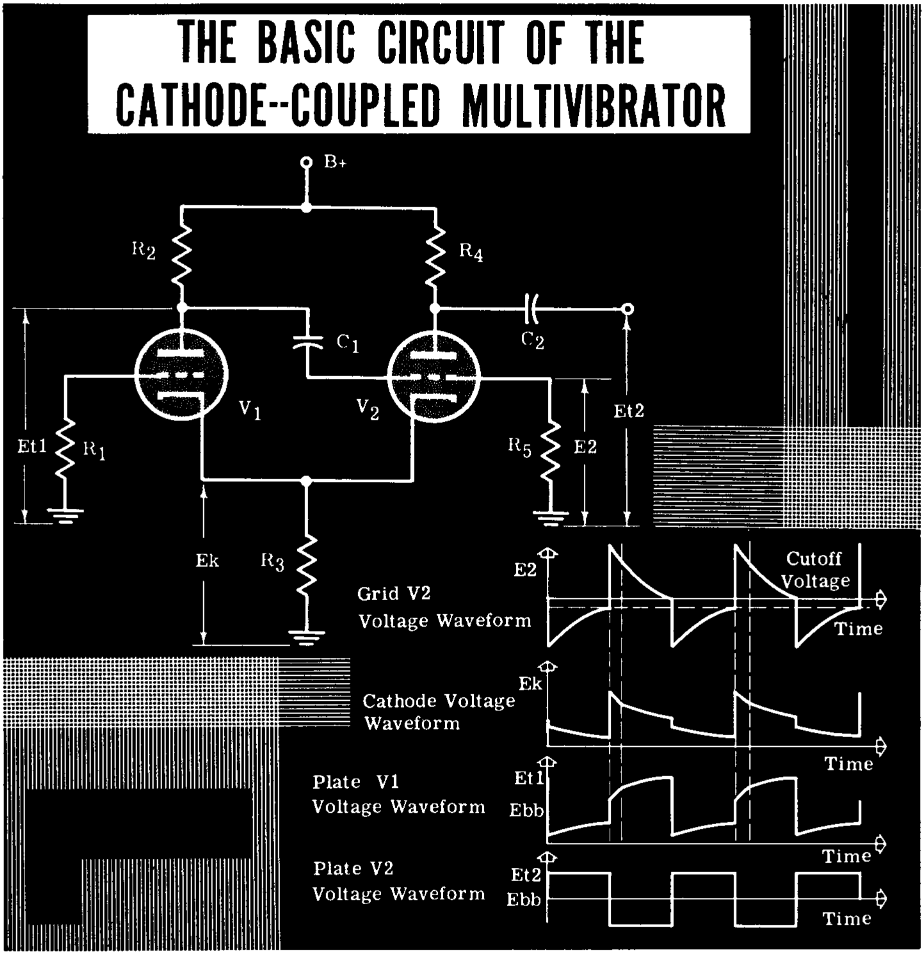
The significant performance feature of the single-shot multivibrator is that the duration of the output pulse is largely governed by the time constant of capacitor C3 in conjunction with resistor R6. It is obvious that the completion of the output pulse will be hastened by any technique which accelerates the depletion of the charge stored in capacitor C3. This fact may be used advantageously in the application of this circuit as a frequency divider.

OPERATION OF THE SINGLE-SHOT MULTIVIBRATOR AS A TEN-FOLD FREQUENCY DIVIDER



Suppose for example that we impress ten pulses at the input. Assume that the group of ten pulses encompasses a time interval slightly less than the time ordinarily required for the stored voltage in capacitor C3 to leak off through resistor R6. We see ten input pulses superimposed upon the discharge curve of capacitor C3. The *tenth* pulse projects the capacitor voltage intc the grid voltage region of tube V2 corresponding to plate-current conduction. Thus, the tenth input pulse initiates the regenerative switching action which completes the multivibrator output cycle. Since ten input pulses produce one output cycle, the circuit functions as a synchronized frequency divider, the dividing factor being ten in this example.

The Free-Running Cathode-Coupled Multivibrator

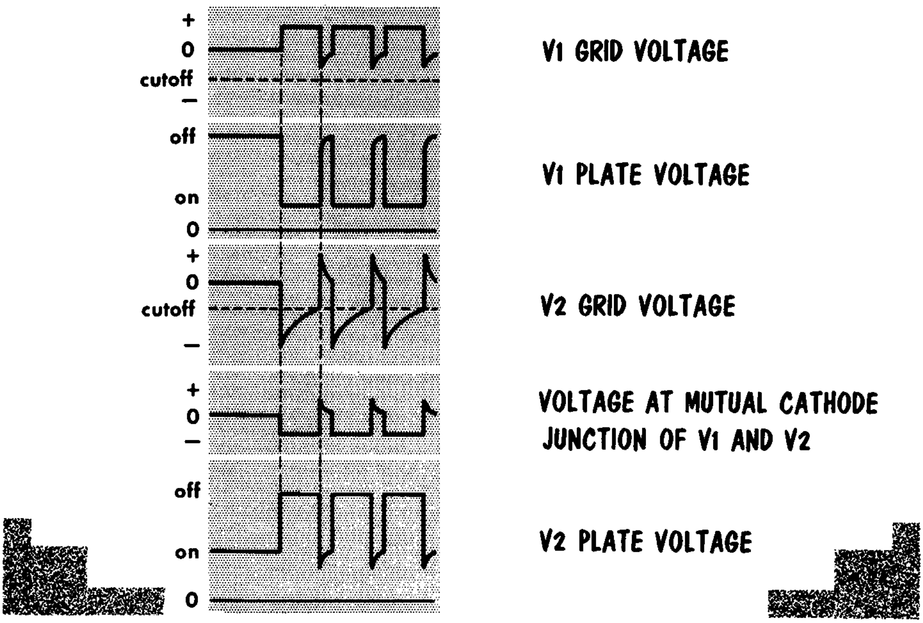


The cathode-coupled multivibrator produces results similar to those of the Eccles-Jordan multivibrator; however, circuit operation involved in the switching transitions between the two tubes is somewhat different from in the Eccles-Jordan arrangement. Let us assume that a positive transient from thermal noise in grid-return resistor R1 is impressed at the grid of tube V1. The resultant in plate-current increase in V1 is accompanied by a decrease in plate voltage due to the voltage drop developed across plate-load resistor R2. The drop in V1 plate voltage is transferred through coupling capacitor C1 as a negative pulse of bias to the grid of tube V2. This causes two effects; capacitor C1 is charged, and the plate current of tube V2 is decreased. These events are identical to those of the Eccles-Jordan circuit.

The Free-Running Cathode-Coupled Multivibrator (contd.)

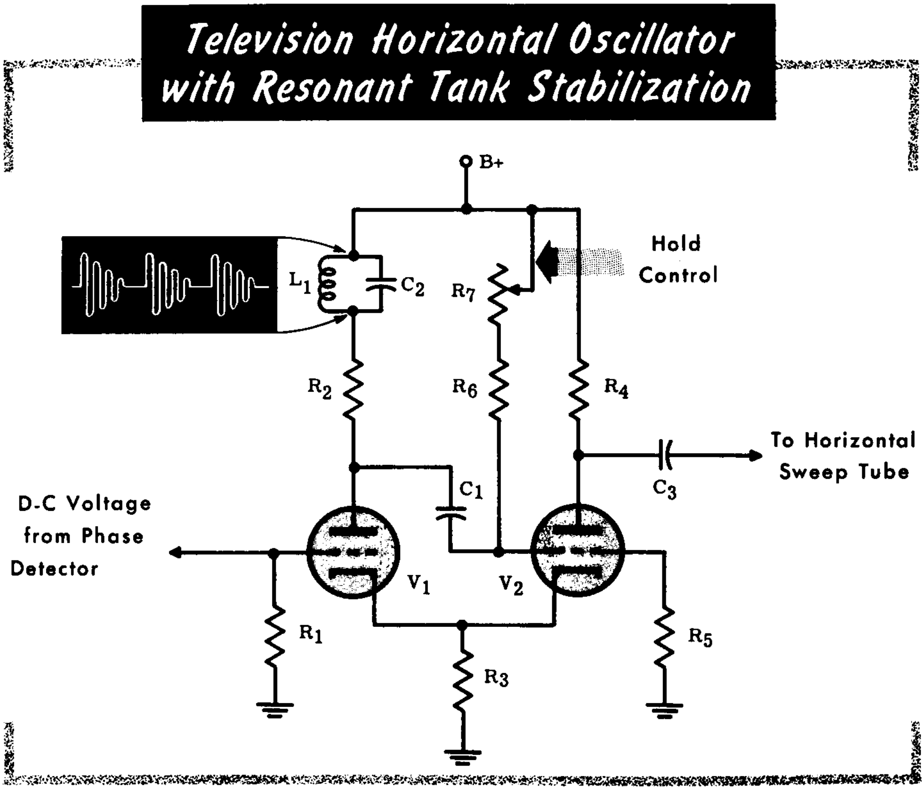
The circuitry state V1 *on*-V2 *off* endures as long as capacitor C1 maintains cutoff-bias voltage on the grid of the tube V2. This time interval is governed by the rate at which the charge stored in capacitor C1 depletes itself through the leakage path provided by grid return resistor R5. The circuit action here is again the same as that existing in the Eccles-Jordan multivibrator.

WAVEFORMS in the FREE-RUNNING CATHODE-COUPLED MULTIVIBRATOR



When capacitor C1 no longer biases tube V2 to cutoff, this tube is projected into its plate-current operating region and a positive voltage jump appears at the cathodes of tubes V1 and V2 by a mutual cathode resistor. This positive voltage produces the same effect on tube V1 plate current as would result from a negative voltage impressed at the grid of this tube, that is, V1 plate current is decreased. The plate-voltage jump which accompanies decreased plate current in tube V1 is transferred through coupling capacitor C1 as a pulse of positive bias to the grid of tube V2. This tube V2 is turned *on* and tube V1 is turned *off*. The action is regenerative-circuit operation which drives tube V2 toward the *off* state and reinforces tube V2 in the *on* state, whereupon tube V2 urges tube V1 toward its off state. The second half of the multivibrator cycle (V1 *off*-V2 *on*) endures for a *much shorter time* than the first half because the charge stored in capacitor C1 is rapidly depleted by the current-consuming positive grid of tube V2.

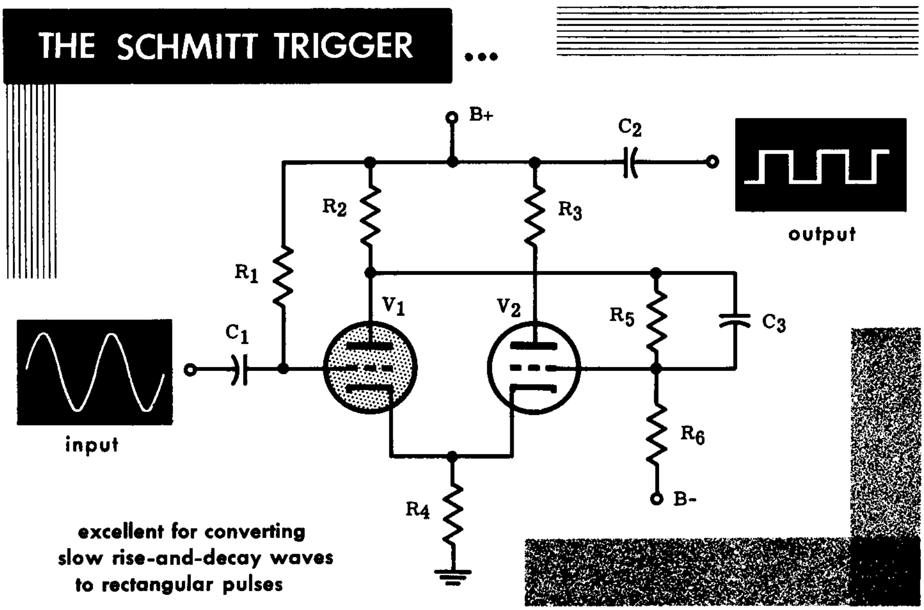
The Cathode-Coupled Multivibrator in Television Circuits



Although we have been referring to tubes V1 and V2 as *on* and *off* tubes which exchange conduction states, tube V1 generally is not completely cutoff in the free-running cathode-coupled multivibrator. In this respect, this circuit differs from the Eccles-Jordan multivibrator. If tube V1 does not remain *alive* in the cathode-coupled multivibrator, the operation of this circuit cannot be initiated by action within the circuit itself, and externally derived positive pulses are required to provoke an interchange of conduction states between the two tubes. This, too, is a useful function, as will be shown. We see a free-running cathode-coupled multivibrator such as is used as the horizontal oscillator in many television receivers. The pulse-repetition rate is controlled by *varying the d-c voltage* applied to the grid of tube V1. The pulse-repetition rate of this multivibrator is stabilized by a resonant L-C tank connected in the plate circuit of tube V1. This L-C combination rings at the desired horizontal sweep rate (15,750 cycles). The shock-excited oscillations produce a synchronizing effect in much the same manner that an externally derived 15,750-cycle signal would tend to lock the multivibrator at that pulse-repetition rate.

The Schmitt Trigger

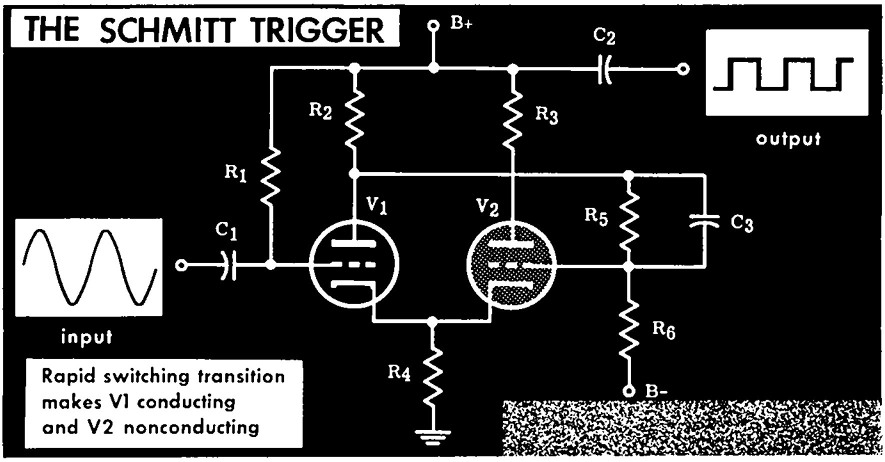
Appropriate biasing provisions convert the basic cathode-coupled multivibrator to the Schmitt Trigger Circuit. The operation of this circuit resembles that of a single-shot multivibrator with the exception that here both the leading and the trailing edges of the generated pulse are timed by the triggering wave. The Schmitt Trigger is extremely useful for converting waves with slow rises and decays to rectangular pulses having steep edges. In this circuit, tubes V1 and V2 alternate their conduction states in response to the rise and fall of the positive excursion of the input triggering cycles. The conduction current of the *on* tube flowing through mutual cathode resistor R4 always reinforces the alternate tube in its *off* conductive state. Free-running operation is prevented by resistors R1 and R5, as well as by the application of a negative voltage to the grid of tube V2 through grid-return resistor R6. Consequently, in the absence of an input triggering wave, the circuit can remain at equilibrium in either of its two conductive states. Such an arrangement is said to be bi-stable.



Assume tube V2 is *on* and tube V1 is *off*. Under this condition, tube V1 is maintained in its *off* state by the cathode bias due to the conduction current of tube V2 flowing through mutual cathode resistor R4. Since the plate voltage of tube V1 is at the most positive of its two possible values, sufficient positive grid voltage is applied through resistor R5 to the grid of V2 to keep that tube in its *conductive* state. Thus, we have the stable equilibrium state with tube V2 conducting and tube V1 cutoff.

The Schmitt Trigger (contd.)

Consider now the effect of the rising positive excursion of a sine wave applied to capacitor C1. This sine wave is transferred through capacitor C1 and, during its positive rise, counteracts the effect of the positively biased cathode of tube V1. Ultimately, the rising sine wave attains a voltage sufficiently positive to overcome the cutoff effect produced by the cathode bias, and the tube is projected into its plate-current conduction region. The resultant reduction in VI plate voltage decreases the positive bias applied through resistor R5 to the grid of tube V2. The diminished conduction current produced in tube V2 then develops less cathode biasing voltage across mutual cathode resistor R4. This, in turn, drives tube V1 further into its plate-current conduction region. This is a regenerative process, since the conduction change occurring in either tube is enhanced by the alternate tube. A very rapid switching transition ensues, culminating with tube V1 conducting, or *on*, and tube V2 nonconducting, or *off*.

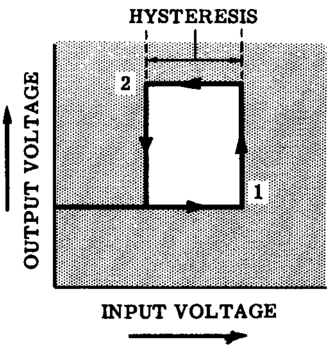


The input sine wave continues its rise and reaches its peak positive value. This produces no further effect in the Schmitt Trigger, but only reinforces the prevailing conduction state (V1 *on*-V2 *off*). As the input sine wave declines from its peak positive value, it passes through the positive voltage corresponding to the value which produced the first switching transition. However, a second switching of the Schmitt Trigger does not occur until the input sine wave falls to a positive voltage somewhat *lower in* value than the triggering voltage associated with the rise of the sine wave. The difference between the two triggering voltages is called the voltage hysteresis of the circuit. The existence of triggering voltage hysteresis is due to the nonsymetrical configuration of the circuit. It is possible to decrease the hysteresis by changing grid-bias parameters. However, as the hysteresis is decreased, the circuit becomes more susceptable to free-running operation.

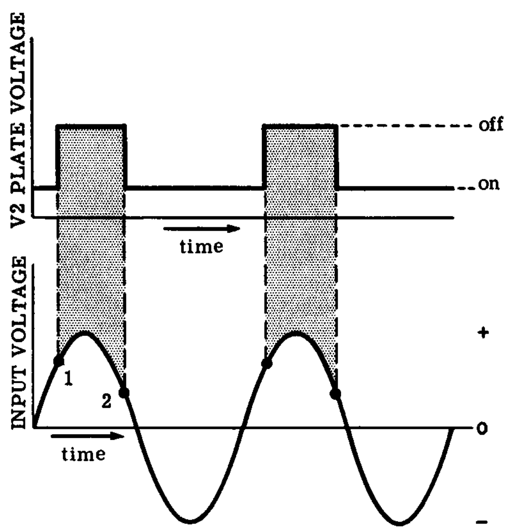
The Schmitt Trigger (contd.)

When the declining sine wave passes through the positive voltage value sufficiently low to release tube V1 from its conductive state, the resultant rise in V1 plate voltage biases the grid of tube V2 positively, projecting this tube into its conductive region. The conduction current of tube V2 flows through mutual cathode resistor R4, developing a positive bias at the cathode of tube V1. This cathode bias reinforces the trend toward plate-current cutoff in tube V1 which was initiated by the decline of the input sine wave to a sufficiently low value. Thus, the circuit transition is regenerative.

SCHMITT TRIGGER OPERATING CHARACTERISTICS



Input Trigger-Voltage Hysteresis -- a Higher Positive Voltage Must be Attained by the Input Wave to Trigger than to De-trigger the Circuit



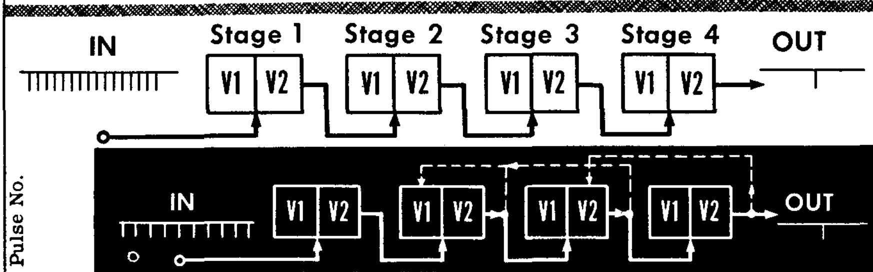
The Relationship between the Input Triggering Wave and the Conduction State of Output Tube V2

A very rapid switching action ensues, ending with tube V1 in its *off* state and tube V2 in its *on* state. The Schmitt Trigger has been restored to its originally assumed conductive state. The negative excursion of the input sine wave does not effect the conductive state of the Schmitt Trigger; no further switching transition is triggered until the sine wave undergoes its next positive excursion and attains a suitably high positive voltage. When this occurs, the action is repeated.

The Multivibrator in Counting Circuits

Each stage of the four cascaded binary stages functions as a frequency-halver in which two incoming pulses cause the generation of a single output pulse. Therefore, cascading binary stages result in frequency division (or pulse-repetition rate division) by a factor of 2^n, where n equals the number of stages. For example, the system of four cascaded binary stages produces division by 2^4 or 16. That is, 16 incoming pulses will cause the generation of a single output pulse. Such a binary is called a scale-of-16 counter.

DIGITAL COUNTING An Important Application of Binaries



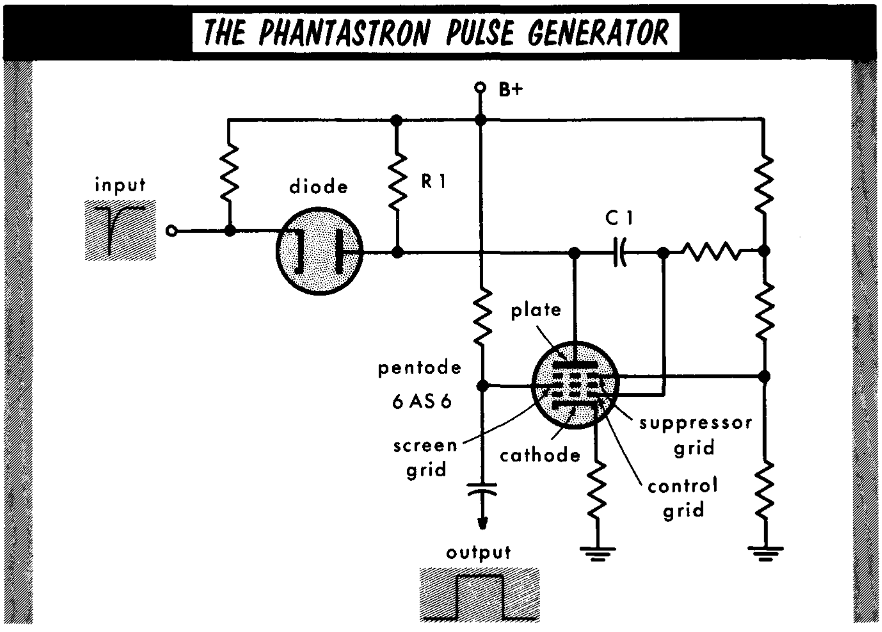
Incoming Pulse No.	Without Feedback: V2 Stage 1	V2 Stage 2	V2 Stage 3	V2 Stage 4	With Feedback: V2 Stage 1	V2 Stage 2	V2 Stage 3	V2 Stage 4
0	ON	ON	ON	ON	ON	ON	ON	ON
1	OFF	ON	ON	ON	OFF	ON	ON	ON
2	ON	OFF	ON	ON	ON	OFF	ON	ON
3	OFF	OFF	ON	ON	OFF	OFF	ON	ON
4	ON	ON	OFF	ON	ON	OFF	OFF	ON
5	OFF	ON	OFF	ON	OFF	OFF	OFF	ON
6	ON	OFF	OFF	ON	ON	ON	OFF	OFF
7	OFF	OFF	OFF	ON	OFF	ON	OFF	OFF
8	ON	ON	ON	OFF	ON	OFF	OFF	OFF
9	OFF	ON	ON	OFF	OFF	OFF	OFF	OFF
10	ON	OFF	ON	OFF	ON	ON	ON	ON
11	OFF	OFF	ON	OFF				
12	ON	ON	OFF	OFF				
13	OFF	ON	OFF	OFF				
14	ON	OFF	OFF	OFF				
15	OFF	OFF	OFF	OFF				
16	ON	ON	ON	ON				

The Decade-Counting Unit is Made by Adding Feedback Paths to the "Scale of 16" Counter

The addition of two feedback paths returns triggering pulses to stage 2 and to stage 3 so that the chain of binaries is caused to deliver one pulse for every 10 received. Furthermore, each of the 10 applied pulses produces a unique combination of *on* and *off* states which can be indicated by numbered neon lamps. This constitutes the decade-counting unit which is the heart of the decimal digital computer. Note that without feedback, 16 pulses must be applied to cause V2 of stage 4 to complete one cycle. With feedback, only 10 incoming pulses are needed.

The Phantastron

An interesting circuit encountered in pulse work is the *phantastron,* which produces much the same result with a single pentode tube as do the more common two-tube section multivibrators. The operation of the phantastron depends upon the different control actions exerted by the control and the suppressor grids of a pentode such as the 6AS6. Note that the control grid governs the *total space current* within the tube; the suppressor grid controls the *division of space current* between screen grid and plate. To aid the understanding of this somewhat unusual circuit, recall that a diode conducts when its cathode is negative with respect to its anode, but acts as an open switch for the opposite polarity condition.

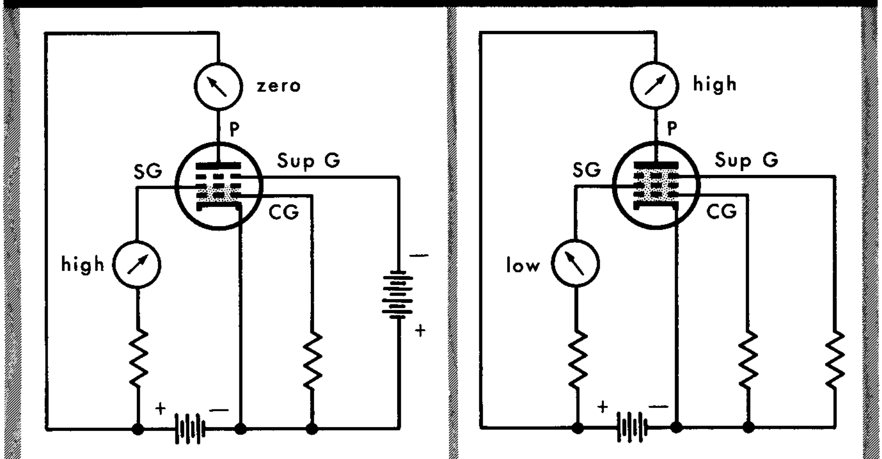


The circuit shown is one of several varieties of the phantastron. All share a common operating mode wherein abrupt switching of the electron stream occurs as a result of an interchange of actuating signals appearing at the control and suppressor grids. The circuit shown is *monostable.* In the quiescent state, the control grid bias is zero and the total space current is high. Due to the voltage drop developed across the cathode resistor, the suppressor grid is impressed with a bias sufficiently negative to cutoff the plate current. Accordingly, screen-grid current is high and screen-grid voltage low due to the resultant voltage drop across the screen-grid resistor. With no plate current flowing, plate voltage is at the highest positive value of its operating cycle.

The Phantastron (contd.)

A positive pulse impressed at the input of the phantastron will not pass through the isolating diode. However, a negative pulse *will* feed through, lowering the plate voltage and delivering a negative bias to the control grid. The latter action causes a reduction in total space current (which has been intercepted by the screen grid.) In turn the voltage drop across the cathode resistor is no longer sufficient to maintain plate-current cutoff bias on the suppressor grid.

THE TWO SPACE-CURRENT CONDITIONS OF THE PHANTASTRON



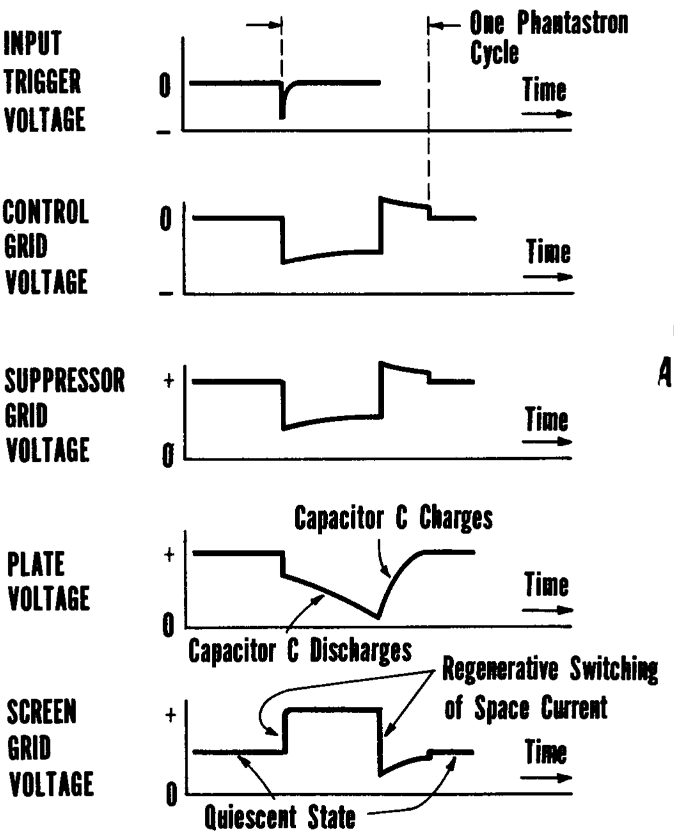
High negative voltage applied to suppressor grid cuts off plate current.

Relative values of plate and screen grid voltages reverse themselves when negative voltage is removed from the suppressor grid.

A portion of the space current now reaches the plate, manifesting itself as *plate current* in the external circuit. The accompanying drop in plate voltage constitutes a negative transient which, as with the original trigger pulse, passes through the capacitor and increases the negative bias on the control grid. Thus the circuit-operating change caused by the negative trigger is *reinforced,* i.e., the action is *regenerative.* The resulting abrupt switching of the space current within the tube culminates the first phantastron switching cycle. The screen grid voltage is now at its highest value. We note that the plate voltage does not respond immediately to the switching action of the tube, due to the time constant of the capacitor C1 and the resistance of the discharge path provided to ground by the several resistors associated with C1.

The Phantastron (contd.)

After the charge stored in capacitor C1 by the tube's first switching cycle has depleted itself, the control grid loses its negative bias. Ultimately, tube-space current is again sufficiently high to develop a suppressor-grid biasing voltage across the cathode resistor that switches space current from plate to screen grid. However, the circuit does not return to its quiescent state until capacitor C1 recovers its charge through R1.



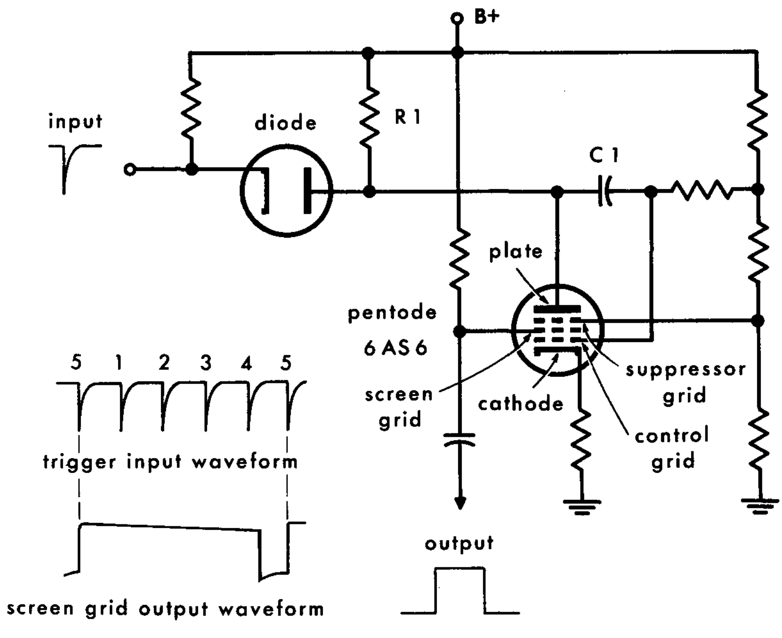
VOLTAGE WAVEFORMS AT THE INPUT AND AT THE ELECTRODES OF THE PHANTASTRON OSCILLATOR TUBE

Each time the switching mechanism occurs within the tube, time is required for capacitor C1 to change its state of charge. The second switching cycle is regenerative, because the charging action of C1 transfers a positive pulse to the control grid, thereby speeding up the return to high space current. Although capacitor C1, in conjunction with its charge and discharge paths, governs the length of the complete phantastron cycle, regeneration causes the switching actions to produce steep wavefronts. This circuit is an excellent time delay, generally capable of better precision and stability than are more conventional multivibrator circuits.

The Phantastron (contd.)

A unique frequency divider is obtained by impressing a periodic wavetrain of negative pulses at the input. Frequency division occurs because the phantastron is periodically triggered by input pulses which are sufficiently spaced in time to re-trigger the phantastron at the culmination of its inherent cycle. The triggers do not speed up the charge or discharge cycle of the timing capacitor, as is true with other circuits. If we divide by *five,* the first pulse initiates the phantastron cycle. The *second, third, fourth,* and *fifth* pulses produce no effect, and could conceivably be absent. However, if the phantastron time constant is correct, its cycle will terminate at some time between the fifth and sixth input pulse. Therefore, the phantastron will be in its quiescent state at the occurrence of the *sixth* pulse, and will again be triggered by it.

THE PHANTASTRON PULSE GENERATOR



What we have described constitutes division by *five;* if we were to produce simple synchronization (division by one) the *second* pulse would be used to re-trigger the phantastron; if we wished to produce division by two, it follows that the phantastron cycle would have to be adjusted to permit re-triggering by the *third* pulse, and so on for other dividing factors.

QUESTIONS

1 A simple gaseous-diode relaxation oscillator is constructed and placed in operation. By progressively decreasing the capacitance, higher pulse-repetition rates are obtained until approximately 10,000 pulses per second are generated. Slightly higher pulse-repetition rates are obtainable from slight changes in the source voltage and the charging resistance. However, it is obvious that some limitaing factor prevents any appreciable increase in pulse-repetition rate. What is this factor?

2 What characteristic of the gaseous diode is responsible for its ability to function as a switch across the capacitor in the relaxation oscillator?

3 Cite advantages of the thyratron relaxation oscillator over circuits employing the gaseous diode.

4 What advantages do multivibrator circuits employing vacuum tubes have over pulse generators designed around gaseous tubes?

5 The oscillation frequency at which a blocking oscillator would operate if supplied with bias proper to prevent periodic blocking is governed largely by the L-C parameters asociated with the feedback transformer. What effect does this frequency have upon operation during normal self-pulsing operation?

6 Why can the binary be considered both a frequency divider and a frequency multiplier?

7 It is desired to drive a 60-cycle electric clock from a 1920-cycle tuning fork. How many binary stages must be cascaded to provide the required frequency division?

8 What trouble can occur in a power supply employing a voltage-regulator tube if a filter-capacitor is connected across the regulating tube?

9 Why does the Schmitt Trigger Circuit produce better square waves from a sinusoidal source than do limiting amplifiers or clippers?

10 Why is it best to cascade univibrator frequency dividers when the required dividing factor is greater than 10?

GLOSSARY

Amplifier—A circuit used to increase the strength of an input signal. The voltage, current, or power of the signal may be increased by the amplifier, which is a vacuum tube or transistor and associated circuitry (stage).
Amplitude Distortion—The changing of a waveshape through circuitry so that it is no longer a replica of the original wave. Amplitude distortion always is accompanied by harmonic distortion.
Area Redistribution—A method of measuring the duration of irregularly shaped pulses. A rectangle is drawn having the same peak amplitude and the same area as the original pulse under consideration. Because the same time units are used in measuring the original and the new pulse, the width of the rectangle is considered the duration of the pulse.
Bandpass Filter—A filter which passes a narrow band of frequencies and rejects frequencies on either side of the desired band.
Binary—Another name for the bi-stable multivibrator.
Blocking Oscillator—An oscillator which, due to plate saturation, cuts itself off after one or more cycles.
Clamping Circuit—A circuit which maintains the extremities of a wave (either the positive or negative extreme or both) at a fixed voltage level. One form of clamping circuit is the d-c restorer.
Counting Circuit—A circuit which receives uniform pulses representing units to be counted, and which produces a voltage amplitude proportional to the frequency of the input pulses.
Critical Damping—The dissipation of the energy in a shock excited L-C-R circuit such that the oscillation is restricted to a single half-cycle. Critical damping is caused by selection of the proper value of a damping resistor.
D-C Component—The net level which exists in an asymmetrical waveform (a wave or pulse which is not symmetrical about a baseline). Such a waveform has a net d-c component between baseline and the peak wave value.
Differentiation—The process whereby an output voltage is produced which is proportional in amplitude to the rate of change of the input voltage.
Duration—The length of time that a pulse persists. In a regular rectangular pulse, the persistence period is readily ascertained. For other pulses, special procedures are used to measure pulse duration. (See Area Redistribution and Energy Redistribution)
Duty Cycle—The ratio of pulse duration to pulse period.
Energy Redistribution—A method of finding the duration of an irregularly shaped pulse by considering it as a power curve. The area under the curve can be represented by an equivalent rectangle of the same area and peak amplitude. The original-pulse duration is equal to the rectangle width.
Eccles-Jordan Multivibrator—A free running multivibrator circuit which attenuates between two conductive states.
Effective Value—The equivalent heating value of an a-c current or voltage which would be produced by a direct current or voltage. For sine waves, the effective value (also called the rms value) is 0.707 of the peak value of the sine wave. The rms values of irregular waveforms can be calculated.
Exponential Waveform—A waveform which is characterized by smooth

curves but which possesses pulse properties because it contains numerous constituent frequencies. The exponential waveform undergoes a rate of amplitude change which is either inversely or directly proportional to the instantaneous amplitude.

Frequency Multiplier—A type of amplifier whose output is rich in harmonics. The frequency multiplier is most effective when operated class C and the plate-tank circuit can be tuned to multiples of the input frequency.

Fourier Analysis—A mathematical method for determining the constituent frequencies of periodic pulse trains.

Fall Time—Time for a pulse to fall from 90% of its peak amplitude to 10%.

Gas Tube—A tube filled with gas at low pressure in order to obtain certain operating characteristics, usually abrupt conduction states.

Harmonic—An integral multiple of a fundamental frequency. The fundamental is considered as the first harmonic. The third harmonic would be three times the frequency of the fundamental.

High-Pass Filter—An R-C, L-R or L-C network designed to attenuate all frequencies below a certain value.

Inductance—The ability of a circuit to generate a counter-emf as the consequence of change of current flow. The greater the opposition to a given change in current, the higher the counter-emf and the greater is the circuit inductance.

Integration Circuit—A circuit whose output voltage is approximately proportional to the frequency and amplitude of the input voltage.

Ionization—The process of ion production within the envelope of a gas tube through electron bombardment of the gas molecules.

Low-pass Filter—An R-C, L-R or L-C network which is designed to pass frequencies up to a certain value and attenuate frequencies exceeding it.

Mono-stable Multivibrator—A type of relaxation oscillator which has only one steady state. When triggered, this multivibrator temporarily assumes its unstable state and then reverts to the steady state after a period of time which is determined by the circuit constants of the multivibrator.

Non-linear Distortion—A distortion of the input waveform by the nonlinear characteristics of the circuit components.

Saturable Inductor—A special type of iron-core inductor in which a low value of current brings the core to magnetic saturation. The nonlinear characteristic of this inductor can produce sharp pulses directly from sine waves.

Schmitt Trigger—A type of multivibrator in which the occurrence of both the leading and trailing edges of the output square wave are determined by discrete amplitude levels of the input wave.

Synchronization—Forcing a normally free-running oscillator to keep in step with a special frequency called a synchronizing frequency.

Transient—Any rapid change in voltage or current.

Thyratron—A hot-cathode gas-discharge tube with one or more control grids to control the firing point of the tube.

Zero-axis Symmetry—A type of symmetry in which the waveform is symmetrical about an axis and does not exhibit a net-d-c component.

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